# Raising Tibet

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**Thermochronologic, sedimentologic, oceanographic, and paleoclimatic studies suggest that rapid uplift and unroofing of southern Tibet began about 20 million years ago and that the present elevation of much of the Tibetan plateau was attained by about 8 million years ago. Hypotheses advanced to explain the tectonic evolution of the India-Asia collision, which began about 40 to 50 million years ago, predict the timing and rates of crustal thickening of the southern margin of Asia. However, these models do not predict the prominently enhanced early Miocene denudation and uplift that are manifested in a variety of geological records. A model involving continental extrusion, development of a crustal-scale thrust ramp of the Main Central Thrust beneath the Gangdese belt, and lithospheric delamination provides a history consistent with these observations.**

The northward convergence of India into Asia over the past 40 to 50 million years has resulted in an uplifted region of such exceptional extent (nearly half that of the conterminous United States) and elevation (averaging 5 km throughout Tibet and the Himalaya) that its equal has probably not existed on this planet for over 1 billion years (Fig. 1). Our fortune in arriving in time to witness this continent-continent collision in progress is the wealth of information available from sources, such as seismic activity, geodetic changes, and sea-floor magnetic stripes (from which the amount of convergence between India and Asia can be calculated), that are generally unavailable when studying older orogens. It is then all the more ironic that, despite these privileged geophysical insights, details of the timing and mechanisms responsible for creation of the Himalaya and the Tibetan plateau remain the subject of considerable dispute.

Because the controversy is principally how the crust came to be thickened rather than what the details of its present structure are (although the two are ultimately related), its résolution requires knowledge that cannot be gleaned from our present-day snapshot of the collision. To answer questions concerning evolutionary paths, one requires constraints on crustal motions over the entire period since collision began. An approach that could determine how much surface uplift and unroofing has taken place, and how it was distributed both spatially and temporally, could aid our understanding of the collision zone because proposed tectonic models make very different predictions about the progress of surface uplift and denudation (by erosional or tectonic processes).

In this article we first review existing tectonic models and then describe several lines of evidence that point to (i) an event in the early Miocene during which there was a dramatic increase in denudation most likely related to crustal thickening and uplift of southern Tibet and (ii) uplift of the Tibetan plateau to something approaching its present form beginning by ~8 million years ago (Ma). We use these observations to derive an internally consistent model containing original and borrowed elements.

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## Theories on the Origin of the Tibetan Plateau

Theories seeking to explain the present structure of the Indo-Asian collision have been proposed in contemporary form since 1924 (*1*). With the acquisition of modern geophysical data, this process has accelerated over the past 20 years with the introduction of new and revised models that are remarkable for their number, diversity, and often seemingly mutual independence (*1–13*).

*Underthrusting of India.* Originally suggested by Argand [in (*1*)], this outwardly attractive model has enjoyed widespread support (*1, 2*). In this proposal, virtually the entire Tibetan plateau is underlain by Indian lithosphere as a result of a continental-scale, ramp-flat thrust (Fig. 2). However, the low S-wave velocities in the upper mantle underlying Tibet (*14*) are inconsistent with the presence of cold, underthrusted lithosphere of the Indian shield beneath Tibet, although a variation of the underthrust model allows that the entire Tibetan mantle lithosphere may have been delaminated (*15*). No evidence for the northward progression of surface uplift from the suture zone at a rate similar to that of the motion of the Indian plate, another model prediction, has yet been obtained. Although uncertainties are large, paleomagnetic studies do not detect greater northward movement of the Indian plate relative to central or southern Tibet since collision began (*16*). These results suggest that less than about one-third of the approximately 2000 to 2500 km of convergence between India and Eurasia since collision began was accommodated by the underthrusting of India, and about one-half of that value was taken up along major thrust faults in the Himalaya. However, the overall role of thrusting along and near the northern margin of the Tibetan plateau, currently occurring at rates approaching those of the Himalaya (*17*), is not well constrained.

*Delayed continental underplating.* Powell (*3*) proposed that from 20 to 5 Ma the Indian lithosphere subducted into the mantle beneath Tibet at an angle of about 30° (Fig. 2). It is hypothesized that at 5 Ma the Indian continental lithosphere rose toward the base of the Tibetan crust, causing uniform, isochronous uplift of the plateau at about 2 Ma. This model shares many of the shortcomings of the underthrusting model but additionally requires that an extraordinarily fluid mantle lithosphere and asthenosphere overlie the subducted continental crust (*3*).

*Continental injection.* Zhao and co-workers (*4*) proposed that the Tibetan lower crust has behaved as a relatively low-viscosity fluid into which additions from India were assimilated; the additional volume acts to raise the plateau hydraulically (Fig. 2). Their model predicts that the entire plateau was raised as an integral unit and that significant topography did not appear until the middle Miocene. However, as described later, it appears that much of the uplift and unroofing of Tibet occurred in distinct episodes and that southern Tibet unroofed independently of the rest of the plateau. Bird [in (*18*)] proposed that Tibet migrated northward by lateral extrusion of lower crust in response to elevated topography—a modification containing elements both of this model and of distributed shortening.

*Distributed shortening.* In this model (Fig. 2), about 50% shortening of the Tibetan lithosphere produced the roughly double-normal-thickness crust (*5*). However, the surface expression of deformation north of the Lhasa block (Fig. 1) expected to result from this magnitude of shortening is not easily recognized (*5, 19, 20*). Eocene clastic sedimentary rocks in the Fenghuo Shan, central-northern Tibet, are shortened by folding and thrusting by at least 50% over a distance of 100 km (*19*). Tertiary compressional deformation is reported in the Ayak Kum Kol basin of northern Tibet (*17*) that suggests several tens of percent of post-Miocene shortening over a distance of about 125 km. The problem is in generalizing these observations to the majority of the plateau where there are rocks that have been similarly deformed, but it remains uncertain if this shortening is a result of the collision. A quantitative version of this model, in which it is assumed that vertical-plane strain is distributed in a viscous plate, predicts that the lithosphere thickened and uplifted progressively northward from the suture and that the entire plateau was further uplifted when the thickened mantle lithosphere was removed (*8*). However, the presence of coarse Eocene red beds in the Fenghuo Shan (*5*), indicative of vertical crustal motion in northern Tibet shortly after collision, is inconsistent with a uniform northward migration of crustal thickening with time. The numerical calculations have proven valuable in exploring the role of thickening versus convergence in dictating deformation mode, but the relevance of the computer prediction to Tibet is limited by restrictions placed on the behavior of the lithosphere. The model describes the lithosphere as a continuum in which flow occurs according to a vertically averaged power-law relation and thus cannot predict the appearance of the thrust and strike-slip faults that have been important deformational styles during collision (Fig. 1).

*Continental extrusion.* It has been proposed that as much as 40 to 60% (*13*) of the northward convergence of India has been taken up by horizontal-plane strain—the localization of deformation along

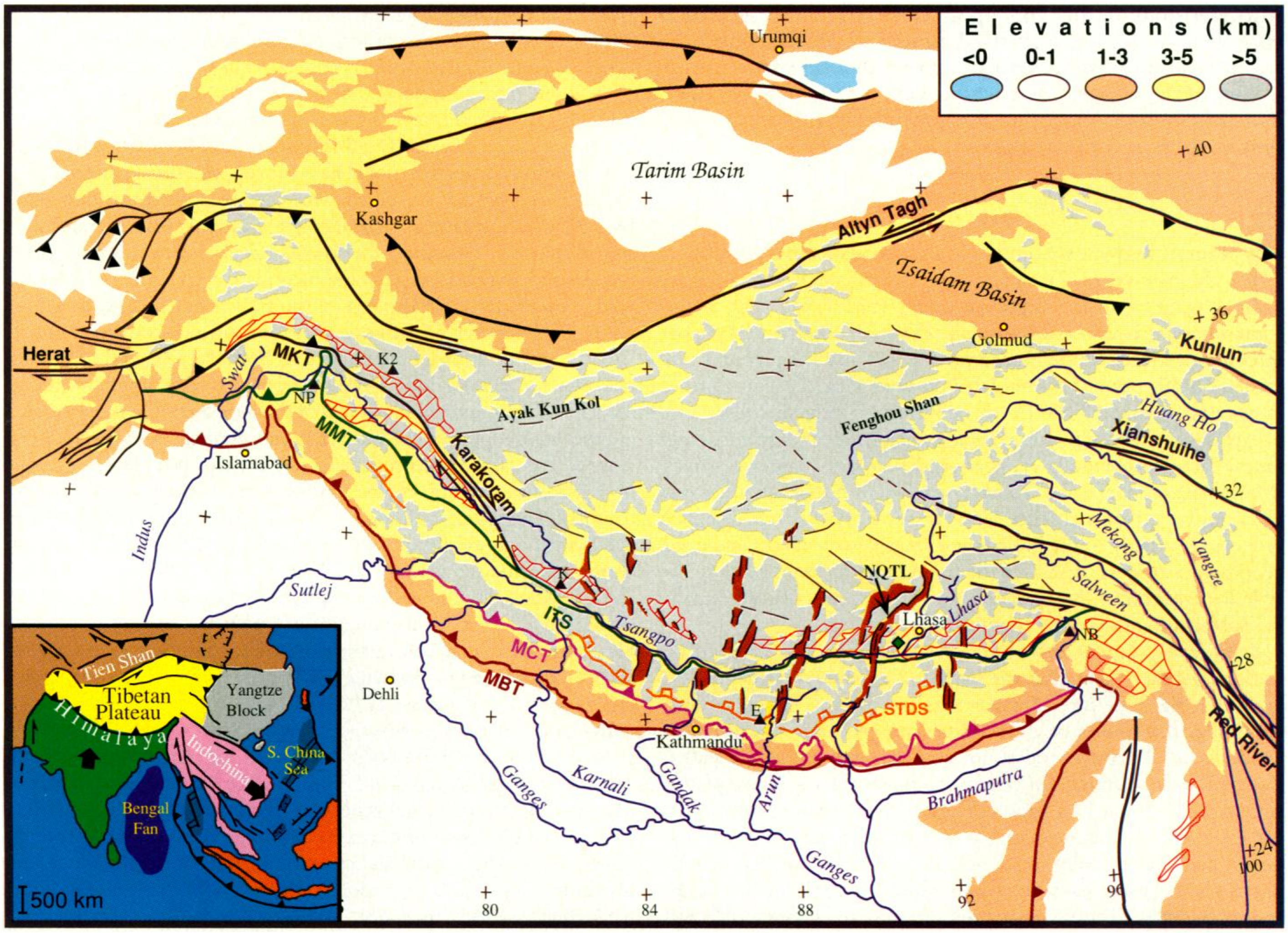


**Fig. 1.** Geological sketch map of the Tibetan plateau and the Himalaya. Heavy lines with triangles are thrust faults that point in dip direction, MBT is the Main Boundary thrust (brown), MCT is the Main Central thrust (purple), MKT is the Main Karakoram thrust (black), and MMT is the Main Mantle thrust (green); STDS is the Southern Tibetan detachment system (orange), horizontally striped patterns are late Neogene grabens, and heavy black lines are strike-slip faults with relative motions shown (Red River, Xianshuihe, Altyn Tagh, Kunlun, Herat, and Karakorum); ITS is the Indus-Tsangbo suture (green); Gangdese belt is shown by red oblique striped pattern; major rivers are identified in navy italics. Selected peaks shown: E, Mt. Everest (8848 m); K, Mt. Kailas (6714 m); K2, Mt. Godwin-Austin (8611 m); NP, Nanga Parbat (8126 m); and NB, Namche Barwa (7756 m). The Nyainqentanghla Shan (NQTL) is a northeast-southwest–trending range to the northwest of Lhasa. The green diamond near Lhasa shows the location of the Quxu pluton thermochronologic studies (*23*). Inset shows the location of other features described in the text (Bengal fan, South China Sea, Tien Shan).

strike-slip fault systems allowing lateral extrusion of continental blocks (*9, 13*) (Fig. 1). Although some have argued that escape is largely restricted to the latter stages of plateau development or is simply a consequence of block rotation about a vertical pole (*6, 10*), recent work has tended to support at least one of the earlier predictions. On the basis of field studies, it is estimated that middle Tertiary left-lateral movement on the Red River fault zone alone may have accommodated 15% of the total shortening of Asia since collision began (*11*). However, a simple balance between the sources, reservoirs (*8, 13*), and sinks of crustal material (that is, 2000 to 2500 km of convergence, the present crustal thickness, and sediment derived from the collision zone, respectively) appears to restrict the role of extrusion to accommodating not more than about one-third of the total convergence.

Featured in virtually all of the above tectonic hypotheses are predictions of the time of initiation, the rate of crustal thickening, and the time of attainment of full crustal thickness throughout the Himalaya and the Tibetan plateau. Although geophysical and geomorphological methods can place constraints on the rates of Pleistocene and Holocene crustal motions [for example, (*12, 21*)], a complete test of each model would be aided by knowledge of the magnitude and spatial distribution of surface uplift and unroofing since collision began. By the establishment of a chronology of these events, significant steps can be taken toward understanding the mechanisms that have operated to produce the Tibetan plateau. At localities that were near the southern margin of Asia just before collision, erosion or tectonic denudation likely would have accelerated rapidly after the establishment of topography at all times since ~45 Ma. Accelerated erosion is likely because the drainage from southern Tibet across the Himalaya is antecedent to elevated topography, and it would have been this area that was first uplifted after collision began, if it was not already elevated.

Thermochronology (*22*), the use of cooling-related isotopic variations preserved within minerals to reveal tectonic and erosional activity, has been used to help constrain vertical and horizontal crustal motions within the Indo-Asian collision zone. Although there is an interpretive step between deriving thermal histories and inferring crustal thickening and uplift, the conditions necessary to make this link appear to be satisfied in southern Tibet and the Himalaya.

## Early Miocene Uplift of Southern Tibet

When did thickening and the resulting surface uplift due to isostasy begin after collision? A growing body of evidence suggests that the period between about 21 and 17 Ma marks an important transition in the development of southern Tibet and the Himalaya.

By examining the variation of mineral ages with elevation, Copeland and co-workers (*23*) recognized a profound discontinuity at 21 Ma in the rate at which the Quxu pluton (near Lhasa; Fig. 1) cooled after intrusion at ~42 Ma. Five samples of biotite collected at 250-m vertical intervals between 4600 and 3600 m yielded $^{40}Ar/^{39}Ar$ ages that monotonically decrease from 26.8 to 17.8 Ma (Fig. 3A). If these data are interpreted to result from conductive cooling due to motion of the samples relative to the earth's surface, denudation rates of 0.07 ± 0.02 mm/year between 27 and 21 Ma changing to rates of >2 mm/year between 20 and 18 Ma are calculated (Fig. 3B). Although they could confidently rule out other thermal regimes (for example, convection of crustal fluids) and disturbance of the isotopic system (for example, reheating by nearby magmatism) as viable explanations for the monotonic increase in age with elevation, several potential limitations inherent in their approach could not be completely evaluated. For example, incorrect estimates of unroofing rates could result from oblique exposure of the sample traverse, nonhorizontal isotherms or from variations in kinetic parameters among samples.

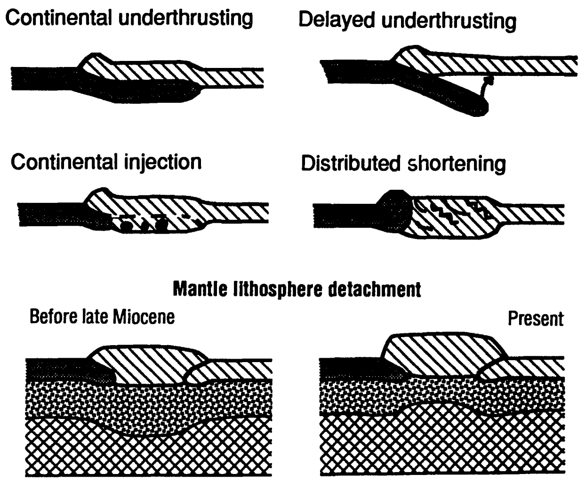


**Fig. 2.** Schematic cross sections of tectonic models proposed to explain the thickening and uplift of the Tibetan crust.

Taking advantage of recent developments in data acquisition and interpretation (*22*), Richter *et al.* [in (*23*)] subsequently obtained a virtually identical unroofing history from $^{40}Ar/^{39}Ar$ age spectrum analysis of a single K-feldspar sample from the Quxu pluton several kilometers to the south, and they extended the low (<0.1 mm/year) denudation rates back to 42 Ma (Fig. 3B). Because the unroofing history was obtained from only one sample, this study transcended potential limitations of the age-dependence-on-elevation approach and reinforced the earlier conclusion that, at least in the Quxu pluton, a profound change in unroofing rate occurred beginning at 21 Ma.

Additional $^{40}Ar/^{39}Ar$ analyses of K-feldspar samples from once deeply buried volcanic rocks northwest of Lhasa (Fig. 1) yielded age gradients between 55 and 40 Ma that are suggestive of relatively slow cooling (~10°C per million years) before and during the initial phase of collision (*24*). The correspondingly low average unroofing rates (<0.3 mm/year) throughout the Lhasa block between 55 and 21 Ma suggest that the Gangdese belt (Fig. 1) was not thickening (and isostatically adjusting elevation) to a significant extent before the late Oligocene (~25 Ma).

Other thermochronological results from the region (*24, 25*) reveal that some rocks at the surface today have not preserved the memory of an early Miocene rapid cooling event. In fact, it is more probable than not that the $^{40}Ar/^{39}Ar$ thermochronometers in the rocks were

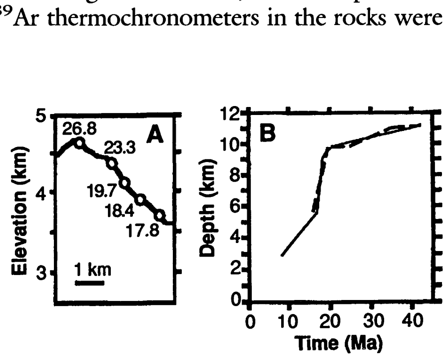


**Fig. 3.** (**A**) Topographic profile and (**B**) exhumation history of the Quxu pluton (near Lhasa). The solid line in (B) was derived from the variation of biotite ages [shown in (A) in million years ago] over the range of elevations from 3600 to 4600 m [see (A)], and the dashed line was obtained from a single K-feldspar sample (*23*). Both curves document an episode of rapid unroofing beginning at ~21 Ma after a protracted period of relatively low denudation. The solid line is insensitive to assumptions regarding crustal thermal structure but is susceptible to errors arising from oblique unroofing, whereas just the opposite is true for the dashed curve. Thus, the shortcomings of one approach are overcome by the strengths of the other. Their congruence gives confidence that the inference of rapid surface uplift in the early Miocene is valid.

not in record mode (that is, below or well above the closure temperatures of the constituent minerals) when rapid cooling occurred, although it remains possible that this event was not experienced at these locations. K-feldspar age spectra from several plutons north of Quxu (Gu Rong granite, Lhasa granite, and Dagze granite) (*25*) indicate that these plutons had cooled below ~150°C (and thus were likely at <6 km depth) when the Quxu pluton was intruded (at ~40 to 45 Ma) at a depth of ~10 to 12 km. Thus, these granitoids were well below the temperature interval for argon closure during the early Miocene unroofing. These data imply that the Lhasa block was tilted to the north between ~50 and 18 Ma; in addition, an oblique unroofing accompanying tilting to the south is recognized within the Quxu pluton between 28 to 18 Ma (*24*).

The origin of the Himalayan-Tibetan drainage is an important component of our interpretation that rapid cooling reflects denudation closely after surface uplift. Rather than being coincident with the line of >8-km peaks of the High Himalaya, the watershed lies well to the north in low-grade Tethyan metamorphic rocks (Fig. 1). Although an early view was that major rivers such as the Arun (which cuts through the Himalaya in several spectacular gorges) formed on the southern slopes of the Himalaya and cut back to capture Tibetan rivers (*26*), Wager [in (*27*)] provided definitive evidence that the course of the Arun was antecedent to the development of elevated topography. This view has been confirmed in many subsequent studies and has become widely accepted (*2, 6, 7, 20, 27*). In an analysis of river profiles throughout the length of the collision zone, Seeber and Gornitz [in (*27*)] identified only 4 of the 25 major rivers, from the Swat in western Pakistan to the Tsangpo-Bramaputra in eastern Tibet and Assam (Fig. 1), that were clearly not antecedent. Some major rivers flowing south to the Tsangpo River also appear to predate uplift of the Gangdese batholith—the major continental-margin plutonic belt just north of the Indus-Tsangpo suture (ITS) that runs virtually the length of the collision zone (Fig. 1). Although many north-south grabens cut across the Gangdese belt, the Quxu-Lhasa River [which flows within tens to hundreds of meters of most samples used in (*23*)] cuts diagonally through the belt and is not associated with those signal features. Although it remains possible that this river valley is structurally controlled, antecedent tributaries (*20*) and the absence of associated fabrics in the rocks suggest otherwise.

Given that the present topography is predated by the principal drainage adjacent our sample traverses, it follows that the onset of the rapid denudation we infer from the cooling studies is associated with the appearance of the mountain ranges. Unless very unusual climatic conditions prevailing throughout the Eocene and Oligocene abruptly changed in the early Miocene (for example, the end of a 30-million-year drought), the rapid unroofing beginning at ~21 Ma must have been shortly preceded by significant uplift of the land surface relative to sea level. Barring a global or local climate change in the early Miocene (for which we know of no supporting evidence), we see no other viable mechanism to explain this discontinuity.

Thermochronological studies from other parts of the collision zone suggest that this abrupt change in the rate of denudation during the early Miocene was not restricted to the region adjacent to Lhasa. In an examination of the elevation dependence of apatite and zircon fission-track ages in the Swat valley of northern Pakistan (Fig. 1), Zeitler [in (*28*)] showed that the denudation rate increased at ~20 Ma, from 0.08 to >0.22 mm/year. Summarizing the now abundant literature, Chamberlain *et al.* [in (*28*)] concluded that large regions of northern Pakistan, perhaps 300 km along the strike of the Main Mantle thrust fault (Fig. 1), underwent rapid cooling associated with denudation just before 20 Ma. Arnaud *et al.* [in (*28*)] found that postcollisional unroofing in the central Kunlun of far western Tibet began at ~20 Ma.

The sedimentary record contains abundant evidence of a change in denudation style at the Oligocene-Miocene boundary (~24 Ma). The widespread Siwalik Group, mostly fluvial sandstones and siltstones interpreted to be molasse deposits from the rising Himalaya, span the early Miocene to Pleistocene (*29*). In central-southern Tibet (Fig. 1), the Kailas conglomerate, which contains clasts from the Gangdese batholith, developed a thickness of at least 3 km (*29*). Although age assessment of this unit (late Eocene to Miocene?) has been problematic (*29, 30, 7*), recent work (*31*) indicates that rapid denudation beginning at about 19 Ma (associated with surface uplift for the same reasons described above) of this batholith was important in its deposition. The $^{40}Ar/^{39}Ar$ dating of individual detrital K-feldspars from modern Tsangpo River sediments near Lhasa yielded a clustering of ages between 15 and 20 Ma (*31*) that is consistent with an episode of rapid unroofing at that time. Similar analyses of detritus from Siwalik Group samples from Pakistan and Nepal are dominated by early-middle Miocene and late Eocene ages (*31*). Much farther south (Fig. 1), the stratigraphy of the Bengal fan (*32*) as well as the $^{40}Ar/^{39}Ar$ dating of individual detrital grains (*31*) suggest that there was a significant episode of early Miocene denudation and that rapid erosion has continued at various places within the collision zone to the present day. The thickness of Indus fan sediments accumulated on the western continental margin of India indicates that rapid subsidence began there at ~25 Ma (*33*).

The southern Tibetan detachment system (STDS) is a crustal-scale, down-to-the-north, low-angle normal fault system in the High Himalaya (Fig. 1) that in general separates high-grade rocks of the Tibetan slab from lower grade Tethyan metasedimentary rocks exposed to the north (*34*). This structure has been interpreted as a result of both gravitational collapse after the formation of a topographic high in southern Tibet and gravitational spreading of an overthickened lower crust (*35*). Measurements of U-Pb on accessory minerals from a footwall amphibolite and an undeformed granitoid that cross-cuts the fault system yield ages of 21 to 22 Ma and 20 ± 0.5 Ma, respectively (*36*). If movement on this fault was due to gravitational collapse, these results indicate that significant elevation had been attained in southern Tibet before 20 Ma. A similar fault system has also been described in the Ladakh region of Pakistan (*37*). Although less precise, available data are consistent with initial movement of this structure in the early Miocene.

Given that about one-quarter of the current Sr flux into the oceans is derived from rivers that have their headwaters in the Himalaya or Tibet, it is reasonable to suspect that the history of seawater $^{87}Sr/^{86}Sr$ variations preserved in marine carbonates might contain a record of past changes in erosion rates from the collision zone (*38*). Richter *et al.* [in (*38*)] investigated this hypothesis and found that the most distinctive change in the rate of Sr addition to the oceans over the past 100 Ma began at 20 Ma and lasted about 3 million years. They concluded that the likely source of the highly radiogenic Sr was rivers draining the Indo-Asian collision zone and that unusually high erosion rates would be required to affect the large addition of $^{87}Sr$ to the ocean during this relatively brief event.

The South China Sea (Fig. 1) appears to be a pull-apart basin at the southeast termination of the Red River fault zone (*13*). Poles of rotation and rates of sea-floor spreading based on magnetic anomalies suggest that the total left-lateral offset along the Red River fault zone was ~500 km between 35 and 17 Ma (*39*). Recent work (*11*) has confirmed that the Red River fault zone is a Tertiary, ductile, left-lateral, strike-slip shear zone. This zone is characterized by rapid cooling between 21 and 19 Ma (*11*); this cooling apparently marks the end of ductile left-lateral motion within the exposed rocks and the abrupt transition to an extensional regime. The growing evidence that this fault had a significant role in accommodating the convergence of India during the early part of the collision (*11*) suggests that significant crustal shortening and consequent uplift in southern Tibet could have been retarded until motion on this fault terminated in the early Miocene. It is possible that motion continued on a presently unexposed portion of the Red River fault zone between 19 to 17 Ma but that little convergence was accommodated owing to the fault having by then rotated significantly away from the direction of shortening. Either way, this scenario could explain why significant movement on the earliest of the major Himalayan thrusts, the Main Central thrust (MCT), did not begin until the late Oligocene to early Miocene (*40*). We return to this point in the summary.

## Tectonic Models for the Early Miocene Uplift

Two related questions pivotal to understanding the interaction between the Indian and Eurasian plates after initiation of the collision remain: (i) What caused the rapid denudation of the Gangdese magmatic belt during the early Miocene and (ii) what were the timing, magnitude, and mechanisms of crustal shortening after the collision but before the early Miocene uplift of the Gangdese belt? Whether the early Miocene uplift of the Gangdese belt was local or regional (that is, including southern Tibet and the Himalaya) in extent must also be addressed because the two mechanisms predict rather different denudation patterns in space and time. Thus, selection between them has an important bearing on understanding physical processes related to the collision of the Indian and Eurasian plates. Before we present details of our working hypothesis, we briefly summarize geologic constraints on the major tectonic elements adjacent to the Gangdese belt.

*Lhasa block.* The Gangdese batholith lies in the southern part of the Lhasa block, bounded by the ITS to the south and the Banggong suture to the north. Major geologic constraints for the deformation history of the eastern (*7, 19, 23, 25, 41*) and western (*42*) Lhasa block are the following: (i) The Upper Cretaceous Takena Formation (dominantly red beds) is folded and unconformably overlain by the Paleocene-Eocene Linzizong Formation (mostly intermediate-felsic volcanic rocks). Near Lhasa, the Linzizong Formation is mildly folded and cut by at least one south-directed thrust fault: total shortening over ~50 km is ~15%. In the northern part of the Lhasa block, several thrust systems of possible Tertiary age show evidence of shortening by as much as 50%. Although overthrusting and mild folding of clearly Neogene strata occur in places, much of this deformation may predate the collision of India. (ii) The contact between the Gangdese plutons and Linzizong Formation may be intrusive, tectonic, or depositional (*41*). (iii) North-dipping faults occur in the southernmost part of the Gangdese plutonic belt between Lhasa and Quxu (*19, 23*). These structures appear synkinematic with intrusion. Several south-directed Eocene (?) thrust faults between Lhasa and the Banggong suture are also recognized (*41*). The amount of shortening is believed to be small because no major juxtaposition of metamorphic grades is seen across those faults, although the timing and extent of these thrusts are poorly constrained.

*Main Central thrust.* The MCT is a major intracontinental thrust system in the Himalaya (Fig. 1) that accommodated >100 km of displacement, likely during the early and middle Miocene (*40*). Balanced cross sections across the Himalaya based on gravity data and flexural analyses (*43*) suggest that the Indian continent has underthrust along the MCT for at least 250 km. Paleomagnetic results (*16*) place an upper limit on underthrusting of about 1000 km.

*Indus-Tsangpo suture zone.* Structures in this suture zone (Fig. 1) are complex, and there are at least three major periods of thrusting and crustal shortening. The first two, Late Cretaceous to Paleocene and late Eocene to Oligocene, show south-verging folds and south-directed thrust faults, whereas the last, late Miocene to Pliocene, shows north-verging folds and north-directed backthrusting (*29, 42, 44*). During middle Tertiary time, a molasse basin was developing along the ITS (*42*). Whether the formation of this basin was related to normal, thrust, or strike-slip faults, or a combination of the three, is uncertain (*42*).

We propose a hypothesis with variants that is broadly consistent with these geological constraints and provides a mechanism for the early Miocene uplift:

*Stage 1 (50 to 35 Ma).* After initiation of the continental collision at some time during this interval, the Gangdese thrust system (GTS) began to develop and offset the Gangdese batholith (Fig. 4A). The Eocene south-directed ductile thrusts found in the southern Gangdese belt (*41, 23*) may be its upper-plate structures (thrust imbricates?). The location of the thrust system along the Gangdese belt may have been controlled by thermal weakening due to the last phase of magmatism along the Gangdese arc in the middle Eocene. Movement on the MCT could have started during this time, as speculated by Dewey *et al.* (7), but the magnitude of displacement was probably small.

*Stage 2 (35 to 21 Ma).* Continental extrusion of Indochina occurred during this interval (*11*). The GTS further developed (Fig. 4B), displacing part of the Gangdese plutonic belt in its hanging wall, and eventually the plutonic belt was thrust over the forearc basin [the Xigaze Formation (*42*)] as well as part of the subduction complex [Yamdrock melange (*42*)]. A consequence of this event was the formation of a hanging-wall anticline and both north- and south-tilting of the fold limbs. The MCT may have been active, particularly during early Miocene time, and may have begun to accommodate a displacement of ~250 km (*43*). The MCT may have been kinematically linked with the GTS along a decollement in the lower crust. The offset of the Moho, shown on the wide-angle reflection profiles of Hirn *et al.* [in (*5*)] across southeastern Tibet, could be a younger feature related to strike-slip faulting (*13*) and may not be related to this event. The north-dipping STDS (*33, 34*) and the Himalayan leucogranites (*40*) started to develop late in this stage and continued well into Stage 3.

*Stage 3 (21 to 18 Ma).* The thrust motion along the MCT during 21 to 18 Ma (*40*) was at a high rate (Fig. 4C) after cessation of extrusion. The emplacement of the Gangdese belt along the MCT across its footwall ramp during this period was associated with a rapid uplift of the Gangdese belt and a southward tilting (*23, 24*). During this last phase, leucogranites intruded into parts of the STDS low-angle normal fault system. The important predictions of this model are that the uplift rate of the Gangdese belt was related to the slip rate of the MCT and that two tilting events consistent with the thermochronological results occurred. This model also explains the proximity of the Gangdese arc to the suture zone. That is, the entire forearc region is largely missing and is proposed to have been mostly underthrust below the Gangdese arc during the Paleogene.

Two variants on this model involving a normal fault system on either the northern or southern margins of the Gangdese are consistent with the tectonic and thermochronological constraints and help reconcile additional observations. (i) During Stage 2, the contact between the Linzizong Formation and the Gangdese batholith is proposed to be the locus of a north-dipping normal fault system (Fig. 4C′). Its initiation and development would probably have been related to the Himalayan north-dipping normal fault system. Motion on this system between 21 and 18 Ma would have caused a local rapid unroofing of the Gangdese plutonic belt and would also have produced a northward tilting. This modification predicts a rapid local uplift (restricted only to the Gangdese belt) and a southward tilting during 21 to 18 Ma. (ii) Alternatively, a south-dipping normal fault system could have initiated along the south side of the Gangdese belt during Stage 2 (Fig. 4C″). The south-dipping normal fault could be the conjugate or antithetic set of the north-dipping normal fault system in the High Himalaya. It would explain why the ITS is topographically lower than both the Himalaya and the Gangdese and would explain the development of the molasse basin along the ITS zone. The normal faulting and development of the molasse basin along the ITS also may have obscured exposure of the proposed GTS. Between 21 to 18 Ma, the south-dipping normal fault would have caused rapid and local uplift of the Gangdese belt due to unroofing and a northward tilting of the Gangdese belt. These working hypotheses can be tested by more detailed structural studies in southern Tibet.

## Maximum Elevation in the Late Miocene

Knowing when the Tibetan plateau reached its present size and elevation has implications that reach beyond fundamental issues of continental tectonics. An understanding of the Neogene topography of Tibet is important to questions of global atmospheric circulation (*45*), the onset of the Asian monsoon (*46*), factors controlling biological and ecological migration (*47*), as well as geodynamics of continent-continent collision (*8*).

Although most of the surface of Tibet was apparently above sea level during the late Cretaceous and Paleogene, only the southern region is likely to have had significant relief just before the onset of collision (*44, 48*). The presence of tropical plants in the Lunpola basin as late as Oligocene (*47*) suggests that at least portions of central Tibet had relatively low relief. Thus, uplift of the plateau in its present form must be a Neogene phenomenon. Although we have some information about the present state of stress in Tibet, we cannot use this knowledge to infer details of past crustal thickening because the tectonics are currently dominated by a different regime.

Much of the Tibetan plateau is currently extending in an east-west direction along north-south–striking normal faults (Fig. 1). This mechanism is believed to have been active in Tibet since at least 2 Ma, and probably since before 6 Ma (*9, 21*). The extension is manifested in a series of north-south– and northeast-southwest–trending grabens in central and southern Tibet (Fig. 1). Although there is general agreement that these features are the result of gravitational collapse of the Tibetan plateau after achievement of the maximum sustainable crustal thickness and elevation (*9, 20, 21*), details are debated. England and Houseman [in (*18*)] concluded that, short of significant changes to the boundary conditions (that is, convergence rate and strength of the encompassing region), the only likely source of east-west extension is an abrupt increase in the potential energy of the Tibetan lithosphere. Alternatively, initiation of movement on the Main Boundary thrust fault in the late Miocene may have sufficiently reduced the component of convergence involved in thickening and sustaining elevation in Tibet to permit extension. Bird [in (*18*)] emphasized that elevated topography of sufficiently long wavelength (>100 km) in isostatically equilibrated crust could be relaxed by lateral extrusion into the surrounding lower crust. This process would tend to level topography, but potentially without deforming the brittle upper crustal layer.

The Nyainqentanghla Shan, a northeast-southwest–trending

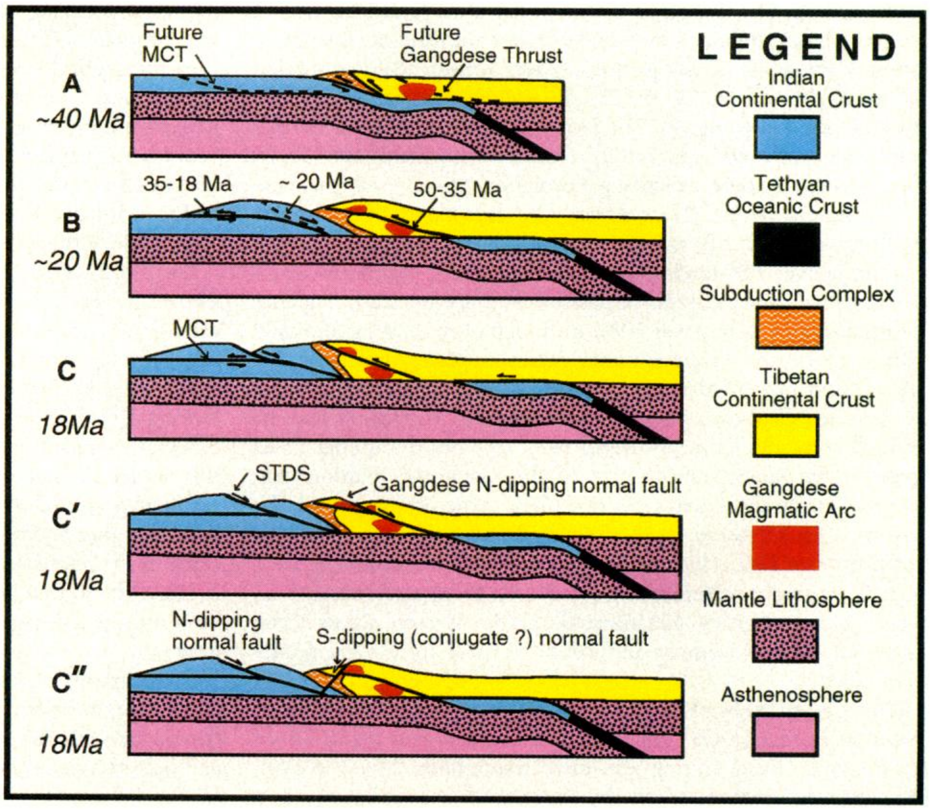


**Fig. 4.** Cross sections showing proposed tectonic evolution of the Himalaya and southern Tibet. They are only qualitatively balanced and aim to show the geologic history and processes rather than a precise conservation of the crustal section. (**A**) After collision, the south-directed Gangdese thrust system (GTS) began to develop and offset the upper part of the Gangdese batholith southward. South-directed ductile thrust systems on the north and south sides of the Gangdese belt may be the hanging-wall structures (thrust imbricates?) of the proposed GTS. (**B**) Further development of the GTS-displaced part of the Gangdese belt on top of the forearc basin as well as part of the subduction complex. This displacement formed a hanging-wall anticline that tilted the fold limbs both northward and southward. The MCT may have been fully developed during the early Miocene and accommodated ~250 km of displacement. The MCT may have been kinematically linked with the GTS along a decollement in the lower crust. The STDS and High Himalayan leucogranites began to develop late in this stage. (**C**) Thrust motion along the MCT between 21 and 18 Ma occurs at a high rate, possibly because of the cessation of continental extrusion. Motion over a footwall ramp of the MCT is proposed to have caused the rapid uplift and southward tilting of the Gangdese plutonic belt. (**C′**) An alternative to the kinematic development of the Gangdese belt shown in (B) and (C). Between 35 and 18 Ma, a north-dipping normal fault system developed along the northern contact of the Gangdese batholith with the Linzizong Formation. Motion on this system between 21 and 18 Ma caused a local rapid unroofing of the Gangdese batholith and also produced a northward tilting. This modification predicts a local (restricted to the Gangdese belt) rapid uplift and a southward tilting between 21 and 18 Ma. (**C″**) A second variant on the kinematic development of the Gangdese belt (B and C) involving a southdipping normal fault system, possibly the conjugate and antithetic set of the north-dipping fault system (STDS) in the High Himalaya, initiated along the southern boundary of the Gangdese belt.

mountain range of unusually prominent relief, bounds the western margin of the Yangbajian graben, a segment of the Yadong-Gulu rift (Fig. 1). The master fault along the eastern margin of the range exposes amphibolite-grade metamorphic rocks (*49*), whereas the hanging wall to the east of the graben has experienced relatively little unroofing (*25*). The ductile quartz mylonitic structures developed in the high-strain zone of the low-angle master fault must have formed at temperatures of at least 300°C: isotopic age constraints on the thermal history between 550° to 200°C thus permit us to place bounds on the timing of motion. The $^{40}Ar/^{39}Ar$ results from two cross-cutting valleys indicate that the rocks exposed in the detachment fault near Yangbajian (Fig. 1) cooled rapidly from 500° to 230°C between 7 and 4 Ma in one and from ~360° to 250°C between 8 to 4 Ma in the other (*25*). We interpret this cooling to be related to tectonic denudation by normal faulting. With this interpretation, significant motion on this fault zone can be constrained to be older than 4 Ma but probably not much older than 7 to 8 Ma. If the Yangbajian graben is representative of the southern Tibetan plateau in general, these results suggest that the Tibetan plateau had a crustal thickness and elevation near its present values by 7 to 8 Ma.

A broad region of anomalous seismicity exists within the central Indian Ocean sea floor that has been interpreted as evidence of a diffuse plate boundary (*50*). On the basis of seismic reflection and paleontologic data (*50, 31*), it is estimated that this boundary formed between 8.0 and 7.5 Ma. A possible explanation for the deformation along this boundary is that after Tibet achieved its maximum thickness and elevation, other mechanisms were needed to accommodate the continuing 5 cm/year of convergence. East-west extension and strike-slip faulting may have been insufficient, and shortening of the Indian plate then developed in response to the increased deformational resistance.

A further suggestion for a late Miocene plateau similar to the present geography comes from the data of Quade *et al.* [in (*46*)]. They investigated the $\delta^{13}C$ and $\delta^{18}O$ variations in pedogenic carbonate in the Siwalik Group sedimentary sequence in northern Pakistan and found a marked shift in these values at 7.4 Ma. This shift suggested that a major climate change induced a transition from forest to grassland. The change in climate in this case is likely the intensification of the monsoon system at ~8 Ma. The presence of a high and large Tibetan plateau is thought by some to be important in driving the modern Asian monsoon (*45*). On the basis of planktonic assemblages and opal accumulation in Arabian Sea sediments, Prell and Kutzbach [in (*46*)] also suggested that a monsoon-related climate change occurred at 7 to 8 Ma.

These results suggest that the plateau had attained a threshold area and elevation by 7 to 8 Ma that was sufficient to trigger these three independent manifestations. This conclusion differs significantly from tectonic models, based on inferences from paleobotanical and paleontological studies (*47*), that view plateau uplift as an essentially Pleistocene phenomenon. This difference may reflect the difficulties of translating fossil remains, useful as a general indicator of prevailing climate, into quantitative estimates of uplift.

The 10- to 15-Ma interval between what we infer to be the time of an abrupt increase in crustal thickening in the early Miocene and the apparent attainment of maximum elevation at about 7 to 8 Ma are not features of any of the endmember hypotheses shown in Fig. 2. However, one of their common points of departure must be to explain the disposition of the "excess" mantle lithosphere resulting from collision. For example, distributed shortening predicts that the thickness of the Tibetan lithosphere has been doubled and that a portion of the Indian mantle lithosphere has been subducted. However, rapid thickening could produce lateral thermal gradients that may lead to a convective instability resulting in detachment of some (*8*) or all (*15*) of the mantle lithosphere (Fig. 2). Its displacement by the less dense and hotter asthenosphere would be immediately accompanied by isostasy-driven uplift of the remaining lithosphere (*8, 15*). This mechanism is physically plausible, and calculations suggest that delamination could occur on a short time scale (*8*), resulting in rapid uplift of the entire plateau.

## Summary

The observation in the Quxu pluton of a 30-fold increase in the rate of unroofing implies that a change in climate, drainage, or topography occurred there during the early Miocene. We rule out a significant influence from all but the latter effect and conclude that the region became elevated because of rapid crustal thickening by ~21 Ma. Taken individually, the other lines of evidence (denudation studies in western Tibet and the Himalaya, the age and thickness of molasse sediments, the erosional record seen from the detrital mineral ages in the Siwalik Group and the Bengal fan, the seawater Sr record, the age of the apparent onset of normal faulting in the High Himalaya, and the termination of motion on the Red River fault) are only suggestive, but in conjunction build a persuasive argument that southern Tibet was significantly uplifted and eroded in the early Miocene.

The past 10 years have been a remarkable period of geophysical and geological discovery of the Himalaya and Tibet. Accompanying this new knowledge is the virtually certain recognition that no one of the endmember models can completely explain the present disposition of crust in southern Asia or even, perhaps, be described as dominant. The state of our understanding of the collision zone is sufficient to allow bounds to be placed on the timing and the amount of convergence accommodated by each mechanism. For example, underthrusting along the southern margin probably accounts for between 350 and ~800 km of convergence (*7, 16, 43*), and a minimum estimate of late Neogene underthrusting along the northern boundary is ~50 to 100 km. About 150 km of shortening can be calculated from fold and thrust features in central-northern Tibet (*5, 17, 19, 41*) and the Lhasa block (*41*). Between 300 and 400 km of convergence is represented by material eroded from the southern margin of the collision zone and removed to the Bengal and Indus fans (*50*). Continental extrusion may have taken up between 400 to 500 km during the Paleogene (*11*) and 50 to 100 km during the late Neogene (*12, 13*). Still-active thickening in the Tien Shan has accommodated perhaps 100 to 300 km (*9*). The sum of these estimates, with their large attendant uncertainties, ranges from 1400 to 2350 km. The upper limit is within the range of the total estimated convergence since collision at 40 to 50 Ma of 2000 to 2500 km; about 800 km of this has gone directly into thickening of Tibet and the Himalaya. Depending on what one assumes the precollisional structure of Tibetan and Indian crust to be (*44*), the latter figure may be sufficient to account for the present average Tibetan crustal thickness of ~65 km (*1*).

The most poorly understood period of deformation in Indo-Asia is the Paleogene. The proposed magnitude of shortening during this period of time varies dramatically [compare (*5, 41*)]. Our model suggests that some crustal shortening and uplift north of the ITS occurred between ~45 and 21 Ma but contrasts sharply with the view that more than 1000 km of shortening was absorbed by Tibet during that time (*7*) or that the entire Lhasa block had attained something approaching its present elevation by the early Oligocene (*44*).

The continuation of Andean-type plutonism into the late Eocene in the central (*30*) and eastern [(*23*), and references therein] Gangdese may be evidence that oceanic subduction continued in this region until the early Oligocene. With the assumption of simple geometries for India and southern Asia, the counterclockwise rotation of India after collision began (*16*) is consistent with initial contact between India and Asia occurring in the western Himalaya at ~50 Ma followed by closure of an eastern basin. A late Eocene to early Oligocene timing for initial collision in eastern Tibet is coincident with the commencement of motion on the Red River fault zone (*11, 39*). Perhaps one-half to two-thirds of the convergence between 35 and 20 Ma was taken up by extrusion along this and associated features. As a consequence, significant crustal shortening (and consequent uplift and erosion) in southern Tibet was forestalled until motion on this fault terminated in the early Miocene. After cessation of strike-slip motion, convergence accommodated by the nascent GTS or MCT was immediately translated into uplift and rapid denudation of southern Tibet and the Himalaya between 21 and 18 Ma. Subsequently, thickening continued in the Himalaya and Tibet until about 8 Ma, when, possibly due to delamination of the mantle lithosphere, the plateau achieved something akin to its present extent and elevation. Gravitationally induced tension was relieved by motion on detachment faults such as the one exposed along the eastern edge of the Nyainqentanghla (Fig. 1).

Although we have emphasized that rapid early Miocene denudation is a recurring theme in an assortment of geological records in and around the collision zone, this congruence should be viewed in perspective with the relative paucity of coverage of the plateau as a whole. Only those areas adjacent to Lhasa have been studied intensively, and much of Tibet remains geologically unexplored. Future geologic, geochemical, geodetic, and geophysical investigations will eventually lead us to a fuller understanding of how continents respond when plate tectonics comes ashore, resolving one of the most controversial questions of modern earth sciences.

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