Eclogae geol. Helv. 82/3: 717–734 (1989)

0012-9402/89/030717-18 $ 1.50 + 0.20/0
Birkhäuser Verlag, Basel

Tectonic evolution of the India/Eurasia Collision Zone

By John F. Dewey[1]), Stephen Cande[2]) and Walter C. Pitman III[2])

ABSTRACT

Since the collision of India with Eurasia at about 45 Ma in the mid-Eocene, roughly north-south intracontinental convergence has occurred at about 5 cma^{-1}. This convergence has been accommodated principally by lithospheric thickening in a widening zone between a western transpressive sinistral megashear from the Makran to Baikal and an eastern dextral megashear from Sumatra to the Tanlu Fault System. Several lines of evidence indicate that underthrusting of the Indian Shield beneath Tibet cannot account for more than a trivial portion of the convergence and numerous data sets show that lateral extrusion or escape was not a major factor in accommodating the India/Eurasia convergence. Balancing shows that there has been a maximum eastwards extrusion of the convergent zone of about 250 km, and that up to 1,000 km of shortening has occurred in the Himalayas.

ZUSAMMENFASSUNG

Seit der Kollision Indiens mit Eurasien vor ca. 45 Millionen Jahren im mittleren Eozän, fand intrakontinentale Konvergenz in genereller Nord-Süd Richtung mit einer Rate von ungefähr 5 cma^{-1} statt. Diese Konvergenz wurde weitgehend durch Verdickung der Lithosphäre in einer sich ausweitenden Konvergenzzone ausgeglichen. Diese Zone wird begrenzt durch eine westliche transpressiv-sinistrale Scherzone, die vom Makran zum Baikal-See reicht und einer östlichen dextralen Megascherzone, die sich von Sumatra bis zum Tanlu Störungssystem erstreckt. Verschiedene Daten belegen, dass Unterschiebung des indischen Schildes unter Tibet nur einen vernachlässigbaren Teil der Konvergenz kompensiert. Eine Vielzahl von geologischen Beobachtungen weist zusätzlich darauf hin, dass laterale Extrusion keine bedeutende Rolle beim Ausgleich der Konvergenz zwischen Indien und Eurasien gespielt hat. Eine Massenbilanz ergibt, dass das Maximum der nach Osten gerichteten Extrusion der Konvergenzzone ca. 250 km beträgt, während bis zu 1000 km Krustenverkürzung im Himalaya selbst stattgefunden hat.

1. Introduction

Perhaps the most spectacular large-scale result of plate tectonics is the broad complicated zone of intracontinental convergence between Eurasia and peninsular India following their collision at about 45 Ma (Dewey et al. 1988). The basic features of the convergent zone in relation to the tectonics of Asia as a whole are shown in Fig. 1 and a simplified interpretive map of the convergent zone is shown in Fig. 2. In essence, the zone consists of the following major parts: a southwestern prong of sinistral transpression from the Makran to the Tienshan, a zone of en-echelon sinistral faulting from the Tienshan to Baikal, a southeastern prong of dextral shear from Sumatra to the Tanlu Fault and a zone of irregular crustal thickening from the Himalayas to the Altay from which a modest amount of eastward extrusion has occurred.

[1]) Dept. of Earth Sciences, University of Oxford, Parks Road, Oxford, OX1 3PR, England.
[2]) Lamont/Doherty Geological Observatory, Palisades, NY 10964, USA.

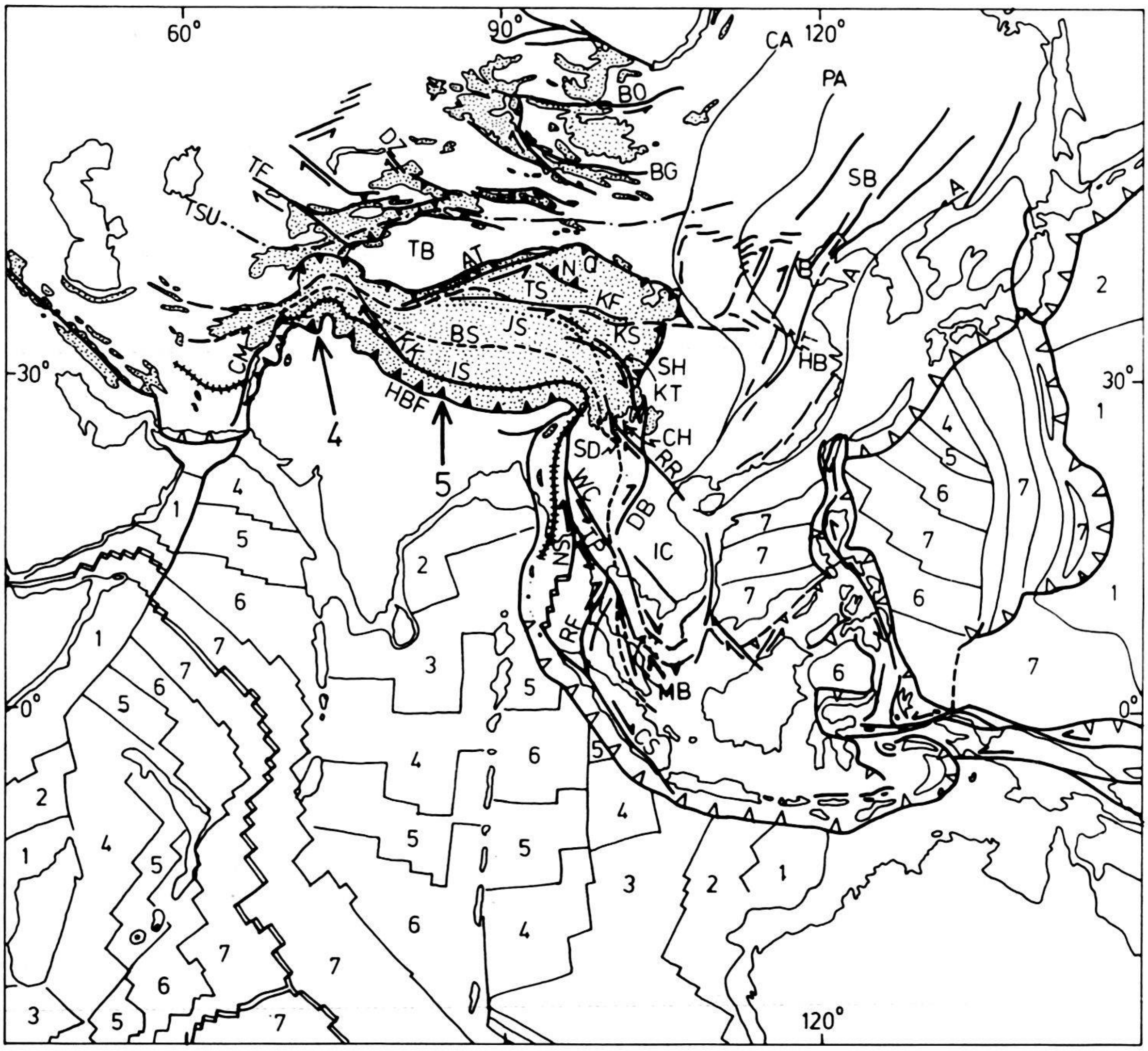

Fig. 1. Simplified tectonic map of Asia and its surrounding oceans. Dotted area – area above 2 km: Ocean floor numbered as follows; 1 – Jurassic, 2 – Lower Cretaceous, 3 – Middle Cretaceous, 4 – Upper Cretaceous, 5 – Palaeocene, 6 – Eocene, 7 – post Eocene. A – eastern edge of Mesozoic/Palaeogene arc, AT – Altun Shan Fault, BG – Bogdo Fault, BO – Bolnai Fault, BS – Banggong Suture, CA – western edge of Cretaceous arc, CH – Chuziong Basin, CM – Chaman Fault, CS – Central Sumatra Fault, DB – Dien Bien Phu Fault, DZ – Dzungharian Fault, HB – Huebai Basin, HBF – Himalayan Boundary Fault, IC – Indo-China Blocks, IS – Indus Suture, JS – Jinsha Suture, KF – Kunlun Suture, KT – Kang Ting Fault, MB – Malay Basin, N – Nan Shan, PA – western edge of Palaeogene arc. Q – Qilian, Shan RF – Ranong Fault, RR – Red River Fault, SB – Songliao Basin, SD – Shandu/Simao Basin, SH – Szechuan Basin, SN – Shan Fault, T – Tanlu Fault, TB – Tarim Basin, TF – Talasso-Fergana Fault, TP – Three Pagodas Fault, TS – Tsaidam Basin, TSU – Tienshan Suture, WC – Wang Chao Fault.

Continents occupy a special role in plate tectonics in that plate boundary systems within them are wide complicated zones of diffuse deformation unlike the generally narrow clearly-defined plate boundaries of oceanic regions although the equatorial Central Indian Basin and northern Wharton Basin show distributed deformation over a very wide area (Neprochnov et al. 1988; Weissel et al. 1980; Wiens 1986; Wiens et al. 1986). This difference results from quartz dominating the strength profile of the continental crust and reducing the integrated shear strength of the continental lithos-

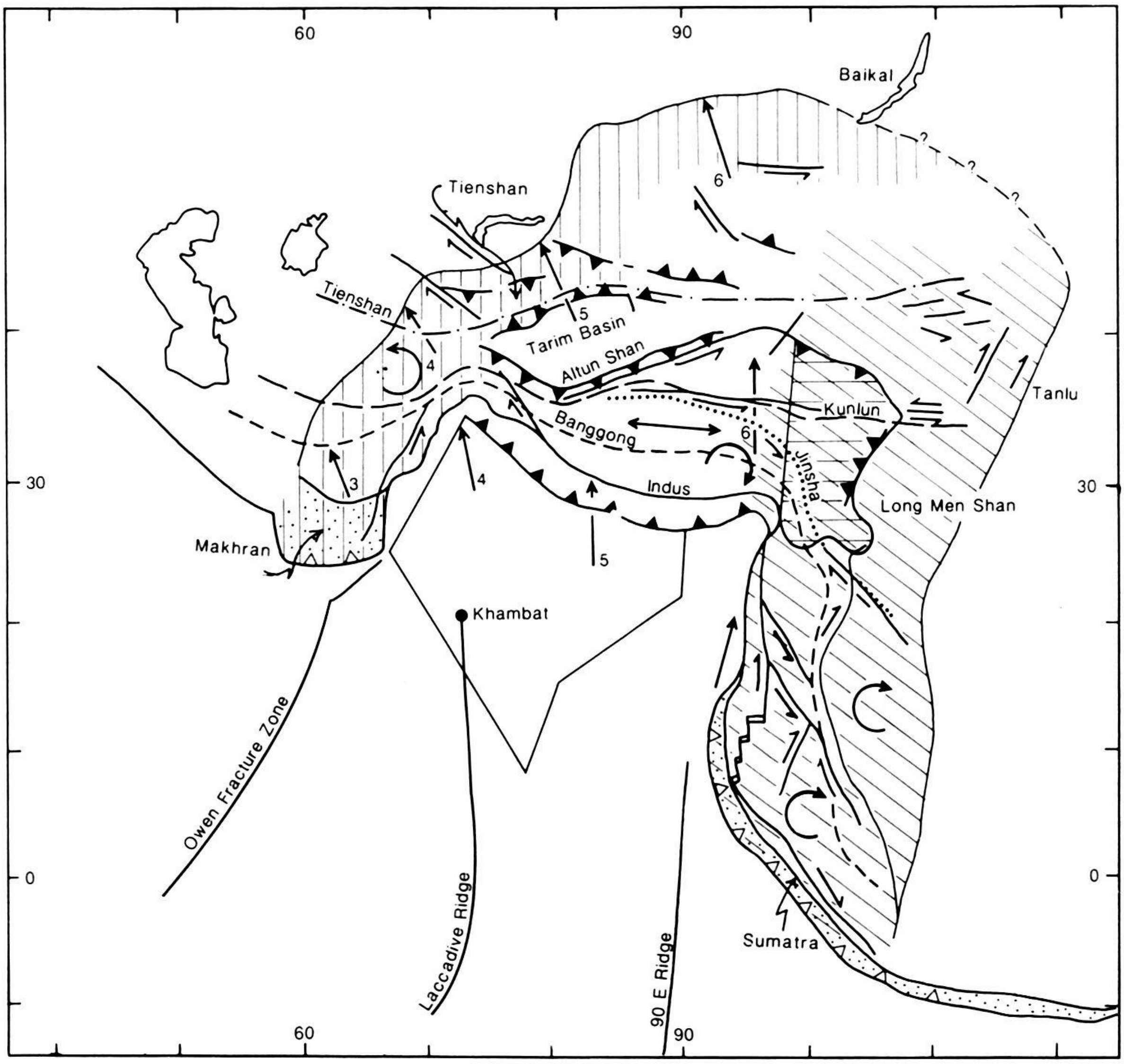

Fig. 2. Tectonic zones of the India-Eurasia convergent plate boundary complex. Numbered arrows refer to present motion of India with respect to Eurasia in cma^{-1} based upon the data of Table 1. Dots – post 45 Ma subduction accretion, verticals lines – zones of sinistral transpression, oblique lines – zone of dextral shear, horizontal lines – maximum area of Tibetan high ground extruded by Indian indenter.

phere especially in regions of thick crust and/or high heatflow. In contrast, the strength of the oceanic lithosphere is dominated by olivine. However, continents resist deformation where the lithosphere is very thick as in the Precambrian shield regions, and the young oceanic lithosphere suffers diffuse compressional deformation near ridge axes.

Particularly important and unresolved problems of continental deformation are the extent to which the deformation of upper crustal and perhaps upper mantle brittle layers is concentrated in dislocation zones between large "rigid" flakes that suffer brittle internal strain and the extent to which deformation of these brittle layers is a passive response to a viscous continuum strain of the ductile lithosphere in the lower crust and mantle. Large earthquakes on major faults with substantial cumulative offsets indicate clearly that a substantial portion of slip in continental plate boundary zones is taken up in this way, but we do not know how much strain occurs on smaller structures between major faults. Also it is not clear whether stresses can be transmitted through and drive the deformation of lithospheric brittle layers or whether displacements, strain and rotations of fragments of brittle layers are a passive response to a gross viscous deformation of the continental lithosphere.

We have recomputed the motion of India relative to Eurasia during the last 84 Ma and show that, since collision at about 45 Ma, India has moved northwards relative to Eurasia by about 1,815 km in the west, and 2,750 km in the east. Three basic models have been proposed to accommodate the post-collisional northwards motion of India: crustal shortening and thickening (DEWEY & BURKE 1973; ENGLAND & MCKENZIE 1982), underthrusting of India beneath Eurasia (ARGAND 1924; BARAZANGI & NI 1982; POWELL & CONAGHAN 1975; ZHAO & MORGAN 1987), and eastward lateral extrusion (MOLNAR & TAPPONNIER 1975, 1977; TAPPONNIER et al. 1986). Our conclusion is that underthrusting is trivial, lateral extrusion is small and that the bulk of India/Eurasia convergence has been accommodated by the viscous, roughly north-south, shortening of the Asian lithosphere within which hard zones resist deformation and upon which the brittle upper crust breaks into flakes of various sizes, which slip with respect to one another and rotate around vertical axes.

In this paper, we examine the way in which the India/Eurasia convergence is partitioned into strain and displacement in Eurasia both instantaneously and by finite area and volume balancing. We show that there is a natural temporal and geometric deformation sequence resulting from the indentation of the more resistant thicker Indian lithosphere into the thinner less-resistant Eurasian lithosphere involving roughly north-south shortening by vertical plane strain in a thrust regime followed by horizontal plane strain and minor lateral extrusion in a wrench regime followed, in turn, by extensional collapse in a vertical plane strain gravity regime. The model presented for the intracontinental accommodation of the India/Eurasia convergence is consistent with data known to us but is strictly a kinematic model based upon the principles of balancing and compatibility.

2. India/Eurasia relative motion

We have recomputed the motion of India relative to Eurasia for the last 84 Ma, using the plate circuits Eurasia-North America, North America-Africa, Africa-India, Africa-Antarctica and Antarctica-India. Plate circuits are redefined *ab initio* and do not incorporate previously published models. The details of our methodology and reconstructions will be published elsewhere and are part of an ongoing analysis of Mesozoic/Cenozoic relative plate motions across the Tethyan realm from Gibraltar to Indonesia. The plate motions are based upon a re-examination of magnetic anomalies and fracture zones in the Atlantic and Indian Oceans using magnetic, bathymetric and Seasat data. Table 1 summarises the rotation poles and angles that we have used to draw the sequential positions of India in the Eurasian reference frame shown in Fig. 3. The reconstruction poles and angles of Table 1 are those used to rotate India from various anomalies times to its present position in the Eurasian references and have no kinematic significance for actual relative plate motion. The stage poles and angles of Table 1, are those that are used to move India in the Eurasian reference for time inter-

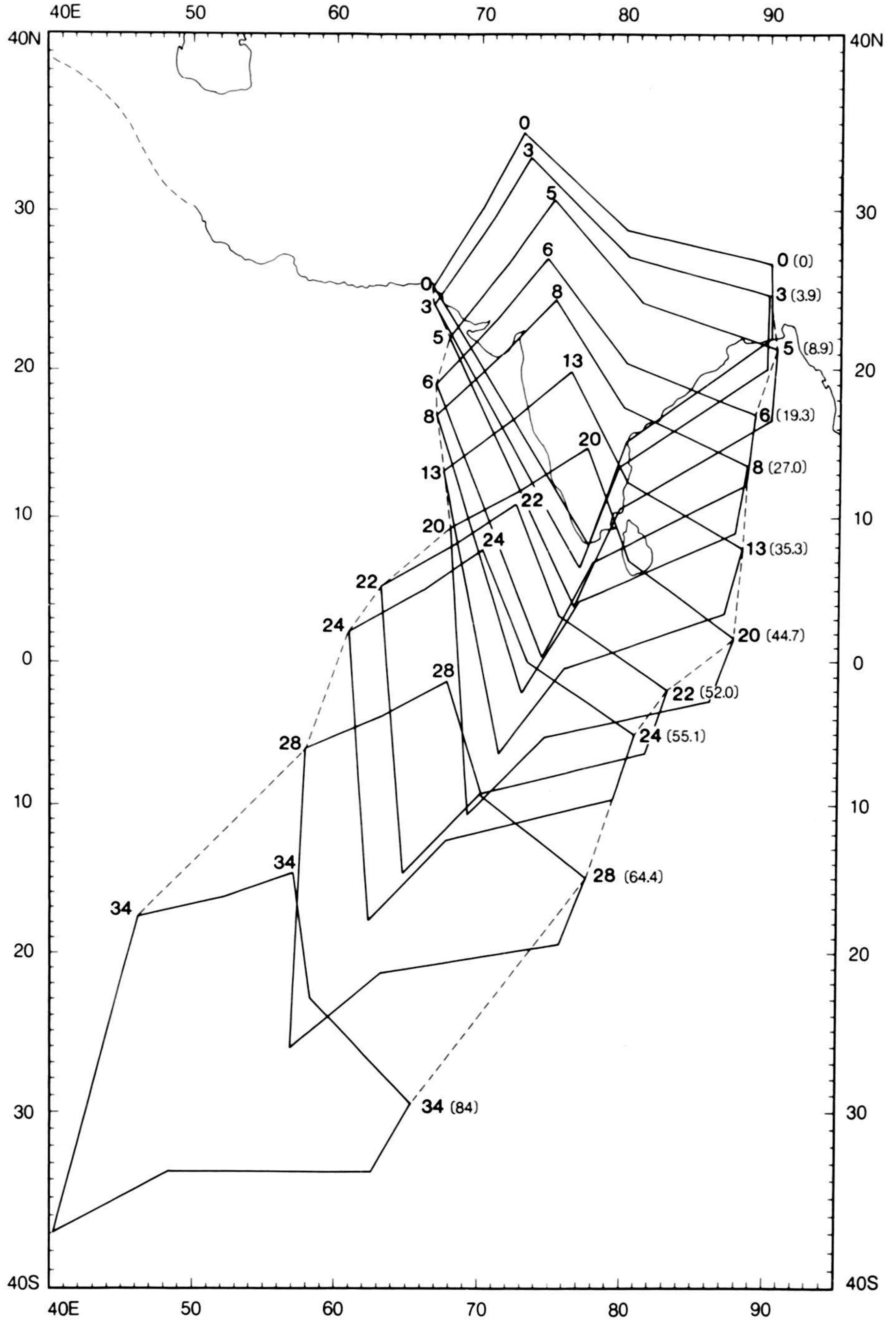

Fig. 3. Successive postitions of India in the Eurasian reference frame derived from the data of Table 1. Numbers refer to magnetic anomalies, numbers in brackets refer to ages in millions of years (HAQ et al. 1987).

INDIA/EUREASIA RECONSTRUCTION POLES				
Anomaly		Latitude	Longitude	Angle
	Ma			
3	(3.9)	19.9	39.8	-2.72
5	(8.9)	12.8	39.9	-7.17
6	(19.3)	18.0	34.9	-12.50
8	(27.0)	17.6	36.8	-17.37
13	(35.3)	15.1	36.9	-24.56
20	(44.7)	13.1	38.3	-33.10
22	(52.0)	17.8	30.0	-35.90
24	(55.1)	18.8	25.5	-38.65
28	(64.4)	16.8	22.0	-49.13
34	(84.0)	18.7	16.5	-66.71

INDIA/EURASIA STAGE POLES (in Eurasia reference frame)			
Anomaly interval	Latitude	Longitude	Angle
3-0	19.9	39.8	2.7
5-3	8.4	39.7	4.49
6-5	25.5	28.5	5.46
8-6	15.8	41.5	4.90
13-8	9.1	35.9	7.25
20-13	6.6	40.4	8.61
22-20	48.7	-32.4	6.19
24-22	35.3	-20.0	3.91
28-24	14.5	8.3	10.86
34-28	30.3	6.1	18.40

Table 1: India-Eurasia reconstruction poles and stage poles from 84 Ma to the present.

vals between the positions determined from magnetic anomaly filling and approximate, as best we can determine, the true motion of India relative to Eurasia. Our motion path is very broadly similar to those of PATRIAT & ACHACHE (1984) and BESSE & COURTILLOT (1988), but differs in significant respects, particularly in the absence of large zig-zag deviations in the early Tertiary.

From 84 Ma (anomaly 34) to about 45 Ma (anomaly 20), India moved roughly northeastwards in the Eurasian reference frame at an average velocity of just over 100 mma^{-1}. From 45 Ma to the present, India's motion changed to a roughly northward direction at an average velocity of just over 50 mma^{-1} and rotated anticlockwise by just over 33°. We cannot be very precise about the exact time of change from fast northeastward motion to slower northwards motion because the successive positions of India in the Eurasian frame are based upon the finite steps determined by magnetic anomaly fitting. However, we believe that 45 Ma (DEWEY et al. 1988) is within a few million years of the time of motion change because a simple extrapolation of the average pre- and post 20 Ma motion intersects very close to the anomaly 20 fit. We take the time of motion direction and rate change at about 45 Ma as the time of the India/Eurasia collision, prior to which convergence was accommodated by subduction beneath a volcanic arc on the southern margin of Eurasia and after which convergence was accommodated by intracontinental convergence within Eurasia. This is supported by geological data that indicate a roughly early to mid-Eocene collision time (Dewey et al. 1988).

3. Arguments against major underthrusting and for indentation

We suggest that substantial underthrusting of the Indian craton beneath Eurasia is not a viable option in accounting for any substantial portion of the post-collisional Indian/Eurasian convergence for the following reasons. First, peninsular India occupies a clearly indentive position in Eurasia with a lateral transpressive zone along its western boundary and a right-lateral zone along its eastern boundary (Figs. 1 and 2). Asian sutures older than 45 Ma show a decreasing northward deflection (Dewey et al. 1988) (Fig. 2). It would be an extraordinary coincidence if an embayment in the Eurasian margin with an existing progressive suture deflection happened to coincide precisely with the collisional arrival position of India. Secondly, the basement and supracrustal Mesozoic/Palaeogene sequences of Tibet are strongly shortened by about 50% in a roughly north-south direction (Dewey et al. 1988). Third, Mesozoic rifted margin facies are preserved in the Himalayas. Fourth, the Himalayas consist of the restacked thinned continental crust of the Mesozoic rifted margins of northern India (Searle et al. 1987). Fifth, palaeomagnetic data shows that the post-collisional northwards displacement of the Lhasa Terrane in southern Tibet, with respect to Eurasia, is greater than about 1,500 km (Besse et al. 1984, Pozzi et al. 1982). Sixth, the flexural rigidity of the Indian lithosphere under the load of the Himalayas, decreases northwards beneath the Himalayas (Lyon-Caen & Molnar 1985); this northward decrease in flexural rigidity is probably related to the superposition of a largely preserved Triassic rifted margin upon the Archaean Indian lithosphere. Seventh, as will be argued in section five, area and crustal volume balancing in Asia indicates that the "indent" area of India into Eurasia is almost exactly balanced by crustal thickening in Eurasia. Eighth, the Tibetan lithosphere is about 150 km thick whereas the Indian lithosphere is some 250 km thick (Dewey et al. 1988), which precludes the existence of the Indian lithosphere beneath Tibet.

4. Arguments against major eastwards lateral extrusion

Substantial eastward lateral extrusion of Eurasian lithosphere as a method of accommodating post-collisional India/Eurasian convergence (Tapponnier et al. 1986) is believed to be unlikely for the following reasons. First, the Indo-Burman Ranges show a post-45 Ma history of right-lateral strike-slip and no evidence of having evolved for the early part of this history in the India/Eurasian head-on collision zone (Mitchel 1981). Second, the Tanlu Fault (Figs. 1 and 2) has been a right lateral fault during the Neogene but was a Mesozoic fault with up to 250 km left-lateral displacement (Atlas of the Palaeogeography of China 1983) or possibly over 1,000 km (Xu et al. 1987). The Tanlu fault clearly is unaffected by any substantial displacement emanating from northern Tibet that is required by major eastward extrusion although Xu et al. (1987) argue that minor extrusion squeeze out has caused convex-eastward arcuate shapes of faults in the Tanlu system. Thirdly, and similarly, a Mesozoic/Palaeogene subduction-related arc in eastern China (Fig. 1) does not exhibit any obvious substantial offset by an extruding Tibetan zone. Fourth, as will be shown in section six, the area that has been displaced by the indentation of India into Eurasia is almost exactly balanced by Eurasian crustal thickening. Fifth, the left-lateral motion on faults, such as the Altun Shan, Kunlun and Kang Ting Faults, which have been argued to be the main loci of escape, is relatively small (Kidd & Molnar, 1988) and far less than the thousands of kilometres inherent in the escape hypothesis. Sixth, the Red River Fault (Figs. 1 and 2), a prominent left-lateral fault in the extrusion hypothesis, is not only demonstrably right-lateral today, but appears to show an approximately 200 km right-lateral displacement of the Chuziong and Simao Triassic/Jurassic basins, which were clearly once continuous (Geological World Atlas 1976). Thus, it is especially difficult to link the opening of the South China Sea as a compatibility termination to the Red River Fault (Tapponnier et al. 1986). Tapponnier et al. (1986), however, have outlined structural evidence for substantial left lateral motion on the Red River Fault and within the adjacent metamorphic terrain of the Ailao Shan but it is not clear that this motion post dates the middle Eocene. Seventh, there is little evidence for a right-lateral zone in southern Tibet and the Himalayas that would accommodate and form the southern boundary of an eastward-escaping zone. The zone of en-echelon right-lateral faults in south Tibet (Fig. 4) cannot accommodate more than about 50 km of right-lateral motion and the dextral shear of stretching lineations in the Himalayas (Brun, Burg & Chen 1985); A. Pecher, pers. comm.) gives not more than about 150 km of right-lateral motion. Thus a maximum of about 200 km of extrusion can be accommodated in the Himalayas and southern Tibet, consistent with a similar left-lateral figure in northern Tibet and the Altun Shan. Eighth, China may be divided into an eastern region dominated by lithospheric extension, perhaps related to slow roll-back in the bordering subduction systems (Dewey 1981) and/or back-arc convection (Froidevaux & Nataf 1981, Nataf et al. 1981), and a western region dominated by lithospheric shortening resulting from the northward motion of the Indian indenter. A zone of dextral shear forms an overlap between the two regimes (Fig. 2). There is no obvious kinematic connection between the two tectonic regimes and it is, therefore, difficult to see how extrusion from the western convergent regimes could be accommodated within, or through, the eastern extensional regime. Ninth, sinistral displacement of about 150 km on the Altun Shan Fault is terminated and balanced by thrusting in the western Kunlun and in the Qilian Shan and Nan Shan. Tenth, a conjugate set of wrench faults and north-south normal faults in Tibet (Fig. 4) indicate a modest eastward extrusion of Tibet of perhaps a few hundred kilometres as will be shown in section 6, but not the thousands of kilometres required by the extrusion hypothesis. Eleventh, the suture zones of Asia show simple progressive northward reduction in offset within the eastern dextral bounding zone (Figs. 1 and 2), and not the eastward Z-shaped looping that would be required by major extrusion of Tibet. Twelfth, the high plateau of Tibet resulting from Palaeogene crustal thickening is largely immediately north of and opposite the Indian "indenter". Only a maximum of 20% of the high ground can be considered to lie east of the eastern margin of the indenter in the Assam syntaxis and, therefore, this area is the maximum that could have been extruded during the Neogene. Thirteenth, the fault kinematics of offshore Malaysia in the southern Gulf of Thailand show that dextral strike-slip motion dominates the Neogene history of the Malay Basin and that the basin cannot curve eastwards around Indo China as an extensional zone, but changes to a convergent zone on the north Sunda shelf. Fourteenth, extrusion alone cannot explain why a large part of the convergent zone has a thickened crust. It will be shown in section 6 that the extra volume of crust under Eurasian elevated terrains is almost exactly balanced by the volume of crust displaced by the Indian indenter. Lastly, it has been argued that plasticine analogue models support a northward progression of eastward wedge expulsion in Asia (Tapponnier et al. 1982). We believe that these models are not useful in quantitatively modelling Asian tectonics because they are incorrectly scaled rheologically and they do not allow vertical stretching in that the models are constrained in a regime of horizontal plane strain.

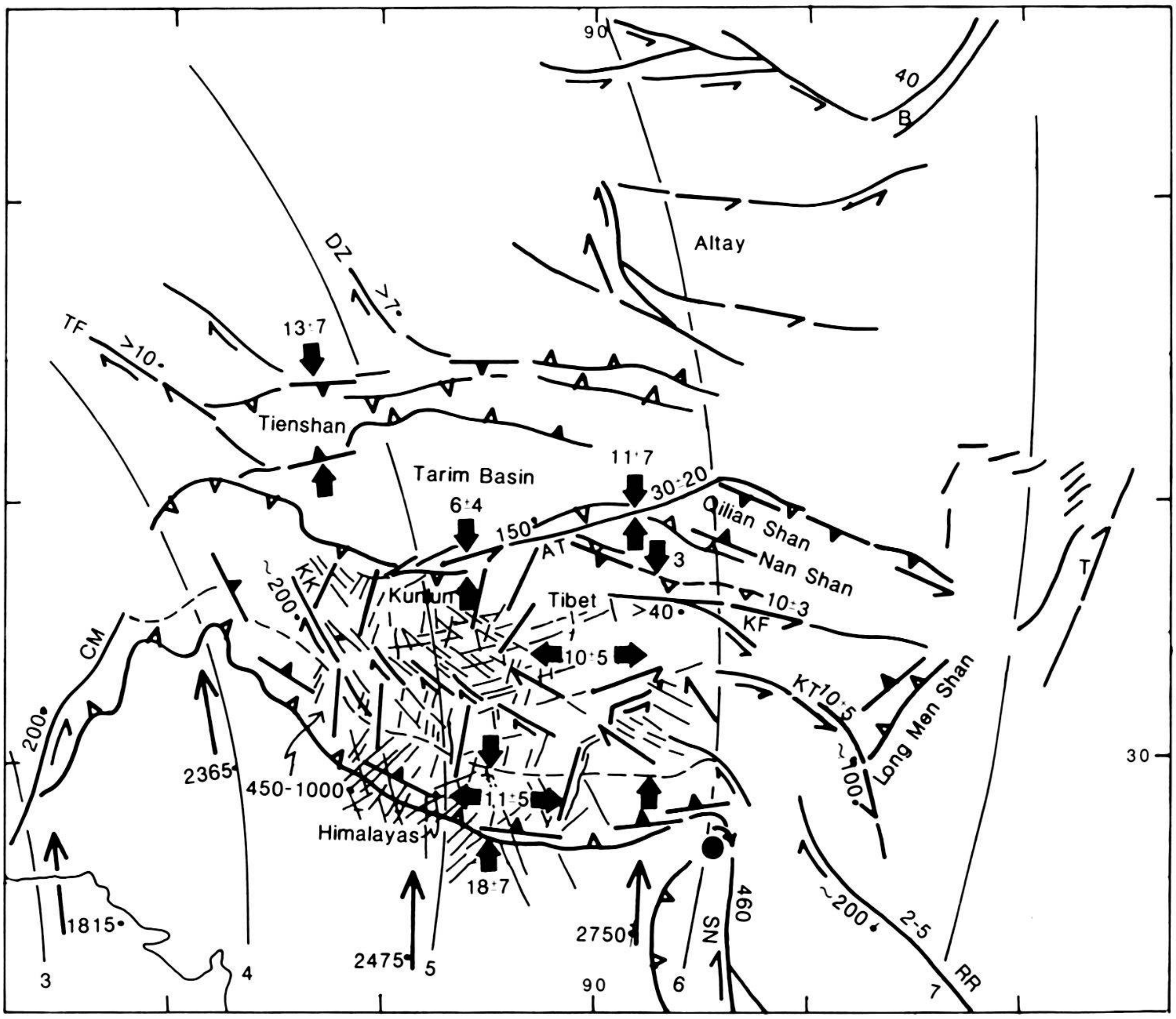

Fig. 4. Displacements and strain with the India/Eurasian convergent zone. Abbreviations as in Fig. 1. Numbers with dots refer to finite displacements, other numbers to displacement rates in mma^{-1}. Long numbered arrows on India give displacement in kilometres of India with respect to Eurasia since 45 Ma. Five numbered slip circles indicate present slip direction and rate in cma^{-1} of India with respect to Eurasia.

We suggest that neither underthrusting nor extrusion are viable mechanisms to accommodate most of the post-collisional northward indentation of Eurasia by India. Although very little or no underthrusting has occurred, a modest amount, perhaps 250 km of eastward extrusion has occurred and the next two sections outline the way in which the India/Eurasia convergence is accommodated, first instantaneously today, and then by finite displacement and strain for the last 45 Ma.

5. Quaternary displacement strain and balancing

Slip circles for the motion of India relative to "stable" Eurasia, derived from the rotations in Table 1, are shown in Fig. 4, rates varying from 30 mma^{-1} in the west to 70 mma^{-1} in the east. This motion must be balanced by integrated displacements and strain in the intracontinental convergent zone. Clearly this does not occur by simple homogenous shortening parallel with the slip vector. The Tienshan and ranges to the east at an average elevation of 3 km north of the Tarim Basin comprise a belt of thrust ranges in which the shorteing direction is not far from parallelism with the slip vector. However, thrusting around the Tibetan/Plateau/Himalayas at an average elevation of 5 km roughly normal to strong topographic gradients is commonly at a very high angle to the slip vector and is probably controlled mainly by gravitational extensional collapse of a plateau recently uplifted very rapidly as a result of catastrophic advective removal of a thickened boundary conduction layer (England & Houseman 1988).

We have insufficient data on strain rates and fault slip rates to convincingly quantitatively balance plate slip against deformation but a crude balance may be made following the method and data of Molnar et al. (1987). If we add 13 mma^{-1} for the Tienshan, 18 mma^{-1} for the Himalayas, 11 mma^{-1} for the Altun Shan Fault and 6 mma^{-1} for the Kunlun along the 50 mma^{-1} slip circle, we have the insignificant remainder of 2 mma^{-1}, which may in any case be accommodated by conjugate strike-slip faulting in Tibet. Any modest errors in these figures could be taken up by a small amount of shortening in the Altay and small adjustments to the rates in other zones. Additions of present displacements within the deforming zone are consistent with the current India/Eurasia slip rate. East west extension in the Himalayas at about 11 mma^{-1} and in Tibet at about 10 mma^{-1} (Molnar et al. 1987) are compatible and result, respectively, from curvature and radial thrusting in the Himalayan arc and from gravitational collapse. East-west extension at these rates is kinematically compatible with slip rates on the Kun Lun and Kang Ting Faults and with en-echelon right lateral faulting in southern Tibet (Fig. 4).

Rotations about vertical axes in the deforming zone are hard to assess but must be occurring, both by the external rotation of fault-bounded blocks and by more penetrative coaxial and non-coaxial shear. For example, left-lateral motion on the Wang Chao and Three Pagodas Faults of Burma and Thailand may result from the clockwise external rotation of blocks in the eastern bounding zones of right lateral shear (Figs. 1 and 2). Two kinds of clockwise rotation are suggested in eastern Tibet, an external rotation around a pole in the Assam syntaxis caused by slip along the Kang-Ting and other curved left-lateral faults, and a more penetrative right lateral simple shear that has caused bending of eastern Tibetan structural trends. Internal rotation by a roughly coaxial bulk horizontal plane strain may be indicated by the strike-slip fault pattern of

Tibet where the conjugate angle facing the shortening direction is obtuse compared with the Himalayas where it is acute (Fig. 4). This suggests clockwise rotation of sinistral faults and anticlockwise rotation of dextral faults, which, in turn, means that fault blocks must be internally deforming (Dewey et al. 1988).

6. Finite deformation and balancing in the collision zone

Since collision with Eurasia at about 45 Ma, India has moved northwards with respect to "stable" Eurasia by about 1,815 km in the west and 2,750 km in the east at rates of about 40 mma^{-1} and 61 mma^{-1} respectively (Fig. 4), and rotated anticlockwise by about 33°, from the data of Table 1. This is consistent with palaeomagnetic data, which indicate a northward motion of some 2,000 to 2,500 km and a rotation of about 25° (Besse et al. 1984; Besse & Courtillot 1988; Klootwijk & Pierce 1979; Pozzi 1982). The palaeomagnetic data support the Indian indentation and bulk north-south shortening of Eurasia by about 2,000 km together with the anticlockwise rotation of southern Tibet.

A very simple crustal area and volume calculation may be used to show that the bulk of the India/Eurasian intracontinental convergence has been taken up by crustal thickening. England & Houseman (1986) calculated the India/Eurasia convergence from an area integral of elevation assuming that all the convergence is taken up by crustal thickening. They derived values of between 2,400 and 3,300 km and between 1,700 and 2,300 km assuming various initial elevations from 500 m to 0 m and two different lithospheric thickness and mantle densities and a likely volume eroded from the elevated topography. These range of values are similar to those calculated from plate circuits and palaeomagnetism. Further, if we compare the area of crust "fed into" the zone of crustal thickening since collision (0.45×10^7 km^2 to 0.36×10^7 km^2 for initial elevations of sea-level and 500 m respectively), derived from England and Houseman's area integral, with the area of crust displaced by the Indian indenter (Fig. 5A) (max. 0.414×10^7 km^2 to min. 0.367×10^7 km^2 depending upon how the pre-collisional subduction zone is drawn between the Makran and Sumatra) the value ranges are strikingly close. Tapponnier et al. (1986) first pointed out the importance of the indentation mark of India into Eurasia, that is the area between the present margin of pre-Tertiary Asia and the reconstructed subduction zone along the southern edge of Tibet prior to 45 Ma. They achieved, however, a different result in balancing this area against the high topography of Asia and concluded that substantial extrusion has occurred.

Excluding any eastward extrusion, about half of the convergence has been accommodated in Tibet calculated from Figure 2 in England & Houseman (1986), the eastward widening of the Tibetan Plateau probably reflecting the increase in finite convergence. Tibet was thickened and elevated to about 3 km by a northward progression of shortening between about 45 and 30 Ma in a regime of roughly north-south plane strain. From 30 Ma to about 5 Ma, buoyancy forces created by the isostatically-compensated elevation prevented further crustal thickening whereupon shortening propagated southwards into the Himalayas and northwards into Eurasia, the little-deformed Tarim Basin being a hard zone with marginal thrusts and strike-slip faults. That the

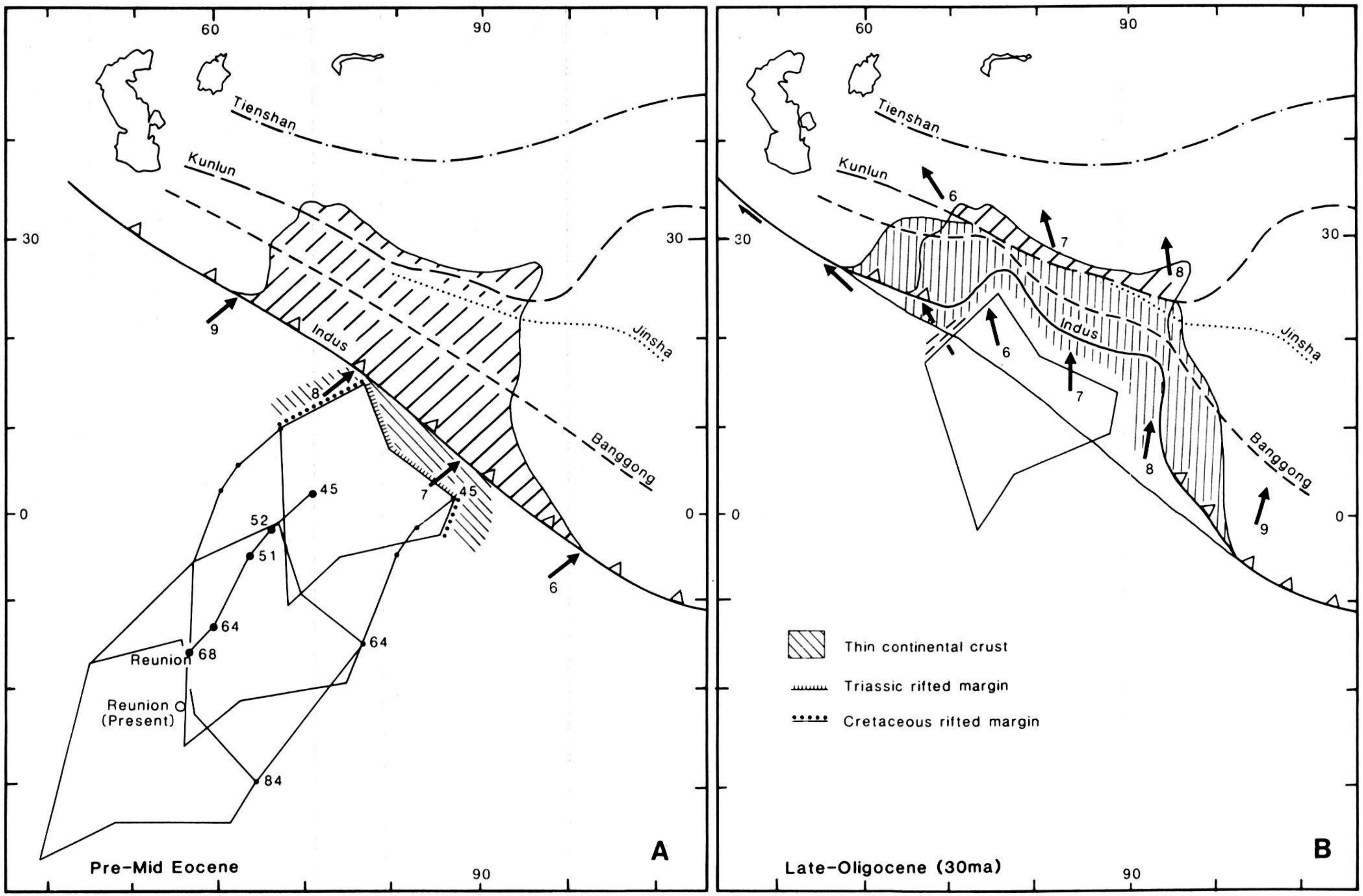

Fig. 5. Palaeotectonic reconstruction of the India-Eurasia collision. Oblique lines – area of Eurasia to be indented by India, vertical lines – area of Eurasia deformed by Indian indentation. The area of "Greater India" along the Cretaceous rifted margin is uncertain.

Tienshan is largely a Neogene zone of shortening is supported by the great thickness of Neogene sediments in flexural basins along its southern margin. Assuming approximately a double thickness of crust beneath Tibet, about 28% of total convergence has been accommodated in the plateau north of the western Himalayan syntaxis, about 36% north of the central Himalayas and 48% north of the eastern syntaxis. In Tibet, some north-south shortening was accommodated from 30 Ma to about 5 Ma in a wrench regime with east-west extension followed by east-west extension in a gravity fault regime consequent upon 2 km of uplift since about 5 Ma. At 10 mma^{-1} (MOLNAR et al. 1987) east-west extension has contributed about 50 km to extrusion over the last 5 Ma. Minimum and maximum amounts of convergence in Tibet during the horizontal plane strain wrench regime may be calculated with various assumptions about fault rotation in Tibet summarized schematically in Fig. 6. Because there is a rough symmetry between crossing sinistral and dextral strike-slip faults, we can probably eliminate external rotation as a rotation mechanism. Vertical plane strain can be eliminated because the conjugate wrench faults largely post-date crustal thickening. If we assume horizontal plane strain and an initial conjugate wrench angle of 70% as seen in the Himalayas, the present conjugate wrench angle is achieved by about 40% shortening which yields an eastward extrusion of 1,160 km and convergence rates in Tibet from 30 Ma to 5 Ma from 17.6 mma^{-1} in the west to 32 mma^{-1} in the east. If we assume a minimum conjugate angle of 90°, Tibet suffered a 29% shortening, an eastward extrusion of 250 km and convergence rates from about 11 mma^{-1} in the west to about 20 mma^{-1} in the east. We believe the latter values to be more appropriate because, adding the 250 km of resultant extrusion to the 50 km generated in the last 5 Ma, we get a maximum of about 300 km of extrusion which is consistent with summing finite displacements on the Altun Shan, Kun Lun and Kang Ting faults (Fig. 4) and with the east west extent of high ground east of the indenter (Fig. 2). Right-lateral accommodation of a few hundred kilometres of wrench regime related extrusion after 30 Ma may be indicated by the eastward deflection of stretching directions in the Himalayas (BRUN, BURG & CHEN 1985; A. Pecher, pers. comm.) that suggests an arc parallel dextral shear strain. The recent smaller gravity regime related extrusion does not need a southern dextral boundary because it is compatible with the arc parallel extension. It is suggested that extrusion is taken up or balanced by shortening in the Long Men Shan and Qilian Shan thrust belts and not by the eastward displacement of eastern China for the reasons given in section 4. We view the Altun Shan Fault as resulting from compatibility problems arising from deformation in Tibet against the non-deforming Tarim Basin, in which case displacement on the Altun Shan should increase eastwards.

Although there is a bulk balance between the amount of Eurasian crust that has been displaced by indentation and the "additional" volume of crust in the deformed zone indicated by elevation, it is instructive to estimate how finite convergence has been accommodated by finite strain and displacement along three crossings of the deformed zone. We show (Table 2) that, along three slip circle transects shown in Fig. 4 (transects 4, 5, 6), about 1,000 km of convergence has been accommodated in the Himalayas since 45 Ma. This is about twice previous maximum estimates from section balancing (COWARD & BUTLER 1985) and also over twice the value permissible if all crust thickened in the Himalayas was, initially, of normal thickness allowing for the volume of sediment now in the Ganges delta and Sumatran accretionary prism. We conclude that much of the crust stacked in the Himalayas, particularly during the Eocene/Oligocene, was originally much thinner than normal across a pre-collisional extensional rifted margin plateau, perhaps like the Exmouth plateau off northwestern Australia.

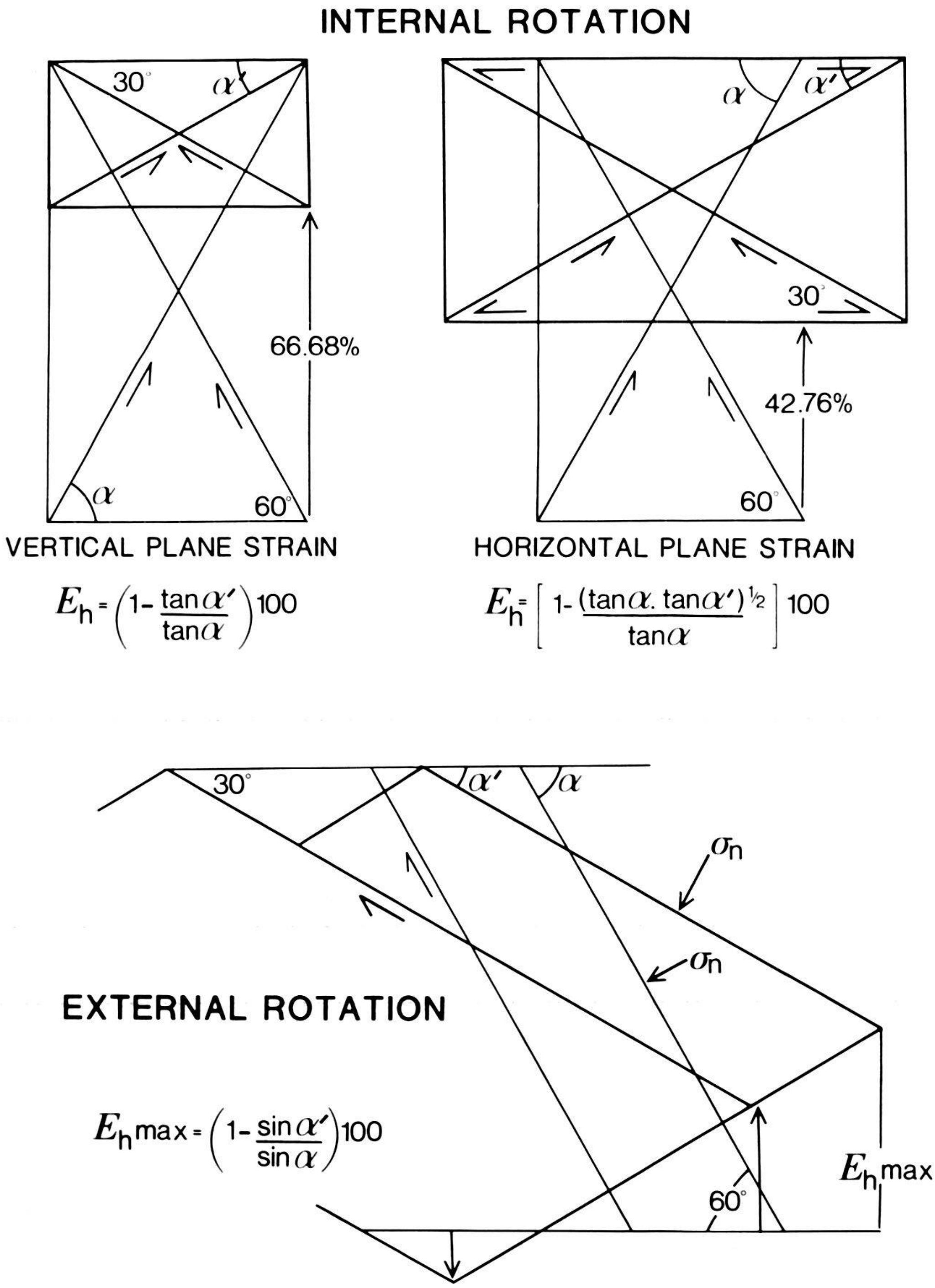

Fig. 6. Rotation of faults about a vertical axis by internal and external rotation. E is shortening percentage given by rotation of conjugate strike-slip faults from an initial angle of 60° to an angle of 30° to the shortening direction.

	Western Syntaxis	Central Himalayas	Eastern Syntaxis
INDIA/EURASIA convergence 45-0ma	2365km (52)mma^{-1}	2475km (55)mma^{-1}	2750km (61)mma^{-1}
TIBET 45-30ma THRUST REGIME	495 (33)	660 (44)	960 (64)
TIBET 30-5ma WRENCH REGIME	202 (8.1)	269 (10.8)	392 (15.7)
TIENSHAN 30-0ma THRUST REGIME	390 (13)	390 (13)	- -
EASTERN TIENSHAN and Altai 30-0ma	- -	- -	~350 (11.7)
ALTUN SHAN FAULT (timing uncertain)		~50	~50
TALASSO-FERGANA DZUNGARIAN FAULT (timing uncertain)	<50	<25	
TIBET 5-0ma GRAVITY REGIME	40 (8.1)	54 (10.8)	78 (15.7)
HIMALAYAS THRUST REGIME 45-0ma	1188 (26.4)	1027 (22.8)	920 (20.4)

Table 2: Balancing of finite convergence, strain and displacement along three transects of the India/Eurasian convergence zone (slip circle transects 4, 5 and 6 in Fig. 4). Motion directions are roughly north-south. The India/Eurasia convergence is from the data of Table 1. Shortening in the Himalayas is calculated as the difference between the India/Eurasia convergence and the sum of other shortening values calculated from geological data.

7. Summary

We suggest that the India/Eurasia intracontinental convergence following collision at about 45 Ma was accomplished principally by crustal/lithospheric thickening in a northward-propagating zone north of the Indian indenter and that strain and displacements in the brittle upper crust are not the result of stress propagation in the brittle crust from the boundaries of the deforming zone but result from accommodate to the more isotropic viscous deformation of the lithosphere.

In Fig. 5, simple palaeotectonic reconstructions for 45 and 30 Ma are shown. If we assume a simple Eurasian subduction margin connecting the Makran with Sumatra, we find that India is about to collide with Eurasia at 45 Ma; it is on this basis (Tapponnier et al. 1986) that we define the area of Eurasia displaced by indentation. During the earliest phase of thin crust restacking in the proto Himalayas, there was probably a close and direct correspondence between the India/Eurasian slip direction and the development of structural transport directions. As the Himalayan crust and lithosphere thickened, India began to indent Eurasia and buoyancy body force became important so that, by about 30 Ma, the Tibetan crust was thickened to its present 65 km, deformation began to spread northwards beyond Tibet and southwards in the Himalayas and wrench regime convergence in Tibet slowed to between 8.1 mma^{-1} in the west and 15.7 mma^{-1} in the east. The lateral shear zones to the indenter gradually spread northwards bounding the thickened zone and show clearly, from the deflection of Eurasian sutures, that shear strain and displacement within them diminish northwards. Palaeomagnetic data (Achache, Courtillot & Besse 1983) support the clockwise rotations that are required in the Indo-Burmese eastern dextral shear zone; Sumatra has rotated 35° clockwise and Indo-China 29° since the Cretaceous and southern Thailand by 13° since the late Neogone (McCabe et al. 1988).

An important corollary of our conclusions that major extrusion is unimportant is that long strike-slip faults need not have large displacements. The Altun Shan, Kun Lun and Kang Ting Faults are all over 1,000 km in length, yet have offsets of 150 km or less. Furthermore, strike-slip faults with transtensional and transpressional zones cannot have very large offsets unless these zones become bypassed; the Kang Ting has a major left-stepping offset, which shows extension today. These faults may be compared with the North Anatolian Fault which has several transtensional zones and a maximum displacement of only about 80 km (Dewey et al. 1986).

The data upon which our model is based are limited and we now need an intensive phase of data collection to test the various kinematic and dynamic models that have been proposed. In particular, we need a great deal of new palaeomagnetic data to systematically determine internal and external rotations, structural data to determine integrated strain and timing, rates and amounts of displacement across discontinuities and geodetic measurements to determine present day displacement rates across and within the convergent system.

REFERENCES

Achache, J., Courtillot, V., & Besse, J. 1983: Palaeomagnetic constraints on the late Cretaceous and Cenozoic tectonics of southeastern Asia. Earth planet. Sci. Lett. 63, 123–136.

Atlas of the Palaeogeography of China 1983. Cartographic Publishing House, Beijing.

Argand, E. 1924: La tectonique de l'Asie. Proc 13th Int. Geol. Congr. Brussels. (1924). 7, 171–372.

Barazangi, M., & Ni, J. 1982: Velocities and propagation characteristics of Pn and Sn beneath the Himalayan arc and Tibetan Plateau: possible evidence for underthrusting of Indian continental lithosphere beneath Tibet. Geology 10, 179–185.

Besse, J., & Courtillot, V. 1988: Palaeogeographic maps of the continents bordering the Indian Ocean since the Early Jurassic. Jour. Geophys. Res. 93, 1791–1808.

BESSE, J., COURTILLOT, V., POZZI, J.P., WESTPHAL, M., & ZHOU, Y.X. 1984: Palaeomagnetic estimates of crustal shortening in the Himalayan thrusts and Zangbo suture. Nature 311, 621–626.

BRUN, J.P., BURG, J.P., & CHEN, G.M. 1985: Strain trajectories above the Main Central Thrust (Himalaya) in southern Tibet. Nature 313, 388–391.

COWARD, M.P., & BUTLER, R.W.H. 1985: Thrust tectonics and the deep structure of the Pakistan Himalayas. Geology 13, 417–420.

DEWEY, J.F. 1981: Episodicity, sequence and style at convergent plate boundaries. In: The Continental Crust and its Mineral Deposits (ed. by D.W. STRANGWAY). Geol. Assoc. Can. Spec. Paper 20, 553-573.

DEWEY, J.F., HEMPTON, M.R., KIDD, W.S.F., SAROGLU, F., & SENGÖR, A.M.C. 1986: Shortening of continental lithosphere: the neotectonics of Eastern Anatolia – a young collision zone. Geol. Soc. Lond. Spec. Publ. 19, 3–36.

DEWEY, J.F., & BURKE, K.C.A. 1973: Tibetan, Variscan and Precambrian basement reactivation: products of a continental collision. J. Geol. 81, 683–692.

DEWEY, J.F., SHACKLETON, R.M., CHANG CHENGFA, & SUN YIYIN 1988: The tectonic evolution of the Tibetan Plateau. Phil. Trans. Roy. Soc. Lond. 327, 379–413.

ENGLAND, P.C., & HOUSEMAN, G.A. 1986: Finite strain calculations of continental deformation. II: Application to the India-Asia plate collision. J. geophys. Res. 91, 3664–3676.

— 1988: The mechanics of the Tibetan Plateau. Phil. Trans. Roy. Soc. Ser. A. 326, 301–320.

ENGLAND, P.C., & MCKENZIE, D.P. 1982: A thin viscous sheet model for continental deformation. Geophys. J. R. astron. Soc. 70, 295-321.

FROIDEVEAUX, C., & NATAF, H.C. 1981: Continental Drift: what driving mechanism? Geol. Rundsch. 70, 166–176.

Geological World Atlas: UNESCO, Paris. (1976).

HAQ, B.U., HARDENBOL, J., & VAIL, P.R. 1987: Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1167.

KIDD, W.S.F., & MOLNAR, P. 1988: Quaternary and active faulting observed in the 1985 Academia Sinica – Royal Society Geotraverse of Tibet. Phil. Trans. Roy. Soc. Lond. 327, 337–364.

KLOOTWIJK, C.T., & PIERCE, J.W. 1979: India's and Australia's pole path since the late Mesozoic and the India-Asia collision. Nature 282, 605–607.

LYON-CAEN, H., & MOLNAR, P. 1985: Gravity anomalies, flexure of the Indian plate, and the structure, support and evolution of the Himalaya and Ganga Basin. Tectonics, 4 (6), 513–538.

MCCABE, R., CELAYA, M., COLE, J., HAN, H., OHNSTAD, T., PAJITPRAPAPON, V., & THITIPAWARN. V. 1988: Extension of tectonics: the Neogene opening of the north-south trending basins of Central Thailand. J. Geoph. Res. 93, 11899–11910.

MITCHELL, A.H.G. 1981: Phanerozoic plate boundaries in mainland S.E. Asia, the Himalayas and Tibet. J. geol. Soc. Lond. 138, 109-122.

MOLNAR, P., BURCHFIEL, B.C., LIANG K'UANGYI, & ZHAO ZIYUN. 1987: Geomorphic evidence for active faulting in the Altyn Tagh and northern Tibet and qualitative estimates of its contribution to the convergence of India and Eurasia. Geology 15, 249–253.

MOLNAR, P., & TAPPONNIER P. 1975: Cenozoic tectonics of Asia: effects of a continental collision. Science 189, 419–426.

— 1977: Relation of the tectonics of eastern China to the India-Eurasia collision: application of slip-line field theory to large-scale continental tectonics. Geology 5/4, 212–216.

NATAF, H.C., FROIDEVEAUX, C., LEVRAT, J.L., & RABINOWICZ, M. 1981: Laboratory convective experiments: effect of lateral cooling and generation of instabilities in the horizontal boundary layers. Jour. Geophys. Res. 86, 6143–6154.

NEPROCHNOV, Y.P., LEVCHENKO, O.V., MERKLIN, L.V., & SEDOV, V.V. 1988: The structure and tectonics of the intraplate deformation area in the Indian Ocean. Tectonophysics 156, 89–106.

PATRIAT, P., & ACHACHE, J. 1984: The chronology of the India-Eurasia collision. Implications for crustal shortening and the driving mechanism of plates. Nature 311, 615–621.

POWELL, C.M., & CONAGHAN, P.J. 1975: Tectonic models of the Tibetan Plateau. Geology 3, 727–731.

POZZI, J.-P., WESTPHAL, M., ZHOU YAOXIU, XING LISHEN, & CHEN XIANYAO 1982: Position of the Lhasa Block, South Tibet, during the late Cretaceous. Nature 297, 319–321.

SEARLE, M.P., & 10 others 1987: The closing of Tethys and the tectonics of the Himalayas. Bull. geol. Soc. Amer. 98, 678–701.

TAPPONNIER, P., & MOLNAR, P. 1977: Active faulting and tectonics in China. J. geophys. Res. 82, 2905–2930.

TAPPONNIER, P., PELTZER, G., & ARMIJO, R. 1986: On the mechanics of the collision between India and Asia. Geol. Soc. London Spec. Publ. 19, 115–157.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., & Cobbold, P. 1982: Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. Geology 10, 611–616.

Weissel, J.K., Anderson, R.N., & Geller, C.A. 1980: Deformation of the Indo-Australian plate. Nature 287, 284–291.

Wiens, D.A. 1986: Historial seismicity near Chagos: a complex deformation zone in the equatorial Indian Ocean. Earth Planet. Sci. Lett. 76, 350–360.

Wiens, D.A., Stein, S., DeMets, C., Gordon, R.G., & Stein, C. 1986: Plate tectonic models for Indian Ocean intraplate deformation. Tectonophysics 132, 37–48.

Wu, H., Zhang, L., & Ji, S. 1989: The Red River-Ailaoshan fault zone – Himalayan large sinistral strike-slip intracontinental shear zone. Sci. Geol. Sinica, 1, 1–8 (in Chinese with English abstract).

Xu, J.-W., Zhu, G., Tong, W., Cui, K., & Lui, Q. 1987: Formation and evolution of the Tancheng-Lujiang wrench fault system: A major shear system to the northwest of the Pacific Ocean. Tectonophysics 134, 273–310.

Zhao, W., & Morgan, W.J. 1987: Injection of Indian crust into Tibetan lower crust: a two-dimensional finite element model study. Tectonics 6, 489–504.

Manuscript received: 2 December 1988
Revised version accepted: 12 July 1989