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Tectonics of Asia 50 years after the death of Emile Argand

By B. CLARK BURCHFIEL and LEIGH H. ROYDEN[1])

ABSTRACT

Emile Argand's magnificent work on the tectonics of Asia (1924) contains many concepts that remain valid today. His interpretation of deformation within Asia, extending from the Himalayan-Indonesian region to the Arctic, as the result of convergence between India and Eurasia would be considered quite modern. Despite the numerous advances in the earth sciences since his death 50 years ago, many of his interpretations can not be fully tested and some remain controversial.

Argand's idea that most of the India/Eurasia convergence was absorbed by plastic deformation within Eurasia is similar to modern problems in relating plate kinematics and intracontinental deformation. His concept that deformation within Asia can be divided into segments bounded by north-south boundaries remains at the heart of what is perhaps the most important controversy in Asian tectonics today; whether the Cenozoic convergence between India and Eurasia produced shortening and thickening of continental crust only within the Tibetan plateau and ranges to its north, or whether it also caused eastward movement of continental fragments and related deformation as far east as the South China Sea and the Gulf of Thailand. Despite modern plate tectonic reconstructions that allow the amount and rate of convergence between India and Eurasia to be calculated, we still do not know the mechanism of crustal thickening beneath the Tibetan plateau or the extent to which crustal fragments have been extruded eastward. Tests to resolve these questions must come from geological and geophysical data, which are at present scanty and indefinitive.

Our analysis of the Pliocene to Recent tectonics of southeast Asia, summarized in this paper, suggests:

1) Significant north-south shortening is occurring in the Himalaya, the Pamirs, the Tien Shan, the Qilian Shan and the Qaidam basin.

2) Strike-slip faults within the Tibetan plateau function as transfer faults that lose displacement to zones of crustal shortening along the northeastern and eastern margins of the plateau. Eastward motions of crustal fragments within the plateau are mainly absorbed by shortening along the plateau margins and probably do not extend much farther east.

3) At least around the margins of the plateau deformation in the upper crust is decoupled from that of the lower crust.

4) Right-lateral shear is occurring along a north-south trending zone roughly coincident with the eastern margin of the Tibetan plateau.

Little data is available for reconstruction of earlier Cenozoic deformation, but from the existing data it is our opinion that:

1) It is difficult to derive regional extension within the eastern part of southeast Asia from the convergent zone in the Himalaya and Tibet.

2) Events within the eastern part of southeast Asia are related to interactions between the Eurasian plate and oceanic plates to the east, which are in turn related to changes in the relative velocity of India and Eurasia at the time of collision.

It is humbling to note that our interpretations of Pliocene to Recent deformation are little different from many of Argand's ideas. Today the data needed to test the applicability of his concepts to earlier Cenozoic deformation remain insufficient. Argand's 1924 work remains a milestone in tectonic synthesis and leaves earth scientists today struggling to improve upon his vision of Asian tectonics.

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RÉSUMÉ

L'excellent travail d'Emile Argand sur la tectonique de l'Asie (1924) contient plusieurs concepts qui n'ont rien perdu de leur valeur. Son interprétation, selon laquelle la déformation de l'Asie entre la région de l'Himalaya-Indonésie à la région arctique serait le résultat d'une convergence entre l'Inde et l'Eurasie a conservé son aspect moderne. Malgré les progrès faits en sciences de la terre dans les 50 années depuis la mort de l'auteur, certaines de ses interprétations n'ont encore pas pu être entièrements vérifiées et d'autres demeurent controversées.

L'idée d'Argand que la majeure partie de la convergence Inde/Eurasie a été absorbée par une déformation plastique dans l'Eurasie contient des similarités avec les problèmes modernes de relation entre la cinématique des plaques et la déformation intracontinentale. Son concept que la déformation à l'intérieur de l'Asie peut être divisée en segments confinés par des limites nord-sud est le point central de la récente controverse sur la tectonique de l'Asie. La convergence Cénozoique entre l'Inde et l'Eurasie a-t-elle raccourci et épaissi la croûte continentale du plateau Tibétain et des chaines au nord du Tibet? Est-elle aussi responsable des mouvements vers l'est des fragments continentaux et de la déformation qui en découle aussi loin à l'est que la Mer de Chine Méridionale et le Golfe de Thailande? Malgré les reconstitutions modernes de la tectonique de plaques qui permettent de calculer la somme et la quote-part de la convergence entre l'Inde et l'Eurasie, nous ne connaissons toujours pas le mécanisme responsable de l'épaississement de la croûte en dessous du plateau du Tibet ni l'étendue de l'extrusion vers l'est des fragments crustaux. Pour offrir des réponses à ces questions des tests basés sur des données géologiques et géophysiques seraient nécessaires. Pour l'instant, ces données sont rares et leur valeur incertaine.

Notre analyse de la tectonique du sud-est de l'Asie entre le Pliocène et les temps modernes, discutée dans cet article, suggère:

1) Un très important raccourcissement nord-sud est présent dans l'Himalaya, le Pamir, le Tien Shan, le Qilian Shan et le bassin de Qaidam.

2) Les failles en «strike-slip» dans le plateau du Tibet ont une fonction de failles de transfert qui séparent le déplacement des zones de raccourcissement le long des marges nord-est et est du plateau. Les mouvements vers l'est des fragments crustaux du plateau sont absorbés par un raccourcissement le long des marges du plateau et ne s'étendent probablement pas davantage vers l'est.

3) Tout au moins autour des marges du plateau, la déformation de la croûte supérieure est séparée de celle de la croûte inférieure.

4) On trouve un cisaillement dextral-lateral le long d'une zone de direction nord-sud qui coïncide approximativement avec la marge est du plateau Tibétain.

Peu de données existent qui permettraient de faire une reconstruction de la déformation du Cénozoique ancien. D'après les données disponibles nous sommes d'avis que:

1) Il est difficile de deriver des extensions régionales dans la partie orientale du sud-est de l'Asie par la zone convergente dans l'Himalaya et le Tibet.

2) Certains événements dans la partie orientale du sud-est de l'Asie sont en relation avec les interactions entre la plaque de l'Eurasie et les plaques océaniques à l'est qui elles mêmes sont en relation avec les changements en vitesse relative de l'Inde et de l'Eurasie au moment de la collision.

Nous constatons humblement que nos interprétations de la déformation du Pliocène au Récent ne diffèrent que peu de bon nombre des idées d'Argand. Même aujourd'hui les données requises pour tester l'application de ses concepts pendant la phase de déformation du Cénozoique ancien sont insuffisantes. L'ouvrage d'Argand publié en 1924 marque un tournant dans la synthèse tectonique et laisse les scientifiques de la terre en mal d'améliorer sa vision de la tectonique de l'Asie.

Introduction

Southeast Asia contains the most spectacular topography on the continents. Its topography is dominated by the massive Tibetan plateau, the greatest area of high topography on any continent (Fig. 1). The plateau and its flanking mountains and basins are the result of deformation related to the collision and continued convergence between the continental lithosphere of India and Eurasia. Rates of deformation within southeast Asia are rapid, making it an ideal area to study processes of intracontinental deformation. Unfortunately, from the period following World War One until a decade ago much of this region was closed to foreign scientists. The difficulty of access and poor working conditions meant that those interested in the geology of the region had to rely on reports from the handful of scientists who were fortunate enough to have worked there. Only in the last decade much of the area has been opened to foreign researchers. During this time many scientists and their Chinese colleagues have focused considerable attention on the geology and tectonic processes that have formed this truly extraordinary region.

Attempts to interpret the tectonics of southeastern Asia must be put into perspective. The region is immense when compared with many of the best known mountain ranges of the world. It is sobering to compare this region to the Western Alps of Europe, whose crustal mass above sealevel is only about 1% that of the Tibetan plateau, and where research has been conducted by generations of geologists for more

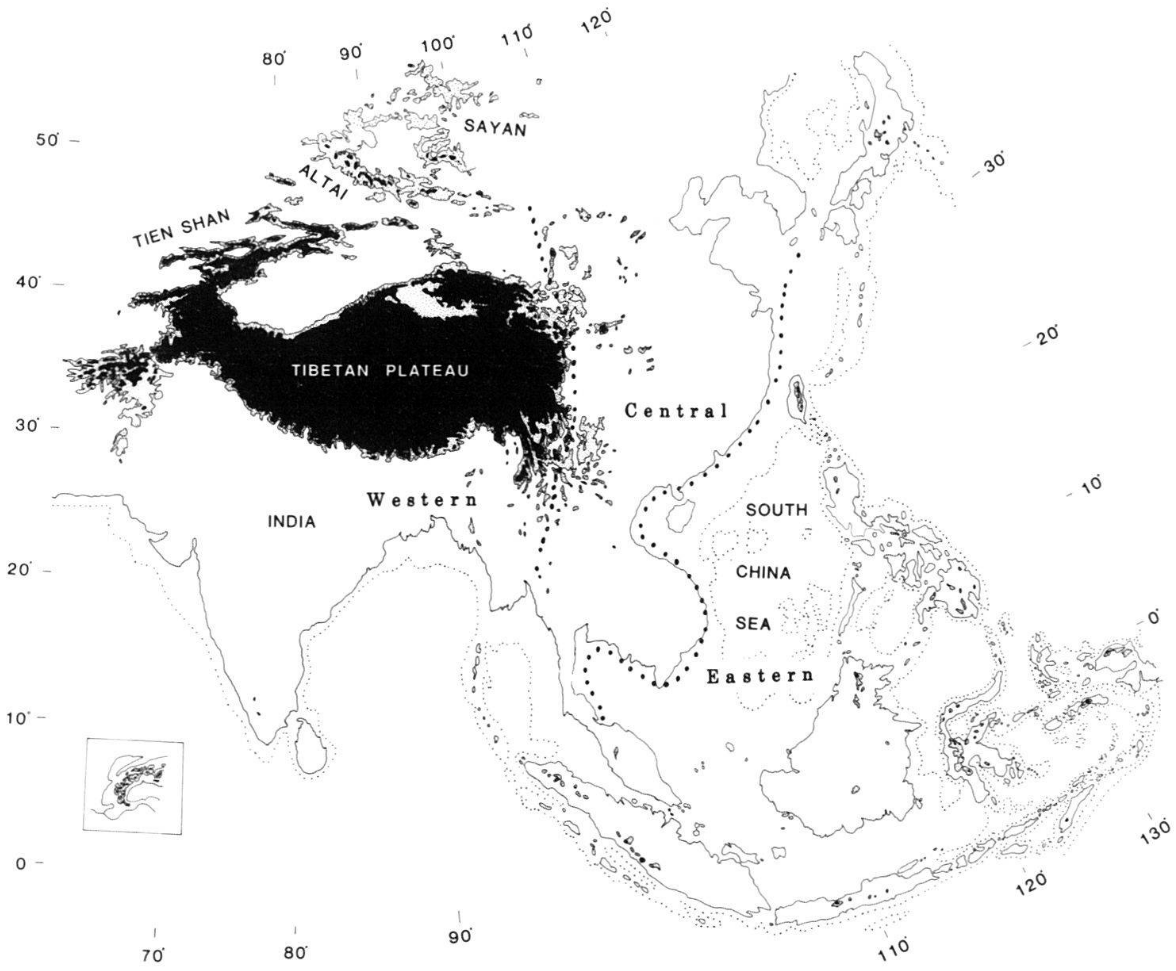

Fig. 1. Generalized topographic map of southeast Asia showing all the areas below 2 km (white), between 2 and 3 km (dotted), and above 3 km (black) above sealevel. Three regions separated by broad generally north-south boundaries can be defined: a western region whose eastern boundary lies along the eastern boundary of the Tibetan plateau, a central region that lies between the Tibetan plateau and the continental shelf of southeast Asia and an eastern region that includes areas east of the continental shelf. It is our opinion that the topography of southeast Asia is a result of Cenozoic tectonics. For comparison the inset map in the lower left corner shows the western Alps of Europe at the same scale.

than 150 years. Even so, new data that leads to major changes in Alpine tectonic models is discovered continuously. In contrast, the geology of much of the Tibetan plateau and surrounding regions still must be considered largely of reconnaissance vintage.

Argand's Legacy

Argand is considered the father of modern Asian tectonics by many of us who work in Asia. "La tectonique de l'Asie" (ARGAND 1924) remains one of the truly creative and imaginative works in the earth sciences, but the interpretations presented in that work were hampered by an even greater lack of data than we have today. On his magnificent map of Asia there are two large areas within and along the eastern part of the Tibetan plateau that are blank[2]) (and probably many other areas that should also be blank). The paucity of data available to Argand only makes his interpretation of Asian tectonics even more extraordinary. During the course of preparing the presentation for the meeting of the Geological Society of Switzerland, we took the opportunity to reread Argand's work. The number of his interpretations that would today appear quite modern is truly remarkable.

The purpose of this paper is not to present a complete synthesis of Asian tectonics, but to examine some of Argand's ideas concerning the broader aspects of Asian tectonics in light of modern interpretations, concepts and technological approaches. Interpretations of Asian tectonics differ significantly among different workers, and some attempt to analyze these differences and to present our own views is attempted, but the overall theme of this paper is to examine how far we have (or have not) advanced since Argand's masterful synthesis of 1924. Toward this end, it is useful to review the beginnings of modern Asian tectonics, starting with Argand. A few of his interpretations will be considered in a modern context below, but these by no means represent the great range of ideas presented in his 1924 synthesis.

Some of the interpretations put forth by Argand in 1924, and which appear to remain generally valid today, include the following:

1) Asian tectonics is the result of closure of Tethys – the "jaws" between two continents;

2) convergence between India and Eurasia caused deformation from the Himalaya-Indonesian region to the Arctic;

3) the deformation within Eurasia can be divided into segments limited by north-south boundaries; each segment containing a coherent tectonic pattern of arcuate folds and faults;

4) most of the deformation resulting from post-collisional convergence was absorbed by Eurasian crust because, having been deformed in Mesozoic and Paleozoic time, it was weaker and more inhomogeneous than the Precambrian crust of India;

5) deformation within Eurasia can be envisioned as plastic deformation of continental crust, but with zones of more intense local deformation.

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[2]) A first version of Argand's map contained no blank spaces, a fact passed on by Prof. Jean-Paul Schaer.

Argand also expressed the opinion that, with the state of knowledge available at that time, it was impossible to treat the deformation within Eurasia in a quantitative way. This makes an ideal point of departure from which to examine progress in understanding the tectonics of Asia. Since Argand's time there has been great technological progress in the earth sciences that permits us to begin to treat continental deformation in a more quantitative way. Perhaps the most significant advance has been the development of plate tectonics which places the collision and continued convergence of India and Eurasia within a quantitative kinematic framework.

Mesozoic evolution of southeast Asia

A brief look at the Mesozoic evolution of the eastern Tethyan region can be used as a starting point from which to examine its Cenozoic evolution, the main focus of this paper. Argand realized that considerable convergence had taken place between the Indian and Eurasian continents, and had even suggested that there might have been an ocean in the region between the two continents. Modern plate tectonic reconstructions indicate the jaws of Tethys, at the longitude of central Tibet, were more than 6,000 km wide at the beginning of Mesozoic time and that much of Tethys was floored by oceanic crust. Plate tectonic reconstructions for many of the continental regions bordering Tethys can be made at least to Jurassic time, and paleomagnetic studies can track the movement of some of the continental fragments not restorable by data from the magnetic anomalies on the sea floor.

The presence of ophiolites along sutures as remnants of oceanic crust and geological evidence for plate convergence adjacent to the sutures comprise data unavailable to Argand. Such geological signatures at active plate boundaries are now well known and can be used to unravel the history of former plate boundary systems. Geological data indicate the closing of at least three oceanic areas with the consequent collision of continental fragments and island arcs within Tibet and southeast Asia (Fig. 2). In fact, the evolution of the eastern Asian continent has been dominated by the closing of numerous oceans and consequent collision of many continental and island arc fragments, from late Precambrian time to present, a fact also noted by Argand (1924, see his Figure 7). There remain, however, fragments of ophiolites that are difficult to place within the presently accepted Mesozoic framework in Tibet that suggest current interpretations still must be considered preliminary. For example, ophiolitic rocks and blueschists are reported within what is now considered one terrane, the Qiangtang terrane, in central Tibet, but whether they define another suture remains unknown (Kidd et al. 1988).

It is certainly because of the lack of geological information within Tibet that Argand was unable to appreciate the complexity of its Mesozoic evolution. What Argand did recognize was that the greater ductility of Eurasia relative to India during Cenozoic deformation was inherited from Mesozoic deformation within Eurasia, which made Eurasia more easily deformed than the older more rigid Indian continent. He also recognized that anisotropy within Eurasia, which we now know is the result of continental and island arcs fragments bounded by sutures, played an important role in localizing Cenozoic deformation.

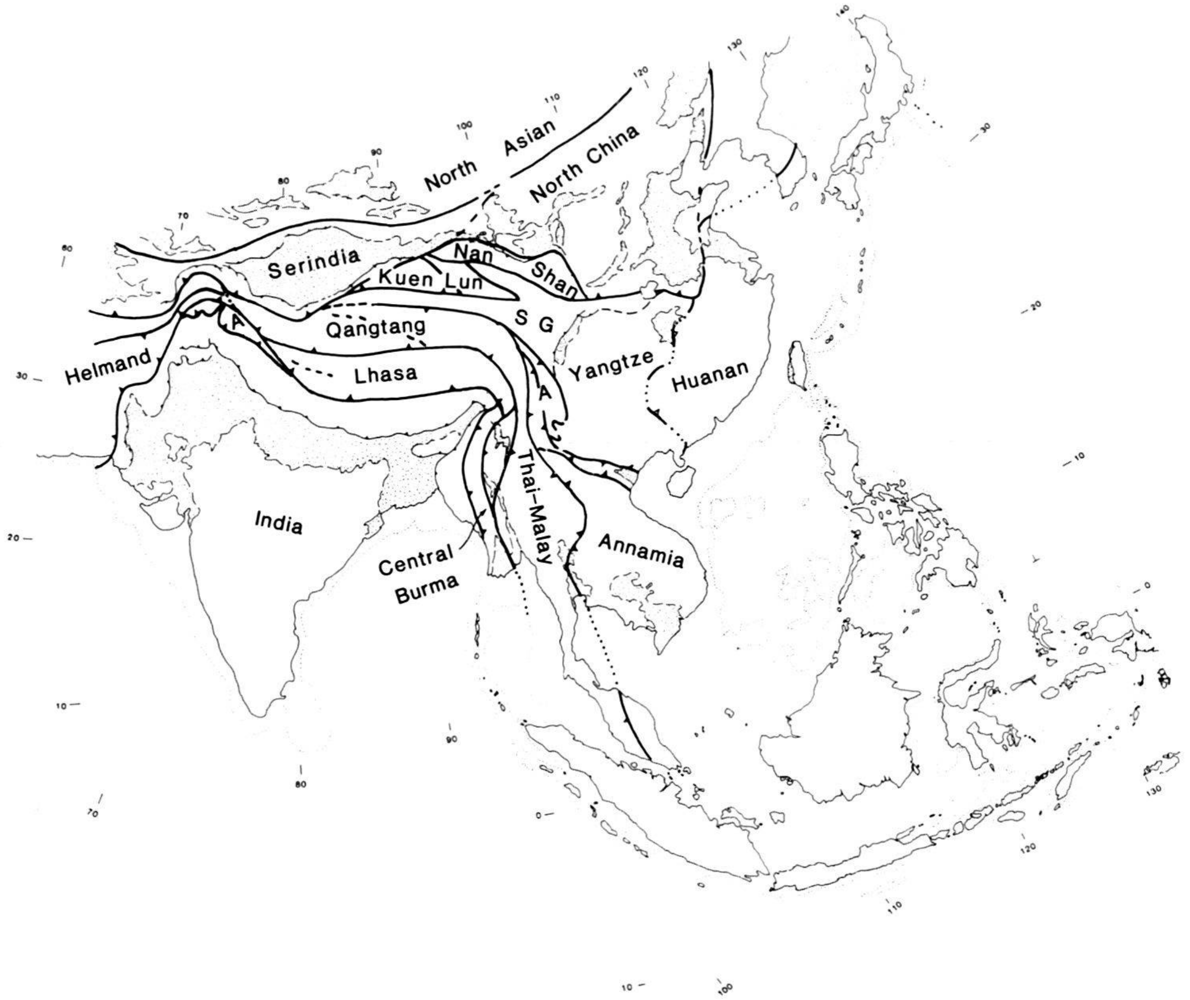


Fig. 2. Major fragments in southeast Asia during late Palaeozoic, Mesozoic and early Cenozoic time (largely taken from ŞENGÖR 1987). Most of these fragments are probably underlain at least in part by older continental crust except for the Songpan Ganze (SG) and island arc fragments (A). Direction of subduction during closure of oceanic areas between the fragments is shown by the barbed suture lines with barbs on the upper plate of the subduction system. Most of the accretionary evolution of Asia was not recognized by Argand because of lack of data from Tibet and the lack of recognition of sutures and their remnants of ocean floor.

Cenozoic evolution of southeastern Asia

The first order topography of southeastern Asia is a direct reflection of Cenozoic tectonics. It can be divided into three regions: a westernmost region dominated by the Tibetan plateau and ranges and basins to its north, a central region characterized by mountains of lower relief and small basins in eastern China and Indochina, and an eastern region consisting of the continental margin of eastern Asia, ocean basins partly underlain by oceanic crust and a great variety of island arcs and continental fragments (Fig. 1).

The Tibetan plateau has figured prominently in all interpretations of the tectonic evolution of the India/Asian collision, but its importance for the tectonics of all southeast Asia has been equivocal. Some workers have regarded the development of the plateau as of primary importance and the most significant part of the dynamic system that includes all of southeast Asia; others, including Argand, have considered it of more local importance. It is, in fact, the significance of the plateau to southeast Asia tectonics that has polarized tectonicians into two camps.

Interpretations of the Cenozoic development of the Tibetan Plateau and its relations to the tectonics of Southeastern Asia

Although Argand clearly recognized that the tectonics of Asia resulted from the closure of Tethys and continued convergence between India and Eurasia, he did not have the data to interpret the tectonics quantitatively. Today, plate tectonic reconstructions together with geological interpretations permit quantitative bounds to be placed on some aspects of Asian tectonics. The time of collision between the continental crust of India with Eurasia remains somewhat uncertain, but probably occurred at approximately 45 ± 5 Ma and about 2,000–2,500 km south of the present location of the collisional boundary along the Indus-Yarlang suture (Molnar & Tapponnier 1977). Since that time, India has moved generally northward at about 45 to 60 mm/yr at the longitudes of the west and east syntaxes respectively, and has rotated counterclockwise by about 30 degrees (see Dewey et al. 1989).

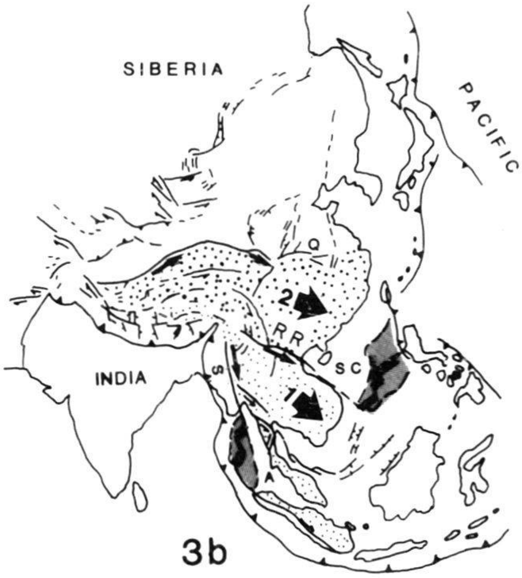
These data do not however, indicate how the kinematics of plate motion is translated into intracontinental deformation, or how the deformation is temporally or spatially partitioned within Eurasia. These remain important unresolved problems and have led to a range of very different interpretations of the development of the Tibetan plateau and its relations to the tectonics of Asia.

Argand realized that the Tibetan plateau was internally deformed, but considered that much of the convergence between India and Eurasia took place by the underthrusting of the Indian continental crust beneath the entire plateau (Argand 1924). This view has been perpetuated to the present, in a more extreme form, by such workers as Barazangi & Ni (1982) and Powell & Conaghan (1973, 1975). In their interpretations the great thickness (50–70 km) of the crust beneath Tibet (see recent review by Molnar 1988) has resulted from the doubling of continental crust by replacement of the Tibetan upper mantle by underthrust Indian continental crust, with deformation in the Tibetan crust being less significant than envisioned by Argand. A variation of this hypothesis was presented by Zhao & Morgan (1985, 1987) who suggested that India has underthrust the southern part of the plateau while the crust of the northern part of the plateau has been thickened and elevated by shortening of the lower crust and mantle, an interpretation that is similar to that of Argand.

In contrast, Dewey & Burke (1973) suggested that the thick crust beneath the Tibetan plateau was the result of shortening of the Tibetan crust due to the India/Eurasian convergence. In their interpretation, India is underthrust only beneath the Himalaya and the southernmost part of the Tibetan plateau. Their diagrams show a rather uniform distribution of crustal shortening both vertically and horizontally. Based on seismic reflection profiles, Hirn et al. (1984) and Hirn (1988) has recently suggested that shortening of the upper and lower crust may have been decoupled along a zone of weakness within the middle crust, an idea that has very important conse-


Fig. 9
d

3a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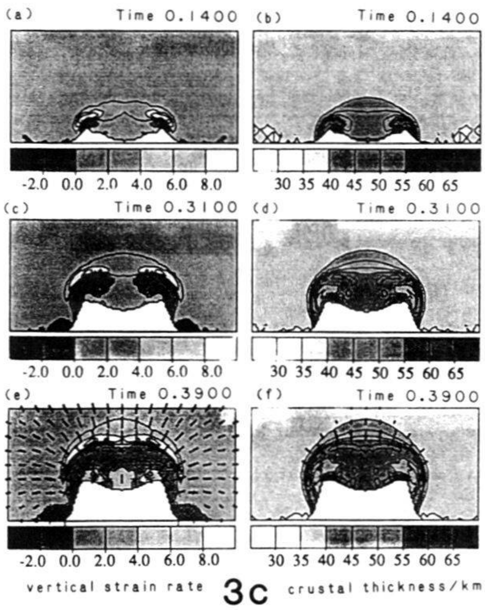
(a) Time 0.1400
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(c) Time 0.3100
(d) Time 0.3100
-2.0 0.0 2.0 4.0 6.0 8.0
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(e) Time 0.3900
(f) Time 0.3900
-2.0 0.0 2.0 4.0 6.0 8.0
30 35 40 45 50 55 60 65
vertical strain rate
crustal thickness/km

3c

quences (see below). In all these models it is either stated or implied that all convergent motion between India and Eurasia is absorbed within and beneath the plateau.

Since the birth of plate tectonics two interpretations have been published that represent two extreme, and generally incompatible, views of how Cenozoic deformation has been partitioned within Eurasia and the role played by the Tibetan plateau. These two radically different interpretations have become the focal point of considerable debate and represent two different views of how intracontinental deformation within Asia, and intracontinental deformation in general, can be modeled. The two models make very specific and different, but testable, interpretations about the relation of the evolution of the Tibetan plateau to the tectonic development of southeastern Asia.

MOLNAR & TAPPONNIER (1975, 1977) and TAPPONNIER & MOLNAR (1977) have presented the interpretation that post collisional India/Eurasia convergence was responsible for all Cenozoic deformation between India and Siberia. They argued that the Tibetan plateau was formed by crustal shortening, but that about 30 percent of the convergence could not be accounted for by crustal shortening within the Tibetan plateau alone. Using known geology, first motion studies from earthquakes, and adding important new data from landsat imagery, they modeled the pattern of active faulting in Asia using mechanical models of indentation and slip-line theory MOLNAR &

Fig. 3. Three interpretations of the tectonic framework of southeast Asia.

3a. The interpretation of ARGAND (1924, fig. 9). The dashed lines represent the horizontal projection of the flow lines for the levels of the flux in which takes place the command of the foldings. d: particular transverse alignments. 3: Central transverse alignment of the Turanian segment and of the Turanian virgation (arc). 4: Western terminator of the segment of central Asia. 5: Transverse alignment common to the Indo-Siberian segment and the Indo-Mongolian segment. 6: Eastern terminator of the segment of central Asia. 7: Transverse alignment of the Lena-loop of the Patoms-northwestern Manchuria. The flux of the Greater Khingan, in the vicinity of a part of this transverse alignment, tends to override the flux of the segment adjacent to the east, the segment of the Aldan-Amur. 8: Central transverse alignment of the latter segment. (Caption translation taken from Carozzi's translation [1976]).

3b. The interpretation of TAPPONNIER et al. (1982) which emphasizes the eastward extrusion of two large crustal fragments bounded by major strike-slip faults as a result of the India/Eurasia convergence. 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) shown in fine dots, and the second (2) shown in coarse dots. Their interpretation is a major departure from that of Argand, because crustal material moves across the north-south boundaries defined in 3a above. RR = Red River fault zone; S = Sagaing fault zone; SC = South China Sea.

3c. The interpretation of ENGLAND & HOUSEMAN (1986, 1988) shows the progressive development of topography and strain in Eurasia during convergence between India and Eurasia where a rigid indenter (India) deforms a thin viscous sheet (Eurasia). This model uses the viscous nature of Eurasia as proposed by Argand and produces results similar to those shown in Argand's figure reproduced above; it suggests India/Eurasia convergence may have little if any effect beyond the segment dominated by the Tibetan plateau. Taken from Figure 8 of ENGLAND & HOUSEMAN (1988). Contours of vertical strain rate and crustal thickness for a thin-sheet calculation. Shaded regions correspond to the deforming lithosphere, the solid lines surrounding them correspond to the boundaries of the deforming material. One portion of the bottom boundary moves with time. Dimensionless times, shown above the parts of the figure, can be converted to times by multiplying by 100 Ma. Figures 8a, c, e show contours of vertical strain rate. Figures 8b, d, e show contours of crustal thickness; before deformation starts the crustal thickness is 35 km throughout. Solid lines superimposed on (e) show the orientations and relative magnitudes of the calculated horizontal principal stresses; thicker lines correspond to compressional stress, the few thinner lines, around the corners of the indenter, to extensional stresses. The longest symbol corresponds to a compressional deviatoric stress of 1.0×10^8 Pa averaged vertically through the lithosphere. The solid lines on (f) show the calculated horizontal principal strain rates; these are parallel to the respective principal stresses, but depend on the *n* the power of the deviatoric stress (e).

Tapponnier 1977). They suggested that the convergent motion unaccounted for by shortening within Tibet took place by the lateral motion of continental material along large strike-slip faults which moved continental material mostly eastward, out of the way of India as it moved northward towards Siberia. The interpretations presented by Molnar & Tapponnier were exciting because they showed how the tectonics of Asia could be integrated into a single dynamic system related to plate motions. Their interpretation can be regarded as a resurrection of Argand's interpretation (Fig. 3a) that the closing of Tethys caused intracontinental deformation from the Himalaya/Indonesian region to Arctic, although their interpretation used quantitative approaches unavailable to Argand.

Tapponnier et al. (1982, 1986) and Peltzer & Tapponnier (1988) have further developed the concept that eastward extrusion of continental fragments has played the dominant role in the tectonics of southeast Asia, and have proposed that its influence reached to the oceanic regions in the South China Sea and the Gulf of Thailand (Fig. 3b). Using indentation of plasticine to simulate the tectonic pattern of southeastern Asia Tapponnier et al. (1982) suggested that two large fragments of continental crust have been extruded eastward; first a southern block south of the Red River fault zone, followed by a second block north of the Red River fault zone and south of the Qinling mountain range (Fig. 3b). Faults bounding these blocks were postulated to have hundreds to at least 1,000 km of left- and right-slip displacement on their north and south boundaries respectively. Divergence and extension of the blocks at their eastern end caused continental extension leading to the formation of extended continental crust (Gulf of Thailand) or oceanic crust (South China Sea). Deformation due to the India/Eurasian collision was thus interpreted as partitioned into movement along discrete fault zones causing eastward movement of crustal blocks that extended from within the Tibetan plateau eastward into the oceanic regions adjacent to southeast Asia (Tapponnier et al. 1986, Fig. 3b).

In contrast, England & Houseman (1986, 1988) used an entirely different model, to interpret the tectonic evolution of Southeastern Asia. They used a numerical model of a thin viscous sheet (Eurasia) indented by a more rigid indentor (India): a resurrection of another Argand interpretation. The pattern of deformation resulting from the England and Houseman models has many similarities to those presented by Argand (compare Figs. 3a and 3c). The model predicts a wave of shortening and thickening crust that expands both in front of and somewhat beyond the longitude of the indentor (Fig. 3c). Unlike the model of Tapponnier and others (1982), their model predicts homogeneous shortening throughout the deforming crust, and no extrusion beyond the limits of the thickened crust in the Tibetan plateau. Their model focuses mainly on the formation of the Tibetan plateau and one of the important consequences of their model is that, while the Tibetan plateau is the primary result of the convergence between India and Asia, most of the other tectonic features of Asia east of the plateau need not be related directly to India/Eurasia convergence.

Comparing models like those of Tapponnier et al. (1986) and England & Houseman (1988) it is clear that one of the major controversies today involves the spatial extent of the deformation resulting from the collision and continued convergence of India and Eurasia. Did convergence result primarily in the formation of the Tibetan plateau and perhaps also the deformation north of the plateau at least to the Altai ranges, or in addition to the development of the plateau, did convergence also bring about deformation within the entire region of southeast Asia through the eastward movement of large continental fragments?

Tests of the models for the Cenozoic tectonics of southeast Asia

Western Regions (the Tibetan Plateau)

The different interpretations of Asian tectonics have very different geological consequences and can be tested. Principally, the test must focus on whether large continental fragments have moved eastward, at the appropriate time, from the region of India/Eurasia continental convergence. Toward this end it is instructive to look at the relevant data from youngest to oldest, because more data has been accumulated for the youngest structures.

1) Studies of earthquakes, active faults and Quaternary structures

The study of slip-rates on active faults has shown a sense of movement consistent with eastward movement of continental blocks as predicted by the models of TAPPONNIER et al. (1982, 1986; Fig. 4). First motion studies on earthquakes also yield similar results (MOLNAR & CHEN 1983). These studies show convergence across the Himalaya at about 10–15 mm/yr (LYON-CAEN & MOLNAR 1985), strike-slip faulting with slip-rates of between 10 and 30 mm/yr, and east-west extension in the southern Tibetan plateau at about 10 mm/yr (TAPPONNIER et al. 1986). However, many of the studies on active faults have used satellite imagery to identify major faults. This works quite well on steeply dipping faults with horizontal displacements (strike-slip faults), so that more data has been gathered for active strike-slip faults than for other types of faults or for folds.

Slip-rates and sense of movement on active faults give only a present day snapshot of rates of displacement and partitioning of deformation by faults. Perhaps more relevant is the duration of motion on these faults, the average slip rate and their total displacement. Few studies have focused on these questions, largely because such studies require considerable mapping before they can be answered and Tibet has now been open to the outside researchers for only about a decade. One of the few field studies, by ARMIJO et al. (1982), has shown that east-west extension in southern Tibet probably began about at 2 Ma, thus the net east-west extension is probably about 20 km, if one uses the modern extension rate of about 10 ± 5 mm/yr.

The only strike-slip faults for which net-slip has been determined are two active faults in the southern Ningxia Autonomous Region. The east-west trending Haiyuan fault has 14–16 km of left slip, while another east-west trending fault, immediately north of the Haiyuan fault, in the western part of the Tianjinshan has about 3 km of left-slip (ZHANG et al. 1990; BURCHFIEL et al. in press: Fig. 4). The Haiyuan fault was one of the faults proposed by MOLNAR & TAPPONNIER (1975, 1977) to accommodate eastward movement of the continental fragment to its south. At 8 ± 2 mm/yr the Haiyuan fault does have a reasonably high slip-rate (ZHANG et al. 1988), but it is not a very old fault, originating only in the last 2 Ma (BURCHFIEL et al. in press). Thus if signi-

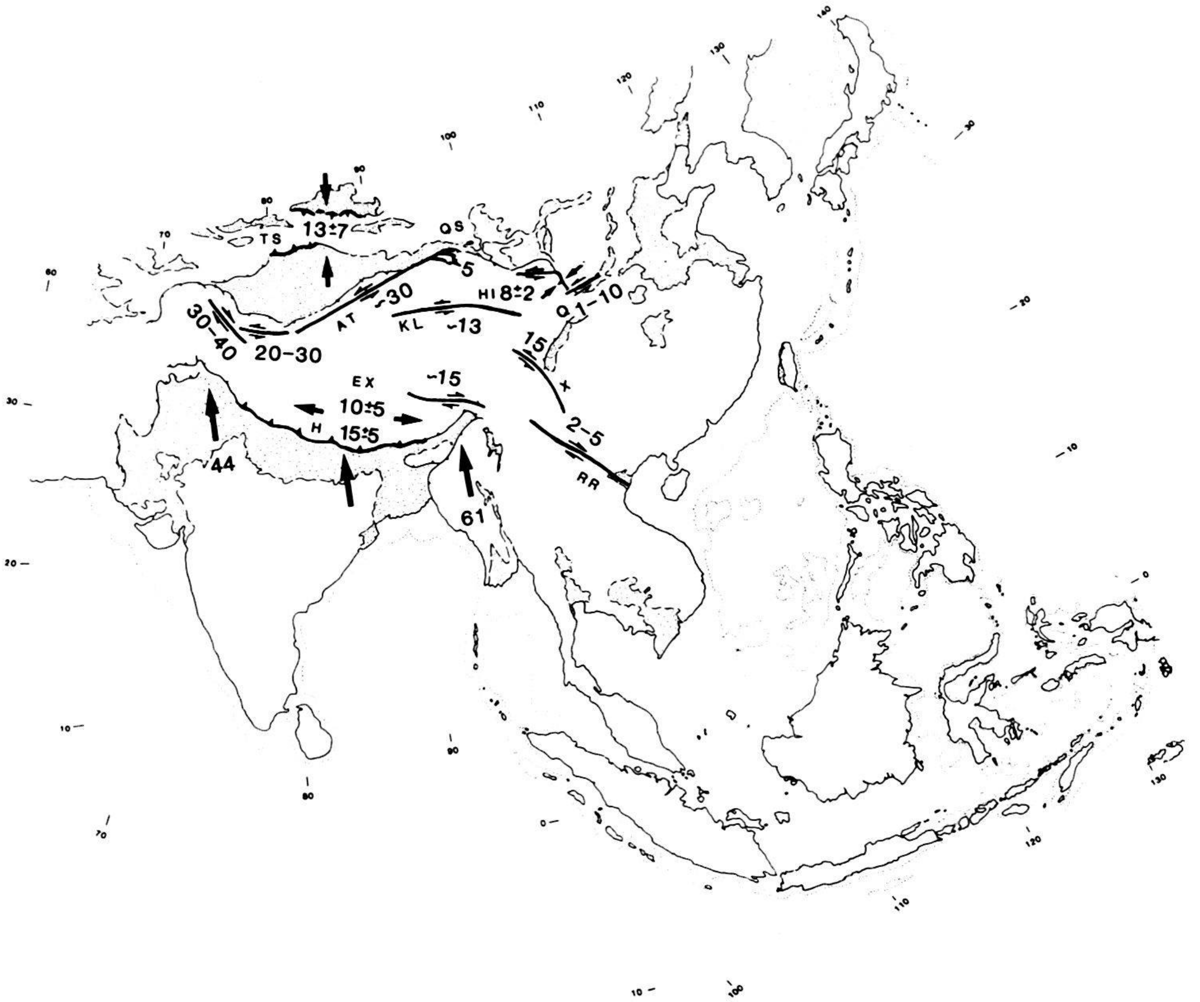


Fig. 4. Slip rates (in mm/yr) on active faults within southeast Asia. Reversed arrows identify slip-direction on strike-slip faults. Medium black arrows that diverge indicate areas and directions of extension; where they are opposed they indicate areas of shortening across thrust faults (and folds) with barbed lines. Large north-pointing arrows south of the Himalaya indicate direction and magnitude of present convergent rate between India and Siberia. These data have been used to support eastward extrusion of crustal fragments due to the post collisional convergence between India and Eurasia. AT = Altyn Tagh fault; EX = Extension in southern Tibet; H = Himalaya; HI = Haiyuan fault; KL = Kun Lun fault; Q = Qinling; QS = Qilian Shan; RR = Red River fault zone; TS = Tien Shan; X = Xianshuihe fault.

ficant extrusion has occurred, it is not on the Haiyuan fault and must be accommodated by faults farther south. Allen et al. (in press) have suggested that the Xianshuihe fault in southeastern Tibet may have several tens of km of left-slip offset, although this figure is not very well documented, and projecting its present rate of slip of 10 mm/yr, this fault may be no older than early Pliocene. Kidd & Molnar (1988) have suggested a 75 km offset on the Kun Lun fault which would indicate that it also is no older than Pliocene. Large offsets have been suggested for other faults in the region, but none have been documented.

Studies in the southern Ningxia region (located at HI in Fig. 5) have produced results that suggest movement on large faults may shift rapidly from one fault to another, thus making extrapolation of Holocene slip-rates dangerous. Fault histories at the eastern end of the Haiyuan fault have shown that two major changes in how the displacement on the Haiyuan fault has been taken up has occurred since 1–2 Ma; the last change occurred no more than about 200,000 years ago (BURCHFIEL et al. 1989; ZHANG et al. in press).

A second important result of the study in the southern Ningxia region was that the eastward movement of crustal fragments along left-slip faults is absorbed at their eastern ends by shortening along the eastern margin of the plateau (Fig. 5). The

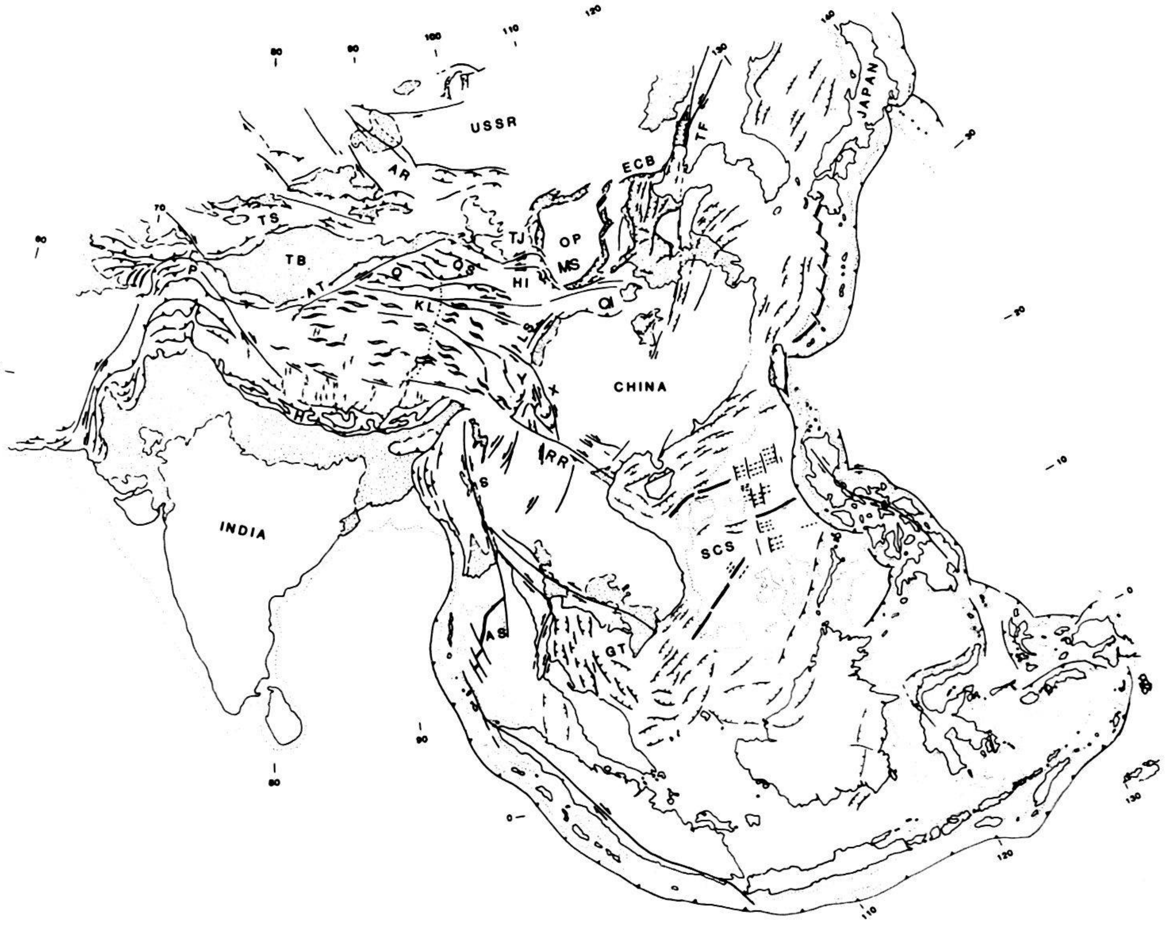


Fig. 5. Generalized Cenozoic tectonic map of southeast Asia. Dotted areas are basins of late Cenozoic deposition. Horizontal arrows indicate sense of slip on strike-slip faults, barbed lines indicate thrust faults in the continental areas and subduction zones in the oceanic areas with barbs on the upper plate, and ticked lines indicate normal faults. Lunate areas in the Tibetan plateau indicate folds, black where Cenozoic, and open where age is unknown but probably Cenozoic. Double lines indicate spreading centers in the South China Sea (32–17 Ma), Okinawa through (Active) and Andaman Sea (Active). Dashed lines in the South China Sea are trends of magnetic anomalies. Dotted line is 1 km isobath in oceanic areas. Compare position of major faults with suture boundaries in Figure 2. ARGAND (1924) recognized that Eurasia absorbed more deformation than India during Cenozoic convergence because it had been deformed more recently than India, and that deformation within Eurasia was unevenly partitioned because of the inhomogeneity of the Eurasian crust. Dotted line in the eastern part of the Tibetan plateau locates the British/ Chinese transect. 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 zone; S = Sagaing fault zone; TB = Tarim basin; TF = Tan Lu fault zone; TJ = Tianjin Shan; TS = Tien Shan; X = Xianshuihe fault; Y = western Yunnan.

amount of shortening is, within limits, the same as the amount of strike-slip, thus no crustal material has been extruded eastward beyond the Tibetan plateau in this area. A similar interpretation was made for the left-slip Altyn Tagh fault and the shortening in the Qilian Shan (Fig. 4, Burchfiel et al. 1989), but there has been no documentation of this relationship (Figs. 5 and 6). If many of the large strike-slip faults in southeastern Asia also transfer fault displacement into thrust faults or folds at their east ends, then determinations of net slip must be interpreted with caution, because faults of this type (transfer faults) have different amounts of displacement along strike as new faults and folds absorb some or all of the displacement.

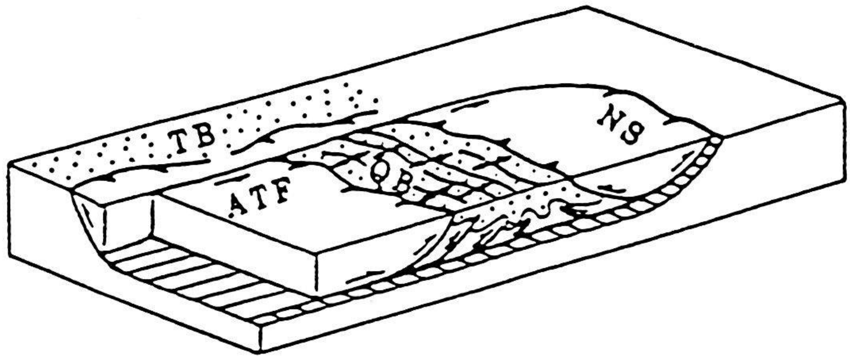


Fig. 6. Schematic diagram illustrating the nature of upper crustal detachment of the structures in the areas of the Qaidam basin (QB), Altyn Tagh fault (ATF), Nan Shan (NS) and Tarim basin (TB) (from Burchfiel et al. 1989). Dotted areas are Cenozoic sedimentary basins deposits and lined area is zone of intracrustal detachment. Diagram shows the relations between transfer fault (ATF) and zones of shortening (QB, NS) as fault loses displacement eastward where shortening structures are present south of the transfer fault but not north of it. It also shows the interpreted relations between parallel thrust and strike-slip faults at depth.

England & Molnar (1990) have suggested that many of the left-slip faults in the eastern part of the Tibetan plateau are not related to extrusion of material at all, but are a consequence of north-south oriented right-slip movement within a broad zone between the plateau and regions farther east. One of the consequences of a zone of north-south oriented right-shear is to produce northwest-trending left-slip faults within the zone. These left-slip faults rotate clockwise within the zone of right-slip, and no material moves eastward beyond the eastern margin of the plateau (Fig. 7). Such an interpretation awaits geological testing.

Finally, an important geological feature neglected when focusing studies on fault slip-rate is that, in some regions, most of the regional strain occurs by folding, an aspect of the deformation emphasized by Argand. Few studies have been directed toward determination of rates of strain in folds. One such study by Zhang et al. (1989; in press) has shown that in the Madong Shan of the Ningxia region nearly all the strain is accomplished by folding (Fig. 5). Thus in order to determine the partitioning of upper crustal strain, rates of deformation must include both faulting and folding. Tapponnier et al. (1990a) have reached a similar conclusion for an active zone of deformation along the north foot of the Qilian Shan.

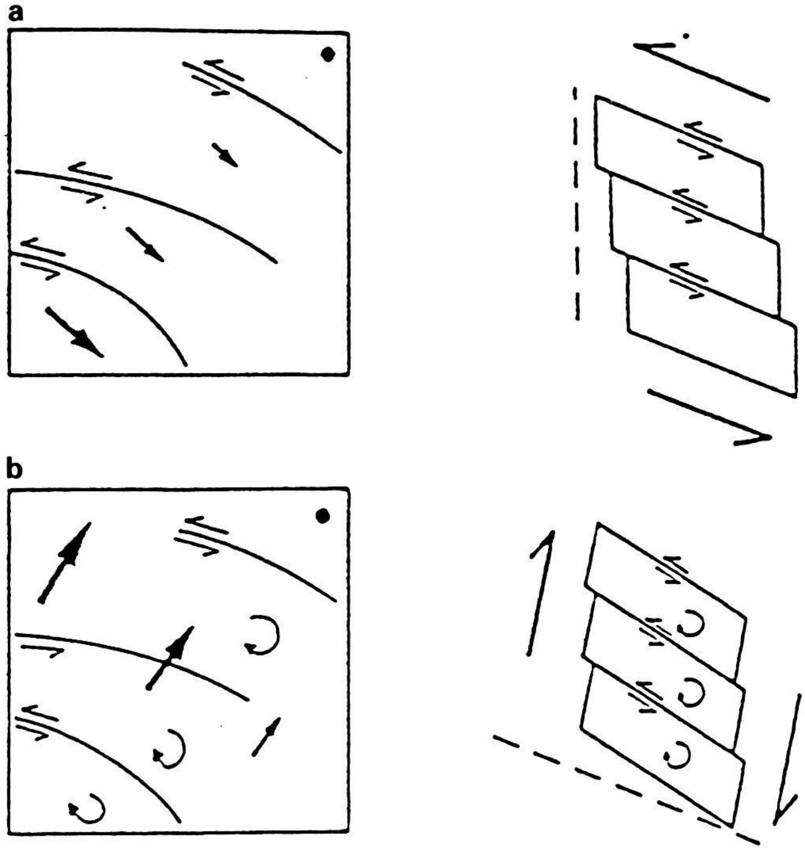


Fig. 7. Sketchs of contrasting interpretations of the faulting in eastern Tibet. For a and b, the left figure shows locations and senses of slip on idealized faults with the inferred velocity field corresponding to the simple interpretation on the right. The velocites are drawn with respect to a fixed point in the upper right-hand corner. In a, as slip occurs, the faults do not rotate with respect to the surrounding material. Left-lateral slip leads to an east-southeastward translation of material on the south side of each fault relative to material on the north side. The sum of slip rates on the faults would give the rate at which material in the south is translated east-southeastward with respect to the material in the north. In b, the eastern boundary of the region defines the fixed reference frame, and the left-lateral slip is a manifestation of north-trending right-lateral shear of the region clockwise rotation of the blocks between the left-lateral faults. Note that for the east-southeasterly strikes of the faults, the continued rotation and slip on these faults leads to a shortening of the east-west dimension and a lengthening of the north-south dimension (from England & Molnar 1990).

2) Field constraints on pre-Pliocene crustal shortening

Few studies have contributed to the understanding the pre-Pliocene evolution of the Tibetan plateau or southeastern Asia. One of the studies made during the joint British/Chinese transect in the eastern part of the Tibetan plateau focused on the magnitude of Cenozoic shortening within the Tibetan plateau. Coward et al. (1988) mapped structures in the Cenozoic basins crossed by the traverse (Fig. 5). The sedimentary rocks in these basins are not well dated, but are mostly Paleogene. They concluded that deformation, mostly pre-Pliocene, in these basins resulted in about 50% shortening, and that the total amount of shortening recorded in these basins was too small to have absorbed all the convergence between India/Eurasia. The difficulty with this data is that the amount of shortening is not well constrained and Cenozoic shortening that did not involve Cenozoic rocks could not be determined. Even among the scientists who participated in the traverse there were differences of opinion as to whether the amount of shortening was or was not sufficient to take up the necessary convergence between India and Eurasia (for example see Dewey et al. 1988, and Coward et al. 1988). Thus studies of the amount and timing of Cenozoic deformation in the Tibetan plateau, conducted in small part of this very large area, have yielded equivocal results. In the same general area Burke & Lucas (1989) presented data to suggest some shortening took place in Pliocene time.

The magnitude of Cenozoic shortening within the Tibetan plateau remains a serious problem. Studies by Coward et al. (1988) along the British/Chinese transect suggested that some Cenozoic shortening occurred in areas where Cenozoic rocks are absent, but the age of that deformation has not been confirmed. Similar observations were made on several occasions during traverses in northern Tibet, where folds and faults that involve Cenozoic rocks appear to continue along strike into areas where Cenozoic rocks were lacking (traverse reported by Molnar et al. 1987). Until the magnitude of Cenozoic shortening can be determined in areas where Cenozoic rocks are not involved, a good estimate of total Cenozoic shortening across the Tibetan plateau will remain unknown.

3) Plate kinematic constraints on crustal shortening and thickening

Several authors have used plate kinematic constraints from marine magnetic anomalies to constrain the magnitude and mode of crustal shortening and thickening within Tibet. Global plate reconstructions show that since the time of the collision at 45 ± 5 Ma, India has moved northward by about 2,000 km at the longitude of western Tibet and by about 3,000 km at the longitude of eastern Tibet (for recent reconstructions see Dewey et al. 1989). Since collision the convergence rate has been roughly constant at about 40 mm/yr at the longitude of western Tibet and about 60 mm/yr at the longitude of eastern Tibet (Fig. 4).

The total convergence between India and Tibet can be conveniently partitioned into shortening and subduction within the Himalaya south of the Indus-Yarlang suture and shortening and convergence in the region north of the suture. Paleomagnetic data collected just north of the Indus-Yarlang suture zone at the longitude of central Tibet (in the Lhasa block) indicate that the suture has moved northward by 2,000 ± 800 km since early Tertiary time (Lin & Watts 1988 and also Achache et al. 1984). This constrains the shortening and subduction of continental lithosphere in the Himalaya to be between 0 and 1,300 km, consistent with estimates from geological field data.

Unfortunately these data are not tight enough to provide useful constraints on the mode of crustal thickening beneath the Tibetan plateau. At one end of the spectrum a number of authors have suggested that the crust of Tibet has been doubled in thickness, without significant crustal shortening, by underplating of Tibet with crust of the Indian plate (eg. Barazangi & Ni 1982). Because the paleomagnetic data do not preclude subduction of 1,300 km of continental crust belonging to the Indian plate, and because the Tibetan plateau is about 1,300 km from north to south, it is possible that a sufficient length of subducted Indian crust was available. On the other end of the spectrum, many authors have suggested that the crust beneath Tibet has been doubled in thickness primarily by shortening and internal deformation of Eurasian crust. This is also permitted by the paleomagnetic data. Thus kinematic data from global plate motions and paleomagnetic data do not permit us to determine of the mode of crustal thickening beneath the Tibetan plateau and we must turn to geological and geophysical field data for answers. From the data presented above it is clear that there is not yet sufficient data to make this interpretation.

4) Plate kinematic constraints on right shear east of the convergent zone

Global plate reconstructions show that northeastern India has moved northward by about 3,000 km with respect to Eurasia since the time of the collision. Regardless of how convergence is accommodated to the north of India this requires a comparable amount of right shear along the active plate boundaries along the eastern side of the Indian plate. Bending of accreted Mesozoic fragments around the eastern syntaxis seems to reflect this (Fig. 2), however because the original configuration of the accreted fragments is unknown, the amount of right shear accommodated by bending remains uncertain.

Post-collisional northward movement of southern Tibet by 1,200–2,800 km with respect to Eurasia (see above) requires a north-south trending zone of right-shear across the eastern part of the Tibetan plateau. If the northward motion of Tibet is accommodated primarily by eastward ejection of continental fragments then this zone of right shear may be very broad, reaching from the western to the eastern limits of the ejected pieces. Alternatively, if eastward ejection of fragments has played a minor role in shortening of the Tibetan crust then the zone of right shear could be relatively narrow and confined to the eastern margin of the plateau. Thus plate-scale kinematic data do not permit us to determine the mode of crustal thickening beneath the Tibetan plateau. Geological constraints on this problem are discussed below in the section on the central and eastern parts of southeast Asia.

5) Pre-Pliocene extension

Studies in the southern part of the Tibetan plateau and northern Himalaya have shown some rather surprising results about the nature of the Miocene structural development, and clearly point out some of the problems in projecting deformation on active tectonic structures back into the Cenozoic. Within the high Himalaya and southern Tibetan plateau there is evidence for large scale north-south extension that preceded the younger east-west extension (Burg & Chen 1984, Burchfiel & Royden 1985, Royden & Burchfiel 1987, and Burchfiel et al. in press a). Extension took place on gently north-dipping normal faults that are parallel and contemporaneous with structurally lower thrust faults in the Himalaya, more specifically the Main Central Thrust (Fig. 5). The normal fault zone juxtaposes rocks of mid crustal levels in the footwall against rocks from more shallow parts of the crust in the hanging wall. Footwall rocks are garnet-sillimanite gneisses that have a 0.5 to 1 km-thick zone of mylonites, developed contemporaneously with normal fault movement, at their top. Hanging wall rocks contain tilted unmetamorphosed Paleozoic and Mesozoic sedimentary rocks and extensional basins of sedimentary rocks of Pliocene to Recent age. Relationships along the normal fault zone are similar to those developed in metamorphic core complexes in regionally extended areas (for example see Davis & Lister 1988; Chen et al. 1989). All these features developed during intracontinental underthrusting of the Indian plate beneath Tibet and indicate that during Miocene time there was complete decoupling between structurally lower levels undergoing shortening and the structurally higher levels undergoing extension.

Burchfiel & Royden (1985) and Royden & Burchfiel (1987) suggested that this normal fault bounds the top of a wedge of mid crustal rocks that was ejected southward in Miocene time. The wedge is bounded below by north-dipping thrust faults. Burchfiel & Royden (1985) further suggested that ejection of this crustal wedge was from an area of high topography to an area of low topography and was driven by gravity. This structural event is preceded by southward directed thrusting because the extensional structures are superposed on earlier south-vergent folds and thrust faults (Burchfiel et al. in press a). The event is post-dated by east-west extension, active from (?) Pliocene to Recent, along north-south striking normal faults. This sequence of events clearly shows that during continued convergence between India and Eurasia structural style changed significantly through time in this part of Himalaya and Tibetan plateau, partially controlling and partially controlled by the evolution of crustal thickness, topography, and thermal structure within the crust. The pitfalls of projecting young or active structures back in geological time are obvious in this example.

Summary

The preceding discussion illuminates several important points about our present understanding of the development of the Tibetan plateau:

1) Studies of slip-rates on active faults yield the present partitioning of deformation on faults, but must be combined with studies on active folds in order to understand how active strain is being accommodated in the upper crust.

2) Studies of active structures yield a snapshot of the present evolution of the region, but many or perhaps most of the active structures may be no older than Pliocene. Thus they can not be projected back in geological time very far with any confidence.

3) The limited understanding of pre-Pliocene structures in the region severely restricts our understanding of the early post-collisional evolution of the region.

4) With present knowledge, existing models for the evolution of the Tibetan plateau can only be incompletely and inadequately tested.

5) Present tectonic models do not incorporate observations of intracrustal decoupling suggesting that the models themselves may be inadequately designed to simulate the tectonics of the region.

6) Plate kinematic, paleomagnetic and geological field data are at present insufficient to constrain the mode of crustal thickening and shortening beneath the Tibetan plateau.

Central and eastern regions

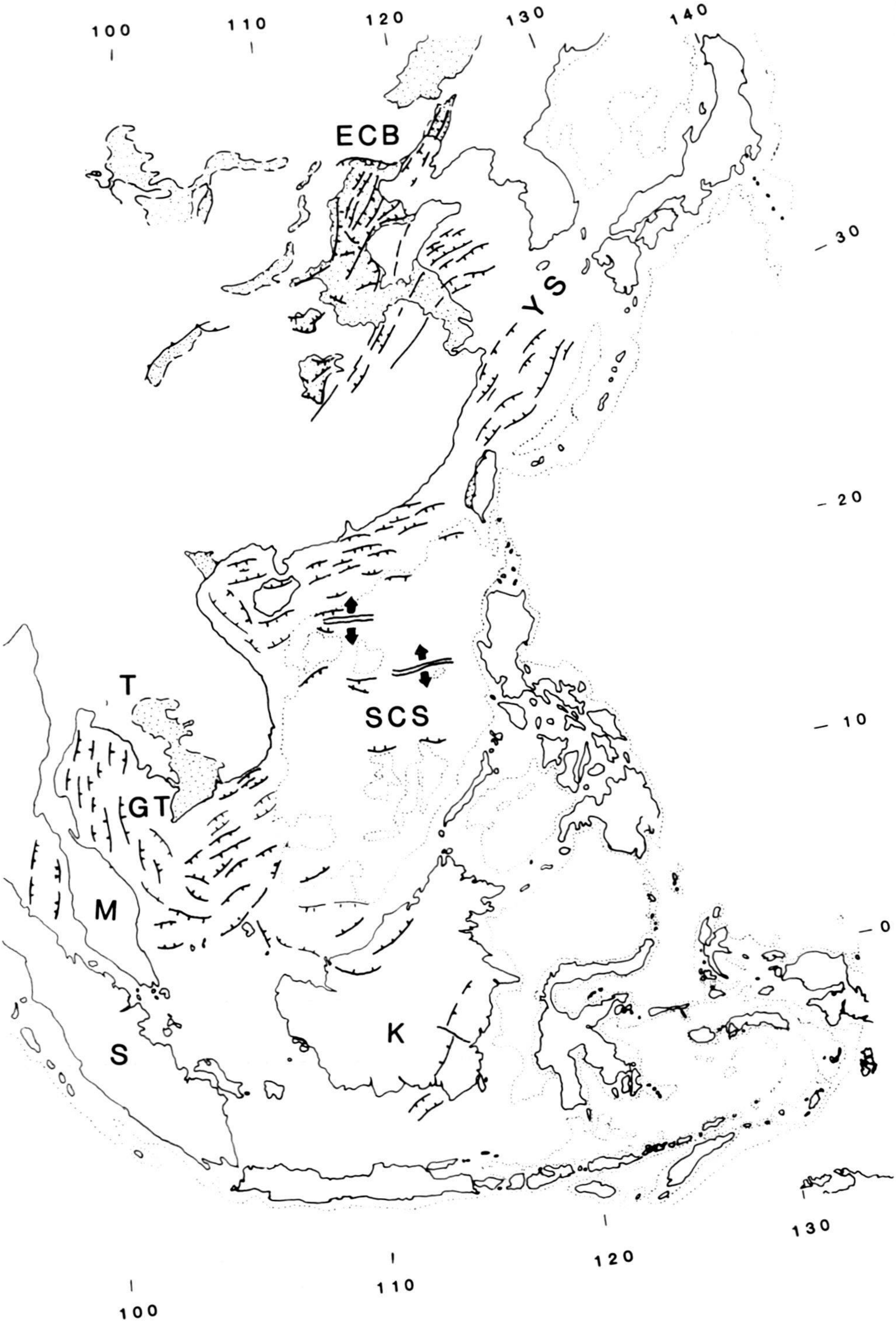
The primary difference between various models for the convergence and collision of India and Eurasia and its importance in driving the tectonics of southeastern Asia is the extent to which crustal fragments have moved east away from the convergence zone in Tibet. In the England & Houseman (1986) model, extrusion is not necessary, but it plays an important role in the model of Tapponnier et al. (1982, 1986) (compare Figs. 3b and 3c). Examination of the tectonic relations between the western (Tibetan plateau) and central parts of southeastern Asia and the eastern parts of southeastern Asia located offshore suggests that crustal fragments have not moved significantly eastward in response to India/Eurasia convergence. Data to support this interpretation are given below.

The geology of the shelf and offshore region show that this entire region was subject to extension during most of Eocene to Miocene time, and locally began much earlier. Figure 8 shows the distribution of Eocene-Oligocene (56–24 Ma) extensional structures along the southeastern margin of the Asian continent. Extension is present along the entire margin, but appears to be variable in magnitude. In areas such as the East China Basins, extension is large, at least 30% (Ye et al. 1987), but it is more difficult to quantify in other regions. Rifting on the northern shelf of the South China Sea is as old as Late Cretaceous/Paleocene (Ru & Pigott 1986) and rifting related to the opening of the South China Sea began in Late Eocene time leading to development of oceanic crust from 32 to 17 Ma (Taylor & Hayes 1983). Rifting began in some of the basins of Sumatra, Java, Malaysia, Thailand and Kalimantan by mid- to late Eocene, but locally may not have begun until the beginning of the Oligocene (Daly et al. 1987).

The first major problem with producing extension in southeastern Asia as the direct result of the India/Eurasia collision is the age of the onset of extension. Several of the extensional areas shown in Figure 8 began to extend before the collision of India and Asia. For example, extension along the northern shelf of the South China Sea began in Late Cretaceous time and continued well into the Cenozoic. Many of the other areas began to extend during or very shortly following the India/Eurasia collision. This requires that the collision instantaneously caused deformation in an area 1,000–2,000 km distant. In the first instance it is impossible that collision caused extension and in the second instance it is highly unlikely.

The second major problem is the regional extent of the extensional deformation. Extension involved a huge region at least 1,000 km wide and stretching from northeastern China to Malaysia. Although extension is inhomogeneously distributed within this zone, almost the entire region has been subject to some extension and large areas have been greatly extended. The extrusion model of Tapponnier et al. (1982, 1986) can produce extension in the South China Sea and the Gulf of Thailand, but requires extension to be localized within these regions. The model requires these extended regions to be separated by extruded blocks that are either undeformed or subject to compressional deformation. This is incompatible with the regional nature of the observed extension and subsidence on the continental shelf of southeast Asia. This model also cannot explain the coeval extension within northeastern China.

A basic element of the Tapponnier et al. (1982, 1986) extrusion model is the presence of left-slip faults of large magnitude (~ 1,000 km displacement) in southeastern China, such as the Red River Fault Zone, and others in southwestern Thailand (Fig. 5). A definitive test of the extrusion model awaits the documentation of the age, sense and magnitude of displacement on these faults.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Late Cenozoic evolution of southeast Asia: a preliminary view

From examination of data for the late Cenozoic history of southeastern Asia, we suggest a preliminary tectonic framework for Pliocene to Recent deformation. Our interpretation is summarized below with brief reference to supporting data (see also earlier sections of this paper).

North-south shortening

The most obvious results of Pliocene to Recent convergence between India and Eurasia are the spectacular zones of north-south shortening in the thrust belts of the Himalaya, the Pamirs, the Tien Shan and the Qilian Shan (Fig. 9). North-south shortening of Pliocene-Recent age also occurs in the broad region of folding and thrusting in the Qaidam Basin. The most northern expression of the shortening, with associated right-slip, is in the Altai ranges in Mongolia and southern USSR. These areas of young and active shortening are inhomogeneously distributed but shortening appears to be transferred from one area to another. For example, shortening north of the Tarim basin in the Tien Shan appears to be greatest in the west and dies out toward the east. Shortening along the southern margin of the Tarim basin appears to be smaller in the west and increases greatly towards the east into the Qaidam basin and Qilian Shan. This suggests that the total north-south shortening across these two belts is roughly the same at any longitude despite the fact that the structures that take up this shortening are not continuous.

Although shortening in the Himalayas and the Pamir has been active since Early Cenozoic time, evidence from the stratigraphic record indicates that deformation only began (or at least accelerated) in the northern and northeastern parts of the plateau and in regions farther north in Pliocene time (Fig. 9). (Data from the southern Ningxia region [Zhang et al. 1990; Zhang et al. in press, and Burchfiel in press b], the Qaidam basin [Bally et al. 1986; our own studies in progress], the Qilian Shan [Tapponnier et al. 1990a; our own studies in progress], the Longmen Shan [Yu 1977; Zhao 1985, and Chen & Chen 1987] and probably the Tien Shan [Windley et al. 1990]).

Strike-slip (transfer) faults within the plateau

Strike-slip faults with rapid rates of displacement are currently active within the plateau and along its northern boundary and many of these appear to have been active

Fig. 8. Eocene – Oligocene deformation of the eastern region southeast Asia. Deformation in the offshore and East China basins began before, during and following collision of India and Eurasia in different areas. The entire margin underwent extension during collision and early post-collisional convergence which makes it unlikely that crustal fragments were extruded into this region from the west. Extension in the eastern region may be related to interaction of the southeast Asian shelf and oceanic plates to the east. Crustal fragments may have moved eastward in the central region. This region can be regarded as transitional between a western region dominated by intracontinental convergence and an eastern region dominated by extension caused by plate interactions with oceanic plates farther east. Lines with ticks are normal faults, and double lines with arrows indicates the spreading center in the South China Sea active between 32 to 17 Ma. ECB = East China basins; GT = Gulf of Thailand; K = Kalimantan; M = Malaysia; S = Sumatra; SCS = South China Sea; T = Thailand; and YS = Yellow Sea.

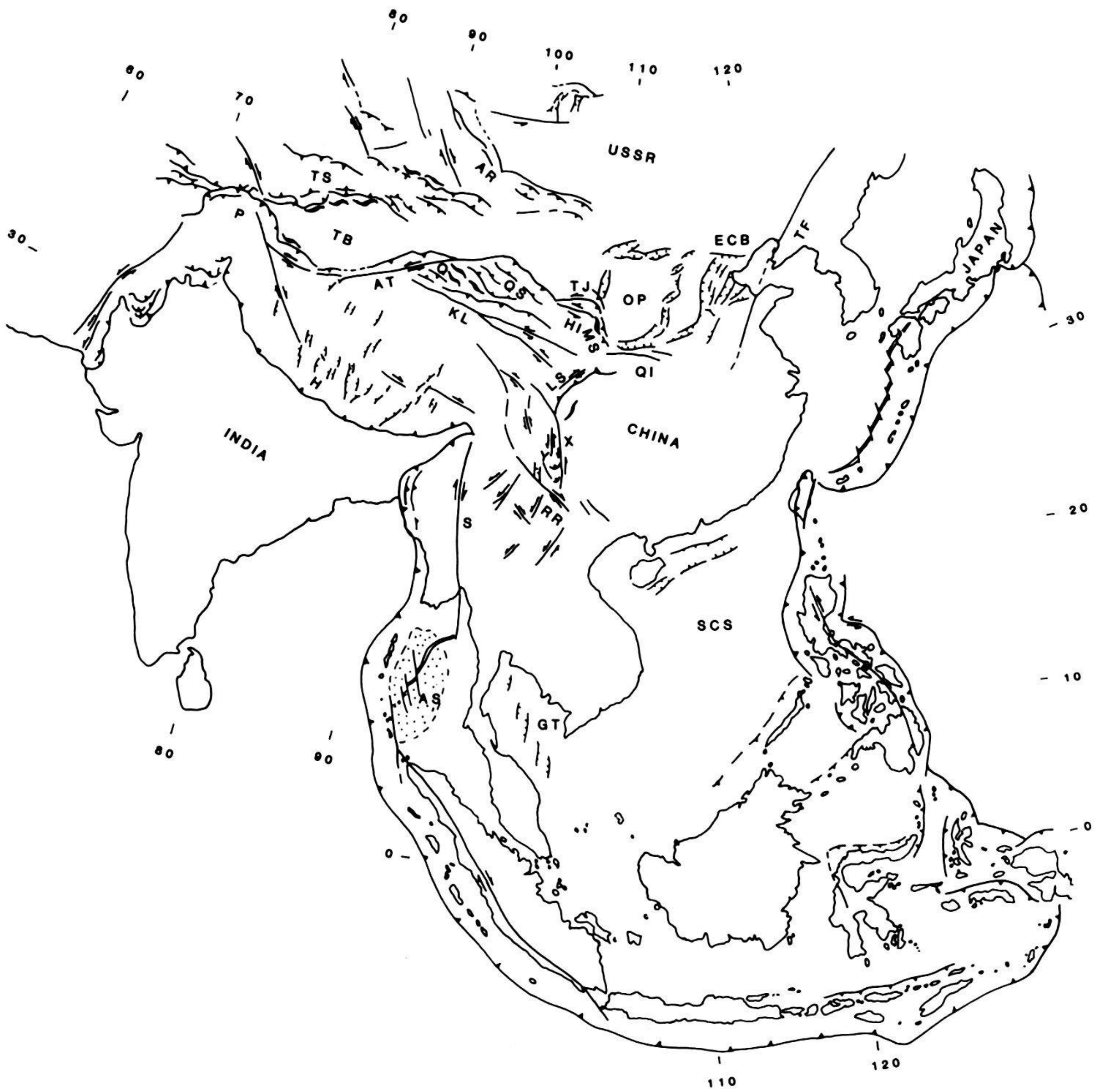

Fig. 9. Generalized map of the Pliocene to Recent tectonic framework of southeastern Asia. Comparison of Figs. 9 and 1 emphasizes the relations between the Pliocene to Recent tectonism with the topography of southeast Asia. AR = Altai Range, AS = Andaman Sea; AT = Altyn Tagh fault; ECB = East China basins; 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; QI = Qinling Mountains; QS = Qilian Shan; RR = Red River fault zone; S = Sagaing fault zone; SCS = South China Sea; TB = Tarim basin; TF = Tan Lu fault zone; TJ = Tianjin Shan; TS = Tien Shan; X = Xianshuihe fault; Y = western Yunnan.

only during Quaternary and perhaps Pliocene time. The pattern of deformation along most of these faults suggests that they are transfer faults and that the strike slip deformation is transferred into shortening along thrust faults and folds at the ends of the faults (see for example Fig. 6). For example the left-slip on faults in the Ningxia region is absorbed in folds and thrust faults at the margin of the plateau. Other examples include the left-slip Kun Lun fault, which does not appear to offset young folds and faults in the Longmen Shan, and so must lose displacement at its eastern end (Fig. 9).

Similar relations probably occur along the left-slip Xianshuihe fault in southeastern China. This fault can be traced south where it branches into several smaller strike-slip faults that appear to end in regions of shortening or extension before reaching the Red River fault.

The total displacements on these faults are mostly unknown but, except for the Altyn Tagh fault, are probably no more than a few tens of kilometers, certainly less than 100 km (see examples of Haiyuan and Tianjian Shan faults above). The Altyn Tagh fault also appears to be a transfer fault but loses displacement to thrust faults and folds along its entire eastern half where it merges with shortening structures in the Qaidam basin and Qilian Shan. If the Altyn Tagh fault is a transfer fault (see BURCHFIEL et al. 1989) and if structures in the Qaidam basin and Qilian Shan are of Pliocene to Recent age, then the Altyn Tagh fault must also be of Pliocene to Recent age. This allows one to estimate an upper bound on its total displacement of about 180 km from its current slip-rate of 20–30 mm/yr (PELTZER 1987) and a maximum age of 6 million years.

Decoupling of upper and lower crust

Several lines of argument indicate that deformation of the upper crust is decoupled from that of the lower crust. First, strike-slip faults that merge with or lose displacement to decollement style thrust faults and folds must be confined to the same upper crustal level as the thrust faults with which they merge. This implies, for example, that where the Altyn Tagh fault loses displacement to the thrust faults and folds of the Qaidam basin it must be detached at the same structural level as the thrust faults and folds (Fig. 6). Because the geometry of these folds and thrust faults strongly suggest that they formed above a subhorizontal decollement at intra-crustal depths, the Altyn Tagh fault must also be confined to upper to mid-crustal depths. Second, strike-slip faults that crop out within the upper plate of parallel and contemporaneous thrust faults must be restricted entirely to the upper plate and not cut the thrust fault at depth. If not, continued movement on the thrust fault would be impossible. For example the Altyn Tagh fault must be detached above the south-dipping thrust faults that crop out along the margins of the Tarim basin (Fig. 6). Similar relations suggest that much of the surface structures near the margins of the plateau are similarly detached within the crust. Third, Miocene north-south extensional structures along the north slope of the Himalaya suggest that extension of the upper crust can occur parallel to and contemporaneous with shortening and convergence at depth (BURCHFIEL & ROYDEN 1985; ROYDEN & BURCHFIEL 1987). Although this structure is pre-Pliocene, it is important in that it indicates that major zones of decoupling can occur within the crust, at least around the margins of the plateau.

Crustal blocks

Left-slip displacements along most of the major strike-slip faults within the plateau produce eastward movements of crustal fragments as suggested by TAPPONNIER et al. (1982, 1986). However with one possible exception these strike-slip faults do not extend east of the Tibetan Plateau. This indicates that eastward movement of crustal fragments must be absorbed by shortening within or along the eastern and northeastern margin of the Tibetan plateau in the Longmen Shan, Ningxia, and Qilian Shan regions. Pliocene to Recent eastward overthrusting has been documented in all of these areas (for example YU 1977; ZHAO 1985; CHEN & CHEN 1987; ZHANG et al. 1989; TAPPONNIER et al. 1990a). Thus it appears that the pattern of active deformation along much of the eastern margin of the plateau is eastward thrusting, also associated with right-slip along north-south trending fault zones (see below). This pattern is not unlike that predicted by the model of ENGLAND & HOUSEMAN (1986, 1988).

In the Yunnan region of southwestern China left-slip and right-slip faults probably bound small crustal fragments that move toward the southeast relative to eastern China, but in our interpretation their motions are mostly absorbed within the southern and eastern parts of the fragments (WANG, work in progress).

Growth of the Tibetan Plateau

During Pliocene-Quaternary time the Tibetan Plateau appears to have grown northward by incorporating rocks of the Qaidam basin and Qilian Shan (Fig. 9). In Miocene time these rocks lay to the north of the pre-Pliocene Tibetan plateau in a region of low topography that was probably the eastward continuation of the Tarim basin. They have since been involved in north-south shortening and thickening and now form a topographically high region along the northern boundary of the plateau. This process is spatially irregular, and may be temporally irregular as well. We infer that throughout its history the Tibetan plateau has grown northward in a similar fashion, incorporating sedimentary and basement rocks along its northern margin.

Right shear along the eastern margin of the plateau

The total convergence rate between India and Siberia at the longitude of eastern Tibet is 60 mm/yr; approximately 10–15 mm/yr is taken up in shortening across the Himalaya (LYON-CAEN & MOLNAR 1985) and most of the remainder is taken up in the Qaidam basin and farther north. This indicates that the Tibetan plateau south of the Qaidam basin is moving north-northeast relative to southern China, probably at a rate of several tens of millimeters per year. This implies that the eastern margin of the plateau is a broad zone of right shear (see also DEWEY et al. 1988) with a component of east-west shortening across it. This right shear is expressed by north-northeast trending right-slip faults such as in the Longmen Shan, by left-slip faulting and clockwise rotation of crustal material (Fig. 7b; ENGLAND & MOLNAR 1990) and perhaps by folding of some faults (eg. the Xianshuihe fault). The Xianshuihe fault that bounds the southeastern margin of the plateau is left slip rather than right slip. In our interpretation the broad zone of right shear must pass west of the Xianshuihe fault and crustal fragments between the two are undergoing rapid clockwise rotation.

It is puzzling that on geological maps east-west structures are shown to continue from the Qinling Mountains into the Tibetan Plateau between the Longmen Shan and the Ningxia region. It is particularly puzzling since the eastern topographic margin of the plateau trends north-south across these east-west structures, as does the most prominent belt of earthquakes in China (Mao 1982). Such north-south trending features suggest that despite the presence of east-west structures in this area there has not been significant movement of crustal fragments beyond the eastern margin of the Tibetan plateau in Pliocene time. Thus during late Cenozoic time the India/Eurasian collision appears to have caused little if any deformation east of the Tibetan plateau, but it is not clear if the same conclusion can be made for earlier Cenozoic time.

Right shear south and east of the Tibetan Plateau

The northward motion of India with respect to Eurasia places western Indochina within a broad zone of right lateral shear (eg. see Hamilton 1979; Curray et al. 1979). Active faults south of the Red River fault zone form a general conjugate shear pattern that indicates north-south shortening and east-west extension (Fig. 9). This area is bounded by the right-slip Sagaing fault zone which currently accommodates much of the northward movement of the Indian plate with respect to the complexly deforming region in western Indochina. This fault zone is part of an en echelon fault system along which the Andaman Sea opened. It is probably of the same age as the Andaman Sea, or no older than about 11 Ma (Curray et al. 1979). Late Neogene clockwise rotation of crustal fragments in central and western Thailand occurred within the broad zone of right-shear and may be responsible for opening of several young basins associated with volcanism in Thailand (see McCabe et al. 1988).

Asian continental margin

In our opinion, the tectonic development of the eastern region on the Asian continental shelf and oceanic areas to the east is controlled primarily by subduction of oceanic lithosphere along the eastern and southeastern margin of the Eurasian plate. Tectonic events within this region do not appear to have been directly affected by convergence of India and Eurasia in the Himalayan-Tibetan region.

Eastern China, northeast of the Tibetan plateau, has undergone extension within the East China Basins and on three sides of the Ordos plateau. This area lies within the region of transition between structures related to intra-continental convergence in the west and structures related to interactions between the Asian plate and oceanic plates to the east. East-striking active faults in the Qinling mountains appear to bound the region of extension on the south (Fig. 9) and may function as transfer faults, but the cause of the extension and its relationship to events within the plateau remain uncertain.

Pre-Pliocene evolution of southeast Asia: a major question

The tectonic interpretation presented above is only valid for about the last 6 million years. Little data are available to address the pre-Pliocene evolution of the region and, except for the few studies mentioned earlier, little of the pre-Pliocene Cenozoic history of the plateau is known in detail.

Tibetan Plateau

Our interpretation for Pliocene to Recent time suggests that most of the crustal thickening beneath the Tibetan plateau was the result of pre-Pliocene deformation. With the exception of the Qaidam basin and Qilian Shan, the most intense deformation has now shifted north of the Tibetan plateau to the Tien Shan and Altai ranges and the present pattern of faults and folds does not contribute to the crustal thickening beneath the plateau except around its margins. Pre-Pliocene growth of the Tibetan plateau probably occurred by processes similar to those currently active in the Qaidam basin and Qilian Shan as material north of the plateau was progressively, but perhaps irregularly, incorporated into it.

The Tibetan plateau may have had a complex Cenozoic evolution with temporal changes in deformational style as the result of progressive deformation. The structural evolution of southern Tibet and the high Himalaya serves as an example. Here the post collision sequence of events is characterized from oldest to youngest by 1) south-vergent thrusting and folding in southern Tibet south of the Indus-Yarlang suture and in the high Himalayan crystalline zones, 2) north-south extensional faulting in sedimentary rocks of the Tibetan zone contemporaneous with shortening in structurally deeper levels, and 3) east-west extension at shallow crustal levels with continued north-south shortening at deeper crustal levels (Burchfiel et al. in press a). This sequence of superposed deformational events can be interpreted as a progressive shortening and thickening of the crust accompanied by consequent changes in thermal structure and gravitational potential energy. Other changes in deformational style have occurred, such as the change from folding to strike-slip faulting documented by the joint Chinese-British expedition, but it is still too early to generalize these results to the entire Tibetan plateau.

Southeast Asia

The geological evolution of the offshore regions of southeastern Asia are reasonably well known through extensive marine surveys and are presented in more detail in an earlier section. Throughout Cenozoic time the region is dominated by extension with variable magnitudes and local formation of oceanic crust. Shortening structures related to subduction are only locally developed.

Relations between western, central and eastern regions of southeast Asia

The tectonic relations between the three regions of southeast Asia, the Tibetan plateau, continental Asia east of the plateau, and the offshore region east of southeast Asia, remains a major unresolved tectonic problem. Formation of the Tibetan plateau and regions at least as north as far as the Altai mountains appears to be directly related to the India/Eurasia collision and post-collision convergence. As discussed earlier in this paper, timing relations and the regional distribution of the extensional structures within the eastern region of southeast Asia make it difficult to drive the extension from the convergent zone in Tibet. In our opinion the geology of the offshore region east of Asia has been dominated by processes that are not directly related to this convergence zone.

However, it seems possible, perhaps even likely, that much of the early Cenozoic extension in the eastern region of southeast Asia is indirectly related to the collision of India and Eurasia. Plate tectonic reconstructions from marine magnetic anomalies show that the relative plate velocity between India and Eurasia at the longitude of the central Himalaya slowed from about 100 mm/yr prior to collision to about 50 mm/yr after the collision. It is tempting to view this change in velocity as the result of a transition from subduction of dense oceanic lithosphere of the Tethys ocean to subduction of more buoyant continental lithosphere of the Indian subcontinent. Such a change in relative motion between two plates must also cause changes in the relative motions of at least some other plates. A dramatic change in the direction of Pacific plate motion occurred at approximately the same time as the collision (see for example, STOCK & MOLNAR 1988) and motion across the Pacific/Eurasia plate boundary changed from northwest-southeast convergence to oblique convergence with a large component of right shear (ENGEBRETSON et al. 1987). This is also the time at which the extension becomes widespread within the eastern region of southeast Asia. Thus we suggest that extension within the eastern region of southeast Asia is related to plate interactions between the Eurasian plate and oceanic plates to the east, which are in turn related to changes in the relative velocity of India and Eurasia at the time of collision.

The central region between Tibet and the extensional areas of the eastern regions is a transitional zone whose tectonic evolution is not well known. It may be affected by the tectonics of the adjacent regions on both sides. On its west side, along the eastern margin of the plateau, the central region is bounded by a complex zone of right-shear that probably shifted position and structural style during the Cenozoic. On its east side it was bounded by a region of early Cenozoic extension that developed within a broad region of right-shear between the Eurasian and Pacific plates.

The study by TAPPONNIER et al. (1990b) is really the only work to address the complex problem of pre-Pliocene evolution in this transitional central region. They determined Miocene cooling ages in high grade metamorphic rocks in the Ailao Shan along the Red River fault zone where syn-metamorphic deformational fabrics suggest left lateral shear. TAPPONNIER et al. (1990b) interpret these fabrics as supporting the idea that in early Cenozoic time crustal fragments of Indochina were extruded southeastward for great distances away from the India/Eurasia convergent zone. In our opinion the significance of these fabrics remains unclear and the magnitude of early left-slip on the presently right-slip Red River fault zone remains uncertain. With the exception of this study little data is available to test the models for the tectonics of this central region during pre-Pliocene time.

More than fifty years ago Argand clearly recognized the significant tectonic position of this central region of southeast Asia when he stated: "L'Asie orientale est l'ensemble des objects tectoniques dans lesquels le grand jeu des chaines circumpacifiques, generalement paralleles aux rivages, se complique des contrecoups lateraux, des jeux de flanc que le puissant serrage frontal de l'Inde et de la Terre de l'Angara, masse dans le segment de l'Asie centrale, declenchait plus a l'est (ARGAND 1924, p. 284).

Asian tectonics 50 years after the death of Argand: how far have we advanced?

Many of the concepts put forth by Argand in his 1924 work on the tectonics of Asia remain valid today, including the five listed in the beginning of this paper. However it is not yet possible to evaluate Argand's idea that the great thickness of crust beneath Tibet results partly from the underplating of Tibet by Indian crust, and partly by shortening of Tibetan crust. Another significant idea put forth by Argand, and which also remains unresolved today, is the partitioning of deformation within Asia into segments separated by north-south boundaries and with little movement of crustal fragments occurring across these boundaries. It is primarily on this crucial point that the extrusion models of Tapponnier et al. (1982, 1986) differ from the deformation models described by England & Houseman (1986, 1988) and Dewey et al. (1988), and from our own ideas presented in this paper for Pliocene to Recent time. While ideas put forth by this last group of authors differ from one another in some important respects, all of these authors implicitly or explicitly partition the deformation within southeastern Asia into north-south corridors similar to those put forth by Argand (see Fig. 3c).

How far have we advanced from Argand? The answer appears to be not as far as might be thought. Even though plate tectonics and technological advancement have permitted more quantitative analyses of geological processes, relating intracontinental deformation to plate kinematics remains one of the major unresolved problems in the earth sciences. Argand had little data on the geological evolution of the region, so it is probably safe to assume that his interpretations were based largely on topography and present geological configurations that are largely the result of Pliocene to Recent deformation. It is sobering that even with much greater access to geological data than was possible for Argand, our overall interpretations have not changed very much – at least for Pliocene to Recent time. It remains to be seen whether his interpretations are valid also for earlier Cenozoic time.

Presently, the models that have been developed to explain the tectonics of Asia have far outstripped the data available to test or modify them. Asia is an immense area that remains to be fully explored, but it is an area that ultimately holds great scientific rewards for the understanding of intracontinental deformation. Hopefully by the 100th anniversary of Argands death we will have made more progress that we have to date. Argand's closing statements include the following: "Que dirai-je? Nous avons interrogé toute l'Asie: elle n'a pas été trop avare de ses dons; elle nous a parlé d'autres terres, et il en est peu qu'elle ne nous ait aidés à mieux voir" (Argand 1924, p. 329). Perhaps Argand was a bit premature in this statement, or perhaps he had a clearer vision of the tectonics of Asia than we do today.

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