21.2 THE TIBETAN PLATEAU AND SURROUNDING REGIONS—An essay by Leigh H. Royden and B. Clark Burchfiel[1]

21.2.1 Introduction

The collision of India with Asia about 50 Ma and their subsequent convergence (Figure 21.2.1) has produced a spectacular example of active continent-continent collision. This immense region of continental deformation, which includes the Tibetan Plateau and flanking mountain ranges, contains the highest mountain peaks in the world, with many peaks rising about 8000 m (the **Himalaya**). Indeed so many mountain peaks rise above 7000 m that many of these remain unnamed and uncounted. The **Tibetan Plateau** proper stands between about 4000 and 5000 m in elevation and covers a region about 1000 by 2000 km^2, and most of it has remarkably little internal relief. It is sobering to compare the size of this region to other mountain ranges; for example, the crustal mass of the Tibetan Plateau above sea level is about 100 times greater than that of the western Alps.

The first synthesis of the tectonic evolution of southeast Asia, including the Himalaya and the Tibetan Plateau, was constructed by the Swiss geologist Emile Argand in 1924. Many of our current ideas about this region are contained in his book "La tectonique de l'Asie," which remains today one of the truly creative and imaginative works in the earth sciences. Unfortunately, from about World War I until about 1980, much of this region (in China and the former Soviet Union) was closed to foreign scientists and only since the 1980s has the area been open to international research. Thus much of our knowledge of the geology of the Tibetan plateau and surrounding regions must be considered as largely reconnaissance, particularly when compared to regions like the relatively small western Alps, where geologic research has been conducted by generations of earth scientists for more than 150 years.

In spite of our relatively sketchy knowledge of the Tibetan region, this exotic, remote, and inaccessible area has long excited the interest of scientists and non-scientists alike. For earth scientists, the rise of the Tibetan Plateau and the creation of the flanking mountain ranges and basins is a dramatic example of continental convergence and collision (Figure 21.2.1). It is exciting because of the youthful nature of the structures that accommodate deformation and the exceedingly rapid rates at which deformation is occurring. One of the great attractions of geologic study in this region is the great promise that it holds for enhancing our knowledge of continental deformation processes, as exemplified by an enormous list of still-unanswered questions (including crust–mantle interactions, driving mechanisms for local and regional deformation, and the interdependence of mountain building and global climate). In this essay we will try to summarize briefly what is known about the deformation history of the Tibetan Plateau and surrounding regions, outline some of the hypotheses and controversies that are unresolved today, and discuss some of the fundamental questions that will direct the future of geologic and geophysical studies in this region.

21.2.2 Precollisional History

At the beginning of Mesozoic time, all of the continental land masses were assembled into a giant continent called Pangea. At this time a Mesozoic ocean, called Tethys, formed a huge embayment into Pangea from the east and separated the part of Pangea that is now Eurasia (called Laurasia) from the part of Pangea that is now the continents of Africa, India, Australia,

[1]Massachusetts Institute of Technology, Cambridge, MA.

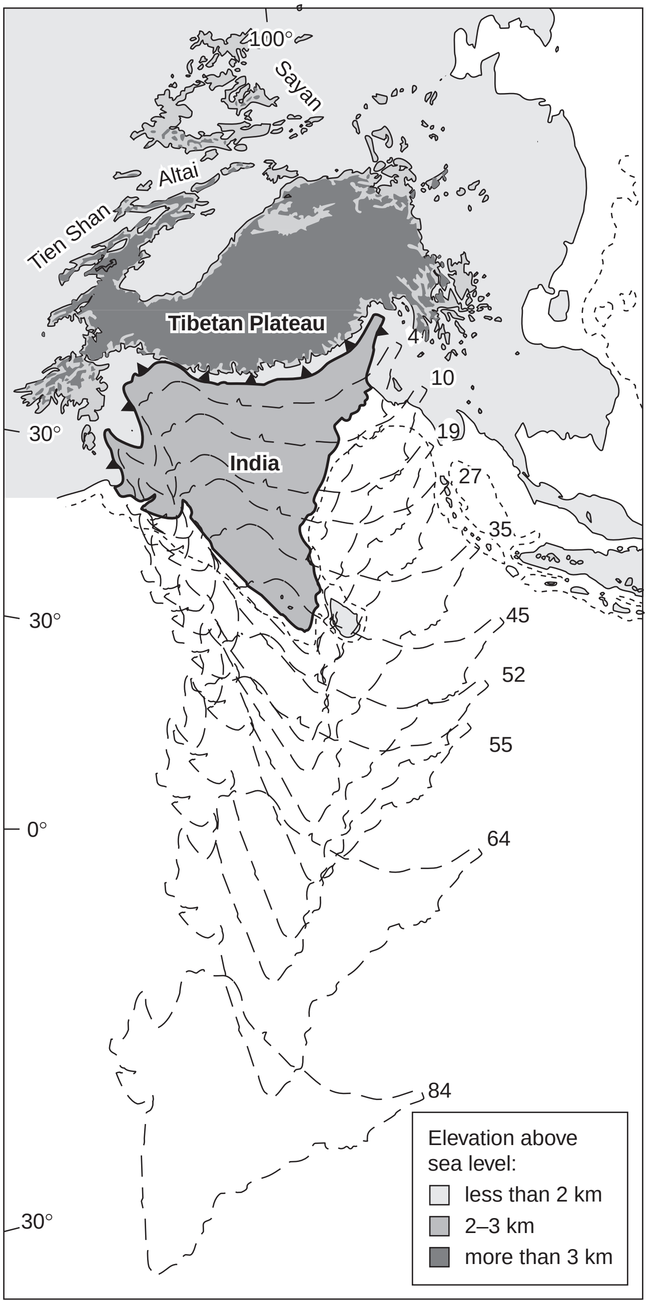

FIGURE 21.2.1 Generalized topographic map of Southeast Asia showing elevation above sealevel (from Burchfiel and Royden, 1991) and positions of India with respect to Asia from Late Cretaceous time until the present. Numbers refer to millions of years before the present. Note the decrease in convergence rate from about 100 mm/y to about 50 mm/y at about 50 Ma.

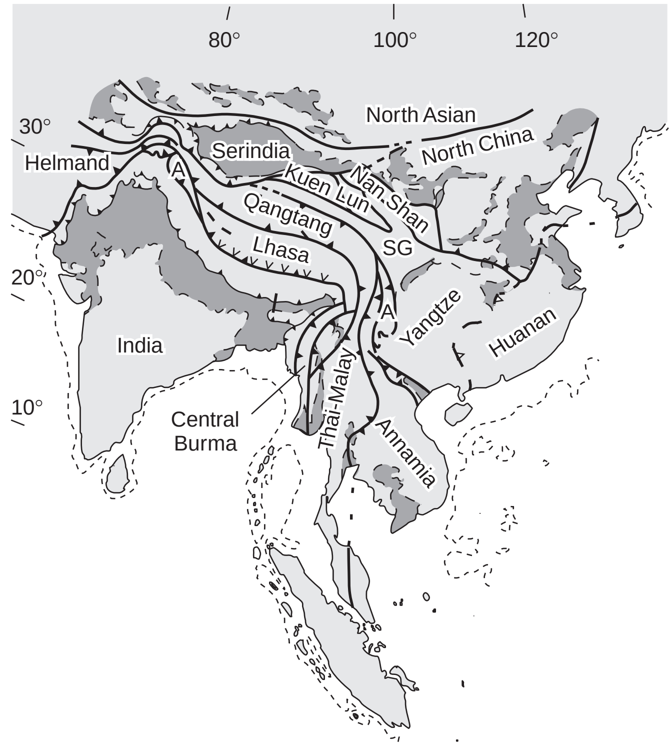

FIGURE 21.2.2 Major fragments in Southeast Asia during Late Paleozoic, Mesozoic, and Early Cenozoic time. The sutures between fragments are shown by barbed lines with the barbs indicating the upper plate of the subduction system. The suture between the Qangtang and Songpan Ganze (SG) fragments is of Mesozoic age and is thought to represent the closure of the Paleotethys Ocean. All sutures north of this are Paleozoic. The suture south of the Lhasa block is the Indus-Tsangpo suture, and represents the closure of Neotethys. A, island arc fragments, V, location of Cretaceous-Early Tertiary arc volcanism. Location of cross section in Figure 21.2.3 is also shown.

and Antarctica (called Gondwana). Tethys was perhaps a few hundred kilometers wide in the westernmost Mediterranean region, but widened toward the east, so that, at the longitude of Tibet, Tethys was approximately 6000 km wide.

At the longitude of Tibet, several sizable continental fragments collided with Asia and became accreted to the Asian continental margin before the main collision between India and Asia (Figure 21.2.2). These continental fragments were rifted from Gondwana and moved northward. As each continental fragment was rifted from Gondwana, it opened a new ocean region between itself and Gondwana. At the same time, the old ocean north of each fragment was closed by subduction. For example, the first fragment to collide with Asia closed the early Mesozoic Tethys (more properly called Paleotethys). The Indian subcontinent is the last fragment to have rifted off of Gondwana and as it moved northward, it opened the Indian Ocean to the south of India and closed the Neotethyan ocean to the north. It is the closure of this Neotethyan ocean and the collision of India with Asia that has produced the 2500-km long Alpine-Himalayan mountain chain, along which continental collision and convergence are occurring today, and many parts of it are still incom-

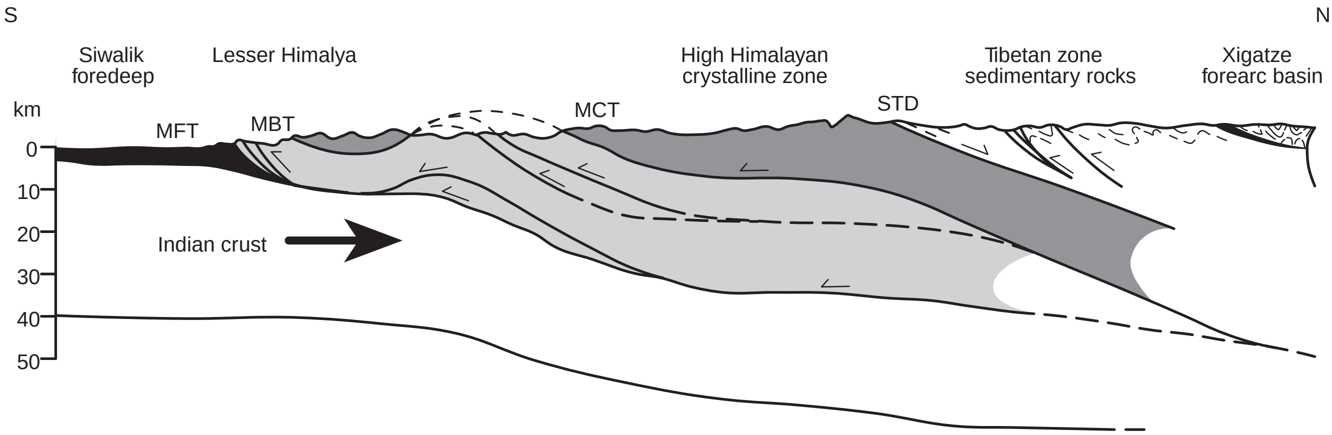

FIGURE 21.2.3 Schematic cross section through the central Himalaya (location in Figure 21.2.2). The Miocene-Quaternary molasse (heavy dots) of the modern foredeep basin are contained within the outer thrust sheets near the Main Frontal Thrust (MFT). Light shading represents low-grade metamorphic rocks north of the Main Boundary Thrust (MBT) and south of the Main Central Thrust (MCT). Dark shading represents high-grade metamorphic and crystalline rocks north of the MCT. These are separated from sedimentary rocks of the Tibetan zone (in white) by the normal South Tibetan Detachment (STD). Also shown are the Cretaceous Xigatze forearc deposits that rest on an ophiolitic basement (black sliver).

pletely closed (e.g., the Mediterranean region still contains Mesozoic seafloor of Tethys).

Prior to the main collision of India with Asia in early Tertiary time, several thousand kilometers of the Neotethys ocean floor was subducted beneath Asia along a north-dipping subduction boundary. Subduction was extremely rapid, resulting in convergence between India and Asia at about 100 mm/y. Evidence for precollisional convergence and deformation is recorded within the Himalayan mountain belt and in the southernmost part of the Tibetan Plateau. For example, within the central part of southern Tibet, Jurassic ophiolites obducted onto the Asian continental margin attest to the existence of an ancient ocean region between India and Asia. A late Cretaceous forearc sequence records subduction continuing at least into the Cretaceous (Figure 21.2.3). North-dipping subduction of an oceanic region is also recorded by a late Cretaceous to early Cenozoic volcanic arc along the southern margin of Asia (e.g., the Gandese batholith near Lhasa in south-central Tibet, which lies just north of the Xigatze forearc basin in Figure 21.2.3). Volcanism in this arc shut off in Eocene time, presumably reflecting the time of collision and the cessation of subduction of oceanic lithosphere. In the western Himalaya, precollisional subduction of Tethys must have occurred partly offshore, south of the Asian continental margin, because a Jurassic-Cretaceous volcanic arc (the Kohistan arc) was developed in a marine environment, and subsequently collided with the southern margin of Asia in latest Cretaceous time, somewhat before the time of the main India-Eurasia collision. It is likely that events before and around the time of collision were very complicated, but at present the geologic data needed to unravel these events has not been obtained so the early evolution of the Himalayan system looks deceptively simple.

21.2.3 Postcollisional Convergent Deformation

At about 50 Ma India collided with Asia, and at about the same time the convergence rate between India and Asia slowed from about 100 mm/y to about 50 mm/y. Since that time India has continued to move northward relative to stable Eurasia at about 50 mm/y, giving a relative convergence of about 2500 km since the time of collision, and shortening and thickening the crust of Asia to produce the elevated Tibetan Plateau. Today, the continental crust beneath the high-standing plateau and flanking mountains is about 70 km, nearly double the more normal values of 30–40 km for continental crust. It is remarkable that in 1924, long before the advent of plate tectonics, Emile Argand already understood that an ocean had closed between India and Asia and that subsequent convergence between India and Eurasia has caused the intracontinental deformation of Southeast Asia. However, it is only in the last few decades that knowledge of the magnetic anomalies on the seafloor and paleomagnetism have allowed scientists to reconstruct the motions of India with respect to Asia in a quantitative manner, and to calculate the width of the subducted ocean.

The boundary where India and Asia first collided, often referred to as the Indus-Tsangpo suture, is marked by a discontinuous belt of ophiolites, mélange, and forearc sedimentary rocks of the Gandese magmatic arc. It has been impossible to reconstruct the early collisional history of this zone because postcollisional deformation involving north-directed backthrusting, strike-slip faulting, and normal faulting has completely obscured the older collisional structures. There is also very little information about postcollisional deformation within the Himalayan belt prior to about 250 Ma, although in the western Himalayan chain geologists have identified early Cenozoic metamorphosis events dated at around 35–45 Ma. This indicates that thrust faulting and crustal shortening were active in the western Himalaya at about this time, and suggests that the creation of high topography within the western Himalaya may have already been underway. However, as we shall see, the time at which high topography developed within most of the Himalaya and Tibet is extremely controversial, not least because of its implications for global climate change.

The evolution of the Himalayan Orogen is better known from about 25 Ma to the present, although there is still much that we do not know about the orogen. A schematic north-south cross section through the Himalaya and into southern Tibet (Figure 21.2.3) shows that regional shortening is thought to have been taken up on thrust faults within sedimentary rocks north of the crest of the Himalaya (called the Tibetan zone sedimentary rocks) and on three major north-dipping thrust faults south of the crest of the Himalaya, the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT). All of these structures appear to be roughly continuous for more than 200 km along the entire length of the Himalayan chain. Shortening across the Himalaya was further accommodated by intense ductile strain within high-grade and crystalline rocks, as well as by folding and thrusting along less important faults.

The oldest of these thrust faults are probably within the Tibetan sedimentary sequence, but their age remains uncertain. The MCT, which may be younger, carries the high-grade crystalline and metamorphic rocks of the High Himalayan zone over the lower grade to unmetamorphosed sedimentary rocks of the Lesser Himalaya. So far, only one date has been obtained for thrusting on the MCT. This date was obtained on rocks just south of Qomolangma (Mt. Everest) in central Tibet, indicating that the MCT was active at 21 Ma. However, we do not yet know how long before or after this time the MCT was active, although in most places it is not active today. In addition, we do not know if this data can be extrapolated to the east or west along the strike of the MCT; it is possible that although the MCT appears continuous along the length of the Himalaya, it is of different ages and different character along different parts of the belt. Metamorphic pressure and temperature data from central Tibet show that at 20–25 Ma the MCT was at a depth of about 30 km and that temperatures of High Himalayan rocks near and just above the MCT were at least 500°C–650°C. Thus the rocks of the High Himalaya must have been brought to the surface from a depth of 30 km during the last 30 m.y.

South of the MCT, the MBT carries the low-grade to unmetamorphosed rocks of the Lesser Himalaya southward over mainly Cenozoic sedimentary rocks. In some places there is evidence that the MBT may be currently active, but the main shortening and convergence across the Himalaya today is probably absorbed by motion along the structurally lower MFT and by folding within its hanging wall. The MFT marks the southern limit of deformation along most of the Himalayan chain and carries rocks and sediments of the Himalaya southward over the Ganga foredeep basin. Sediments being deposited in the Ganga Basin today are similar to those now exposed by erosion within the Himalayan foothills, suggesting that the latter were also deposited in a foredeep position in front of the frontal thrust faults, and have been subsequently incorporated into the thrust belt.

Seismic studies and examination of the rate of advance of the Ganga Basin southward over the Indian foreland indicate that about 10–25 mm/y of shortening is currently being taken up by thrust faulting and shortening within the Himalaya. Seismic studies also show that the main active thrust fault beneath the Himalaya dips gently northward by about 10°, until it becomes aseismic at a depth of about 18 km. At these depths we assume that this active, gently dipping thrust boundary is somewhat analogous to the Early Miocene MCT, but of course there are no direct observations to support this hypothesis.

Because the current rate of convergence between India and stable Eurasia averages about 50 mm/y, this means that only about one-quarter to one-half of the convergence between India and Eurasia is accommodated by shortening within the Himalaya. The rest must be taken up to the north within and around the margins of the Tibetan Plateau. The way in which the remaining convergence is absorbed remains a highly controversial topic, for which there are perhaps more models than data. However, considerable amounts of convergence are clearly absorbed by thrusting and shortening within mountain belts that lie north of the plateau, particularly in the Pamir, Tien Shan, Quilian Shan, and southern Ningxia (e.g., Madong Shan) thrust systems (Figure 21.2.4). The rates of shortening across these belts are not very well known, but they are probably at least 10 mm/y, perhaps considerably more. Although shortening across the Pamirs began in Early Cenozoic time, shortening across the other northern thrust belts probably began only in Late Miocene to Quaternary time. The onset of thrusting in these regions is primarily constrained by stratigraphic data because Cenozoic metamorphic rocks are not found in any of these young thrust belts.

The onset of uplift and shortening along the northern and northeastern margins of Tibet is probably best regarded as the northward growth of the Tibetan Plateau. We can only surmise that the early history of rocks now contained within the central part of the plateau might have been similar to those now being incorporated into the plateau by shortening along its northern boundary. It is clear that the northward growth of the plateau has not been a smooth process. The map of present-day deformation north of the plateau shows a very irregular pattern of thrust belts, with a huge undeformed region, the Tarim Basin, sandwiched between the Tibetan Plateau proper and the very active region of shortening within the Tien Shan, and overthrust from all sides. Active shortening, albeit at much lesser rates, also occurs far to the north within the Altai Ranges in north China and Mongolia. The northward growth of the plateau has not been a smooth process in time either. For example, shortening appears to have begun sometime in late Pliocene to early Quaternary time in much of the northeastern portion of the plateau. However, examination of individual ranges and thrust belts in this region does not reveal a steady northward progression of the deformation front, but rather a more haphazard onset of shortening, in part caused by the reactivation of pre-Cenozoic structures. On a scale of hundreds of kilometers, the deformation along the northern margin of Tibet appears to be controlled largely by strength heterogeneities and preexisting structural trends within the Asian lithosphere.

The structure of the thick crust beneath the Tibetal Plateau is not known, although a number of different hypotheses have been presented, each linked to a different model for plateau growth. On one hand, a number of authors, beginning with Argand, believe that the crust beneath the Tibetan Plateau has been doubled by underthrusting of the Indian crust and lithosphere beneath the Asian crust (Figure 21.2.5). In some of

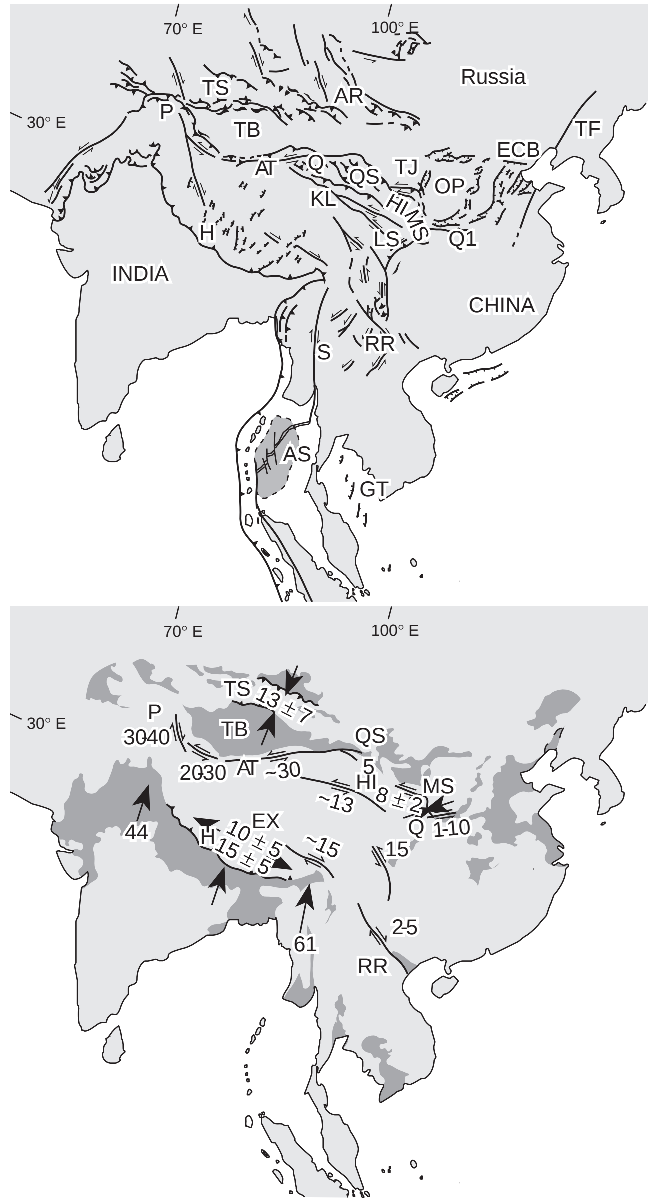

FIGURE 21.2.4 (a) Generalized Cenozoic tectonic map of Southeast Asia. Horizontal arrows indicate sense of slope on strike-slip faults; barbed lines indicate thrust faults in the continental areas and subduction zones in the oceanic areas, with barbs on the upper plates; and ticked lines indicate normal faults. Lunate shapes are folds. AR = Altai Range, AS = Andaman Sea, AT = Altyn Tagh Fault, ECB = East China Basins, GT = Gulf of Thailand, H = Himalaya, HI = Haiyuan Fault, KL = Kun Lun Fault, LS = Longmen Shan, MS = Madong Shan, OP = Ordos Plateau, P = Pamirs, Q = Qaidam Basin, QS = Qilian Shan, QI = Qinling Mountains, RR = Red River Fault, S = Sagaing fault zone, TB = Tarim Basin, TF = Lan Lu fault zone; TJ = Tianjin Shan, TS = Tien Shan, X = Xianshuhe Fault, Y = western Yunnan. (b) Slip rates (in mm/y) on active faults within Southeast Asia. Reversed arrows identify slip direction on strike-slip faults. Medium black arrows that diverge indicate areas and directions of extension; medium black arrows that converge indicate areas of shortening across thrust faults (and folds) with barbed lines. Large north-pointing arrows south of the Himalaya indicate direction and magnitude of present convergence between India and northern Asia.

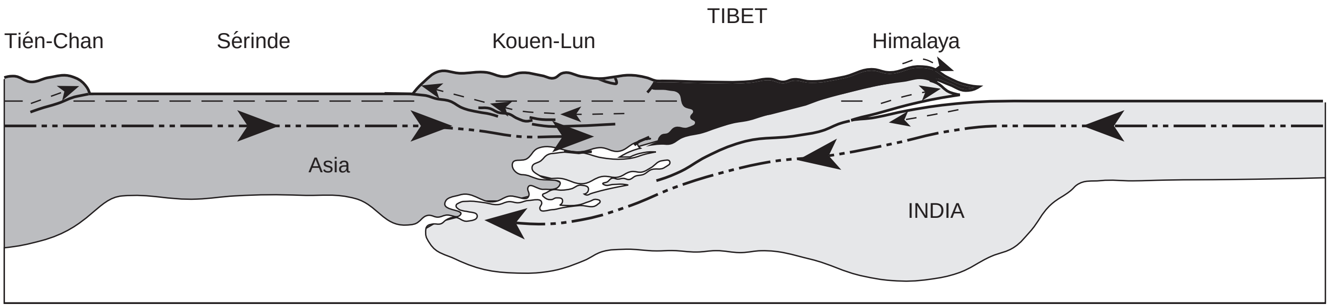

FIGURE 21.2.5 North-south cross section through Tibet and the Himalaya published by Emile Argand in 1924. Modern interpretations have not added much to our understanding of the deeper structure beneath Tibet. Light gray is Indian crust, dark gray is Asian crust, mantle material is white.

these models it is suggested that essentially no deformation of the upper (Asian) crust has occurred, while others include moderate amounts of upper crustal deformation or deformation only within the northern part of the plateau. In contrast to the first model is the suggestion that the Indian lithosphere only extends beneath the Himalaya and southernmost Tibet, and that the doubling in thickness of the Tibetan crust was mainly the result of shortening and thickening of the Tibetan crust due to the India-Eurasia collision. To date there are little conclusive data that bear directly on this problem.

21.2.4 Crustal Shortening and Strike-Slip Faulting

A heated controversy surrounds two extreme, and basically incompatible, views of how the India-Eurasia collision and crustal shortening in Tibet are related to Cenozoic deformation throughout much of Southeast Asia. One group of workers, in a ground-breaking set of papers, suggested that the postcollisional convergence of India and Asia has been responsible for most of the Cenozoic deformation of Southeast Asia. They argued that although the Tibetan Plateau did indeed form by crustal shortening, the total crustal mass beneath the plateau is too little (by about 30%) to account for all of the convergence between India and Eurasia since the time of the collision. Using earthquake seismology and newly available satellite imagery, they suggested that the remaining convergence was accommodated by eastward ejection of continental crust away from the plateau and out of the way of India as it moved northward toward Siberia (Figure 21.2.6a). Later, experiments on plasticine were used to suggest that eastward extrusion of continental fragments was also responsible for the Early Cenozoic extension within the South China Sea and the Gulf of Thailand. This requires displacements of hundreds to a thousand kilometers on the large strike-slip faults within the Tibetan Plateau.

In a very different model, a numerical computer simulation was used by other workers to model Asia as a viscous sheet deformed by a rigid indenter (India). These numerical models predict a zone of shortening and thickening crust that grows northward and slightly to the side of the northward-moving indenter (Figure 21.2.6b). Because no deformation occurs beyond the boundaries of this zone of crustal shortening and thickening in front of the indenter, they have argued that only the Tibetan Plateau and flanking mountain belts have resulted from the collision of India and Asia. In this interpretation, the other regions of Cenozoic deformation in Southeast Asia are mainly unrelated to the India-Eurasia collision.

Both of these interpretations are based mainly on models, although the early work incorporated the geologic and geophysical data available at that time. What do current data say about this debate? The study of slip-rates on active faults shows that continental blocks within Tibet are indeed moving eastward at rates between 10 and 30 mm/y, as predicted by one set of models. However, these motions record only a snapshot of present day motions and do not answer the question of how much eastward ejection of material has occurred within Tibet. So far, geologic mapping has determined the total offset on the large strike-slip faults in only a few places. These data show about 15 km of left slip on the Haiyuan Fault, 200 km of left slip on the Altyn Tagh Fault, and 50 km of left slip on the Xianshuhe Fault (see Figure 21.2.4 for locations). Thus, while all of these strike-slip faults are moving very fast, they are also very young, and the total offset on these faults, while large, is not of the magnitude predicted by some models. While a definitive test of the extrusion model is not yet possible, the data sug-

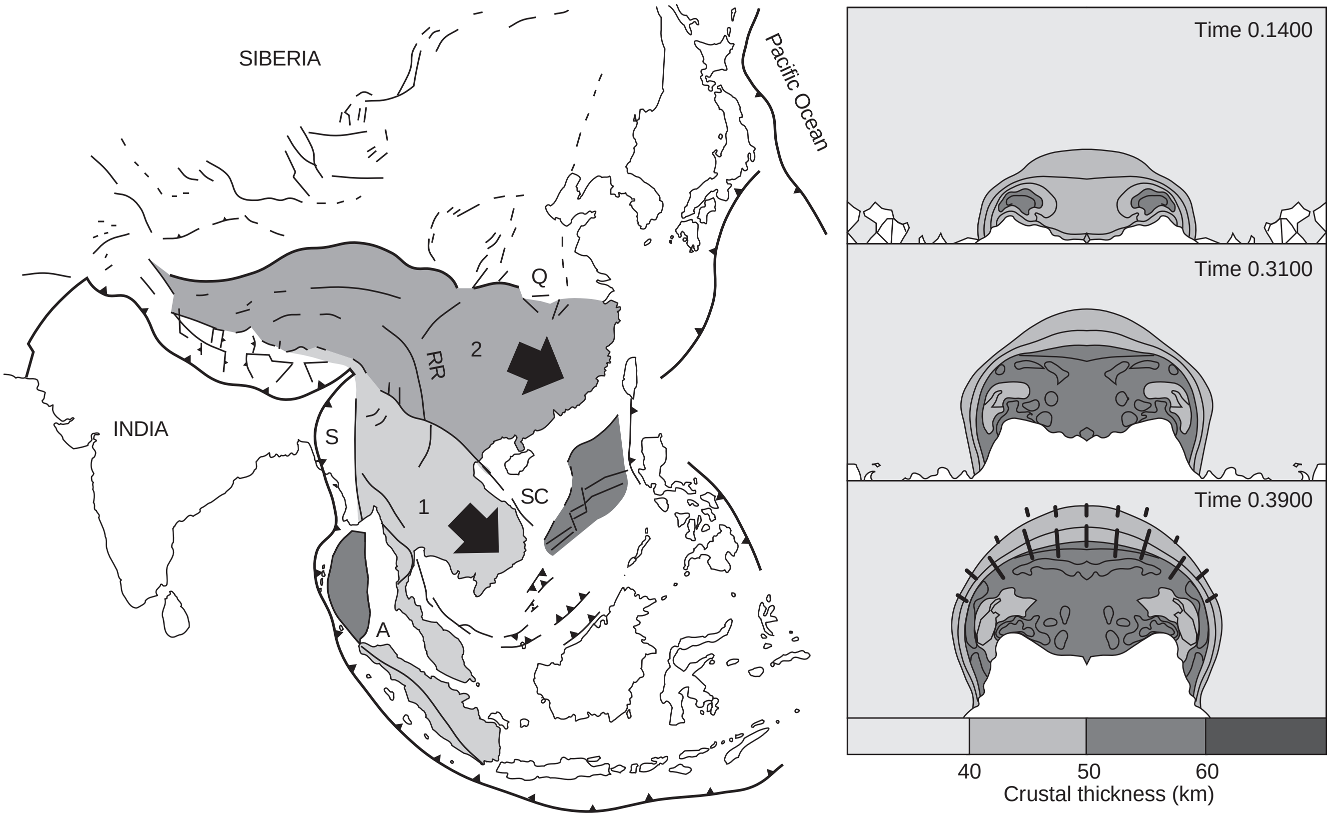

FIGURE 21.2.6 Two interpretations of the tectonic framework of Southeast Asia. (a) The interpretation of Tapponnier and coworkers, which emphasizes the eastward extrusion of two large crustal fragments bounded by major strike-slip faults as a result of the India-Eurasia convergence. In this interpretation, eastward movement of these fragments results in the extension on the Southeast Asian continental shelf and creation of oceanic crust in the South China Sea. The first crustal fragment to move (1) is indicated by a large arrow and shown in light gray and the second to move (2) is indicated by another large arrow. RR = Red River Fault, S = Sagaing Fault, SC = South China Sea, A = Andaman Sea. (b) The interpretation of England and Houseman shows the progressive development of topography in Asia by computer modeling of a rigid indenter (India) deforming a viscous sheet (Asia). This model suggests that India-Eurasia may have little if any effect east or west of the Tibetan Plateau, and so is very different from that of Tapponnier. Contours are of increasing crustal thickness at different times (times are dimensionless, but the bottom panel would approximately correspond to the present topography of Tibet).

gest that while extrusion does occur, it is of much smaller magnitude than that predicted by this model.

Strike-slip faults within the Tibetan Plateau also have a very interesting relationship to thrust faulting and crustal shortening occurring around the margins of the plateau. At the eastern end of some of the strike-slip faults, they merge with, or end against, the active thrust faults that rim the margins of the plateau. This is best illustrated for the Haiyuan strike-slip fault in the northeastern corner of the plateau, where geologic mapping shows that 15 km of left slip on this east-west trending thrust fault is absorbed by 15 km of shortening on a north-south trending thrust belt in the Liupan Shan (Figures 21.2.4 and 21.2.7). In addition, the onset of strike-slip faulting on the Haiyuan Fault is of approximately the same age as the onset of shortening in the Madong Shan (early Quaternary). Thus the left-slip motion on the strike-slip faults is absorbed by thrusting at the plateau margins, suggesting that lateral extrusion of crust within the plateau does not extend beyond the topographically high region.

Probably one of the reasons that so much emphasis has been placed on strike-slip faulting within the Tibetan plateau and surrounding regions is that many of the studies of active faulting have used satellite photos to identify important faults. Faults that dip steeply and are straight show up very well on these photos, while gently dipping faults with a complicated outcrop pattern can be difficult to recognize. Therefore the strike-slip faults within the plateau were recognized

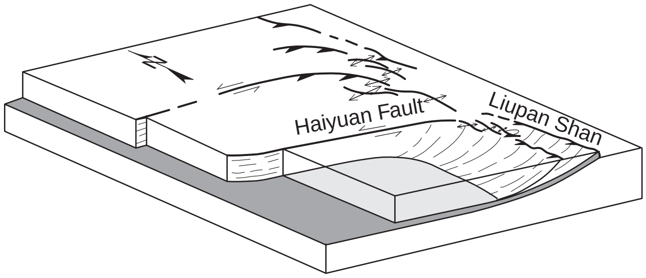

FIGURE 21.2.7 Schematic block diagram illustrating that strike-slip faults (such as the Haiyuan Fault shown here) end against thrust belts that bound the margins of the Tibetan Plateau (such as the Liupan Shan), and indicating how both thrust faults and strike-slip faults may be detached from the deeper crust by a zone of detachment within the mid-crust. See Figure 21.2.4 for locations.

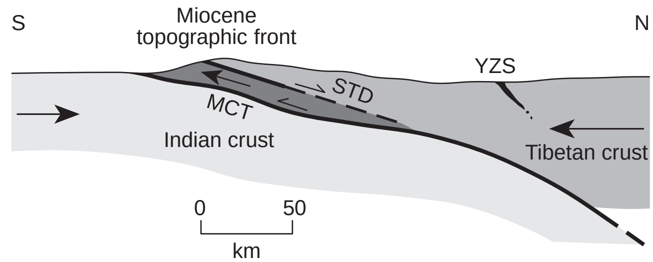

FIGURE 21.2.8 Diagrammatic cross section through the Himalayas and southern Tibet showing the southward ejection of a crustal wedge bounded below by the MCT and above by the South Tibetan Detachment (STD). Near Qomolangma (Mt. Everest) both faults were active at about 20 Ma, during the convergence of India. Faulting is thought to be due to gravitational collapse of the Miocene topographic front. The geometry shown at depth is speculative. YZS is the Indus-Tsangpo suture zone.

very quickly, while many of the important thrust faults have probably not yet been identified. Another problem is that large amounts of shortening around the margins of the plateau occur not only by faulting, but by folding, which is aseismic and not recorded by earthquakes. Thus it is easy to underestimate the rates of crustal shortening relative to the rates of strike-slip faulting from looking at first-motions from earthquakes on and around the plateau.

21.2.5 Extension of the Tibetan Plateau

Not all of the deformation of the Tibetan Plateau is compressional. A series of north-south striking grabens in southern Tibet is accommodating active east-west extension of the plateau at about 10 mm/y (Figure 21.2.4). These grabens are very young, with extension beginning at about 2 Ma, giving a total amount of east-west extension of about 20 km. The significance of this extension is unclear and is also somewhat controversial. Some workers relate the east-west extension to the eastward extrusion of material from the Tibetan Plateau and argue that the presence of east-west extension supports their interpretation. In contrast, others have suggested that east-west extension of the plateau records the delamination (falling off) of the mantle lithosphere beneath the plateau sometime in the Late Miocene or Pliocene. They argue that the removal of the dense lithosphere from beneath the plateau caused uplift of the plateau surface (as cold, dense mantle lithosphere was replaced by hot, buoyant asthenosphere), and that the surface elevation of the plateau is now decreasing by east-west extension within the plateau. At present, the significance of these north-south trending grabens remains highly uncertain and represents a crucial point in developing new models for the deformation of the plateau. It is perhaps noteworthy that the grabens occur mainly in the western two-thirds of the plateau and that some of the grabens extend southward through the Himalaya and nearly to the Himalayan thrust front.

Within the High Himalaya there is also evidence for large-scale north-south extension that preceded the younger east-west extension and occurred on gently north-dipping normal faults (the South Tibetan Detachment zone) that parallel the MCT (Figure 21.2.3) and form a major structural break between the crystalline rocks of the High Himalaya and the rocks of the Tibetan Sedimentary Zone (Figure 21.2.3). Extension occurred simultaneously with thrusting on the Main Central Thrust zone, as indicated by dates of 20 Ma on both fault systems near Qomolangma (Mt. Everest). The normal fault zone juxtaposes rocks of mid-crustal levels in the footwall against shallow-level sedimentary rocks in the hanging wall, and has a minimum displacement of 40 km (although the total displacement could be much greater). A north-south cross section through the fault shows that it bounds the top of a mid-crustal wedge that was ejected southward at about 20 Ma (Figure 21.2.8). This wedge was bounded at its base by the Main Central Thrust zone. Southward ejection of the wedge was from an area of high topography to an area of low topography and probably reflects gravitational collapse of the steep topographic slope along the southern margin of the Tibetan Plateau. Collapse may have occurred due to weakening of the crust by melting of granites at mid-crustal depths, as suggested by the presence of ductiley deformed synkinematic granites along and just below the South Tibetan

Detachment Fault. Several other areas within Tibet contain low-angle faults with normal displacement, but at present they are only recognized on short fault segments and their regional significance remains uncertain.

The occurrence of north-south extension of large magnitude along the southern margin of the plateau is somewhat surprising, since extension was not only contemporaneous with north-south shortening along the MCT but also occurred during continued north-south convergence of India and Eurasia at about 50 mm/y. This indicates that the extensional processes that controlled deformation within the mid- to upper crust in this region were essentially decoupled from the convergent motions occurring deeper in the crust and within the mantle lithosphere. It is probable that the mid- to upper crustal deformation under many, if not all, parts of the plateau is decoupled from the lower crust and mantle. For example, the general style of deformation within the thrust belts that rim the northern and northeastern margins of the plateau, and in some cases balanced cross sections constructed across the thrust belts, show that the thrust faults sole out at depths of about 15 km. Moreover, the relationship of the large strike-slip faults (such as the Haiyuan Fault) within the plateau to adjacent thrust-fault systems also indicates that many of the strike-slip faults are probably restricted to upper and mid-crustal depths (Figure 21.2.7). Thus the motions of crustal fragments within the plateau and along the margins of the plateau may not reflect the motion or deformation of the underlying lower crust and uppermost mantle.

21.2.6 Closing Remarks

Many fundamental questions remain to be answered within the Himalayan-Tibetan region. Some of these appear straightforward, but addressing them will require many years of intensive field work. For instance, how is active crustal deformation partitioned within the plateau? How can we unravel the active and young deformation of the plateau to learn about the pre-Pliocene history of the plateau and its growth through time? Finding the answers to these and other questions will require the use of sophisticated geophysical techniques in combination with field geologic data; for example, how is the deformation partitioned vertically within the crust of the Tibetan plateau? How is crustal deformation related to motions within the underlying mantle? On what length scale is crustal deformation related to motions within the mantle? On the scale of the plate boundary system as a whole (a region 1000 by 2000 km^2) it is likely that the averaged motions of the upper crust and the mantle lithosphere are reasonably similar. Is this also true at smaller scales, such as over regions a few hundreds of kilometers in length and width? How do we go about determining the degree of coupling between the crust and the mantle?

Lastly, one of the most controversial issues surrounding the geologic evolution of the Tibetan Plateau is the history of uplift of the plateau surface to its present elevation of about 5000 m. This is important not only to geologists, because it bears on the mechanisms by which the plateau has been deformed, but also to a wide range of scientists in fields from marine geology to climate modeling. Because the Tibetan Plateau is so large and stands so far above sea level, its uplift is thought to have influenced global circulation patterns within the atmosphere and to have been responsible for the onset of the Indian monsoons, which did not exist prior to Late Miocene time. Uplift of the plateau can also be correlated with changes in faunal distributions within the oceans and with huge changes in the isotopic ratios of elements such as strontium within the worldwide oceans. Indeed, the record of plateau uplift and erosion, as preserved within the composition of marine sediments found worldwide, as well as the geologic record from the plateau itself, suggests that collisional events of the magnitude found in Tibet and the Himalaya are probably rare events, even on a geologic timescale, and that collisional events of comparable magnitude may not have occurred within the last 600 my.

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