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Cenozoic Tectonics of Asia: Effects of a Continental Collision

Features of recent continental tectonics in Asia can be interpreted as results of the India-Eurasia collision.

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Subduction of lithosphere at island arc structures occurs along relatively narrow zones, apparently in a simple manner, but because of the buoyancy of continental lithosphere, subduction of one continent beneath another is often assumed to be impossible (*1*, *2*). Instead the motion between the two continents is presumed to stop abruptly, suturing them together along a young orogenic belt and causing a marked change in the relative plate motion or the formation of a subduction zone elsewhere (*1*, *3*). Several old orogenic belts between stable cratons, such as the Appalachian-Caledonian system (*3*) and the Urals (*4*), are interpreted as former plate boundaries between converging lithospheric plates. In these regions island arc structures seem to have existed for long periods of geologic time, but with the subsequent continental collision, major tectonic activity presumably ceased. Unfortunately, the intense deformation that occurs during such a collision destroys much of the evidence needed to answer such questions as how rapidly suturing takes place, to what extent the collision of continents affects plate motion, how much shortening of continental crust occurs, how this shortening occurs and how it is distributed in space, and others.

The current tectonic activity in Asia is often cited as the consequence of continental collision, in progress, between India and Eurasia (*3*, *5*, *6*). In this article we analyze aspects of Asian tectonics in order to understand better the details of this particular continental collision. Continental reconstructions show steady convergence of India and Eurasia since the late Cretaceous, but suggest that since the collision between them in the Eocene the rate decreased by one half (Figs. 1 and 2). Nevertheless, at least 1500 kilometers of crustal shortening must have occurred by deformation solely within continental lithosphere. Both seismic data, including the spatial distribution of earthquakes, associated fault plane solutions, and surface deformation (Fig. 3), and geologic evidence of recent tectonic activity (Fig. 4), discussed in the literature or recognized on Earth Resources Technology Satellite (ERTS) photographs (Figs. 5 to 7), imply deformation in a broad zone extending as much as 3000 km northeast of the Himalayas. The inferred orientation of stress and sense of displacement on faults and the approximate timing of events are consistent with nearly all of the present seismicity, tectonics, and relief being a consequence of the India-Eurasia continental collision.

Of the calculated convergence since the collision we estimate that shortening and underthrusting of India beneath the Himalayas and Tibet probably accounts for at least 300 and perhaps 700 km. Probably another 200 to 300 km can be accounted for by thrusting and crustal thickening in the Pamir, Tien Shan, Altai, Nan Shan, and other mountain belts (Fig. 5). We conclude, however, that a major fraction of the convergence occurs on major east-west trending strike-slip faults (Figs. 6 and 7) in China and Mongolia. Movement on them may allow material lying between the stable portions of the India and Eurasia plates to move laterally out of the way of these two plates. The pattern of deformation is thus similar to that proposed by McKenzie (*7*) for Turkey and Iran, but occurs on a much larger scale and is more complicated, involving several subparallel strike-slip faults. We infer that probably a total of 500 km, and conceivably 1000 km, of east-west motion could have occurred and could account for a comparable amount of shortening. Hence, the recognition of large strike-slip motion may obviate the need for postulating the underthrusting of India beneath the whole of Tibet.

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Relative Motion between India and Eurasia

The ophiolite suite that follows in part the Indus and Tsang Po valleys, northeast of the Himalayas (*8*), apparently marks the precollision boundary along which the ancient India plate was subducted beneath the Eurasia plate (*3*, *5*, *9*, *10*). The extensive acidic volcanism in southern Tibet (*11*) is consistent with this contention. The most likely time for initial contact between India and Eurasia appears to be some time in the Eocene (*3*, *5*, *12*). Fossils of large mammals have not been found in rocks older than middle Eocene, but in middle Eocene sediments fossils of mammals similar to those in Mongolia are prevalent (*12*). Moreover, in the northern Himalayas, marine sedimentation ceased in the Eocene (*8*, *10*). However, as Gansser (*9*) infers that thrusting within the Himalayas began in the post-Eocene, intimate contact between India and Eurasia may have occurred slightly later. The Eocene-Oligocene boundary, in fact, appears to mark a change in the tectonics throughout Asia. During the Cretaceous and most of the Paleocene, Asia was a tectonically stable platform, but the large-scale vertical motion that led to the present relief began in approximately the Oligocene (*13*). Moreover, many of the basins and graben of eastern China appear to have developed since the Eocene (*14*).

Assuming rigid plate motion, the sea-floor spreading histories of the Indian and Atlantic oceans (*15*) allow us to calculate precisely the relative positions of the India and Eurasia plates at the times of various anomalies since the late Cretaceous (Fig. 1). These reconstructions show that between the late Cretaceous and approximately 38 million years ago (near the Eocene-Oligocene boundary) the rate of relative motion was quite fast (about 100 to 180 mm/year), but more recently it has been only about 50 mm/year (Fig. 2). That the motion between the India and Eurasia plates changed drastically at this time supports the contention that the collision between continental plates strongly affects the rate of relative plate motion. Nevertheless, since this time the motion between India and Eurasia has continued at a relatively fast rate. Given the uncertainty in the precise data of the collision, at least 1500 km of relative motion between Eurasia and India must then be accounted for solely by deformation of continental lithosphere, which can take place in several possible modes. Two extremes are giant underthrusting of one block of continental crust beneath the other along a very long, very shallow dipping fault zone and more diffuse deformation over a broad zone, involving crustal thickening through thrusting and folding, and lateral strain through strike-slip faulting.

Crustal Deformation in Asia

Although in the late Cretaceous and early Tertiary the boundary between the Eurasia and India plates was probably relatively narrow, evidence of several types suggests that deformation now is spread over a large part of Asia. Seismicity in Asia is widespread (Fig. 3): not only are there numerous small earthquakes north of the Himalayas, but of the seven great earthquakes that B. Gutenberg lists for Asia since 1897, four occurred far north of the Himalayas, as did more than half of the 75 earthquakes with magnitude (M) equal to or greater than 7 during this interval (*16*). Abundant geomorphic data demonstrate from 2 to 5 km of late Tertiary vertical motion of the earth's crust north of the Himalayas in the Pamir, Tien Shan, and Altai ranges (*13*). Moreover, numerous major young structures—folds, thrust and normal faults, and especially very large strike-slip faults—can be recognized on the ERTS photographs (Figs. 4 to 7). Important problems are what fraction of the convergence between India and Eurasia is absorbed north of the Himalayas, and how does this occur.

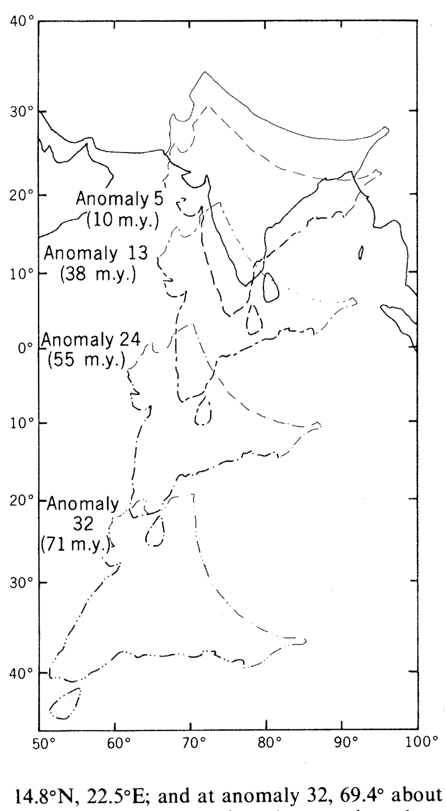
Deformation at the Himalayan Belt

Geologic (*8–10*), seismic (*6, 17*), and gravity (*18*) data imply a northward underthrusting of the Indian subcontinent beneath the Himalayas (Fig. 3). Although the Himalayas are composed of slivers of the ancient Indian subcontinent (*8, 9*) and there no longer is active subduction at the Indus suture zone, several aspects of the underthrusting of India beneath the Himalayas are similar to subduction of oceanic lithosphere at island arcs (*6*)—the shallow dipping fault planes of earthquakes, the deep Ganges trough with normal faulting beneath it similar to a trench at an island arc, and an outer topographic rise. In contrast with island arcs, where the length of the deep seismic zone gives a measure of the rate of subduction (*2*), however, no intermediate or deep earthquakes have been reliably located in the Himalayas.

The amount of underthrusting since the continental collision is difficult to estimate. From the throw on the important faults within the Himalayas, Gansser (*9*) calculated a total of about 300 km of overthrusting. Evans (*19*) obtained a similar estimate for the Assam region. If the approximately double thickness of crust, inferred from gravity anomalies (*18*), results from continental crust underthrusting itself, then from the approximate width of the Himalayas (300 km) this same estimate of 300 km is obtained. Little evidence, however, allows a determination of possible underthrusting of the ancient Indian subcontinent beneath Tibet at the Indus suture zone, but surely some is likely to have occurred, perhaps as much as 200 km (*9*).

E. Argand, A. Holmes, and others have suggested that the uniform, very high altitude in Tibet is due to an underthrusting of India beneath the whole of Tibet, causing a double thickness of the crust (*10*). Such an idea calls for a very long (~1000 km) and very shallow dipping (0° to 5°) fault zone separating the underthrusting India plate from the overlying Tibetan crust. Neither seismicity nor fault plane solutions provide evidence for such a fault zone at the present time, and nowhere on earth today is there an inclined seismic zone that dips at such a shallow angle for such a long distance. The close proximity of andesitic volcanic rocks in Tibet to the Indus suture zone (*11*) implies that prior to the continental collision, oceanic lithosphere did not descend into the asthenosphere beneath Tibet at an unusually shallow angle. Thus this long thrust fault would have formed since the collision. Its formation, either by fracturing through normal continental lithosphere or by sliding beneath Tibetan lithosphere thinned by thermal processes beneath it, is difficult to visualize without intense deformation of the overlying Tibetan crust.

Mechanically, shortening might occur



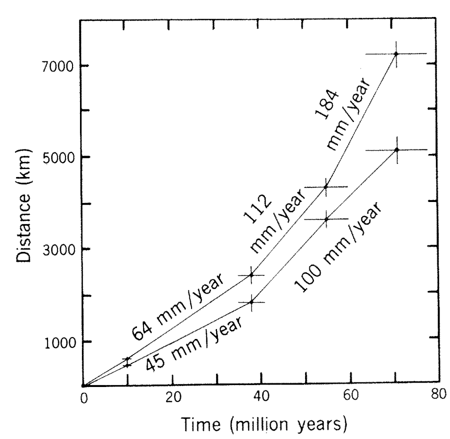


Fig. 1 (left). Position of India with respect to Eurasia at different times in the past, corresponding to magnetic anomalies in the oceans (*15, 40, 41*). Eurasia is arbitrarily assumed fixed; and the northern, eastern, and western boundaries of India are drawn arbitrarily to reflect different positions at different times (m.y., million years). We do not know the northern boundary of Indian subcontinent before the collision and do not mean to imply that it was as drawn. At the time of anomaly 5, India has been rotated 6.5° about a pole at 23.0°N, 33.9°E; at anomaly 13, 27.1° about a pole at 18.8°N, 35.6°E; at anomaly 24, 42.2° about a pole at 14.8°N, 22.5°E; and at anomaly 32, 69.4° about a pole at 6.3°N, 23.7°E. Fig. 2 (right). Distance from present position of northeast and northwest tips of India (Fig. 1) as a function of time. Uncertainties in the abscissa are from (*41*) and uncertainties in the ordinate are assumed to be 10 percent.

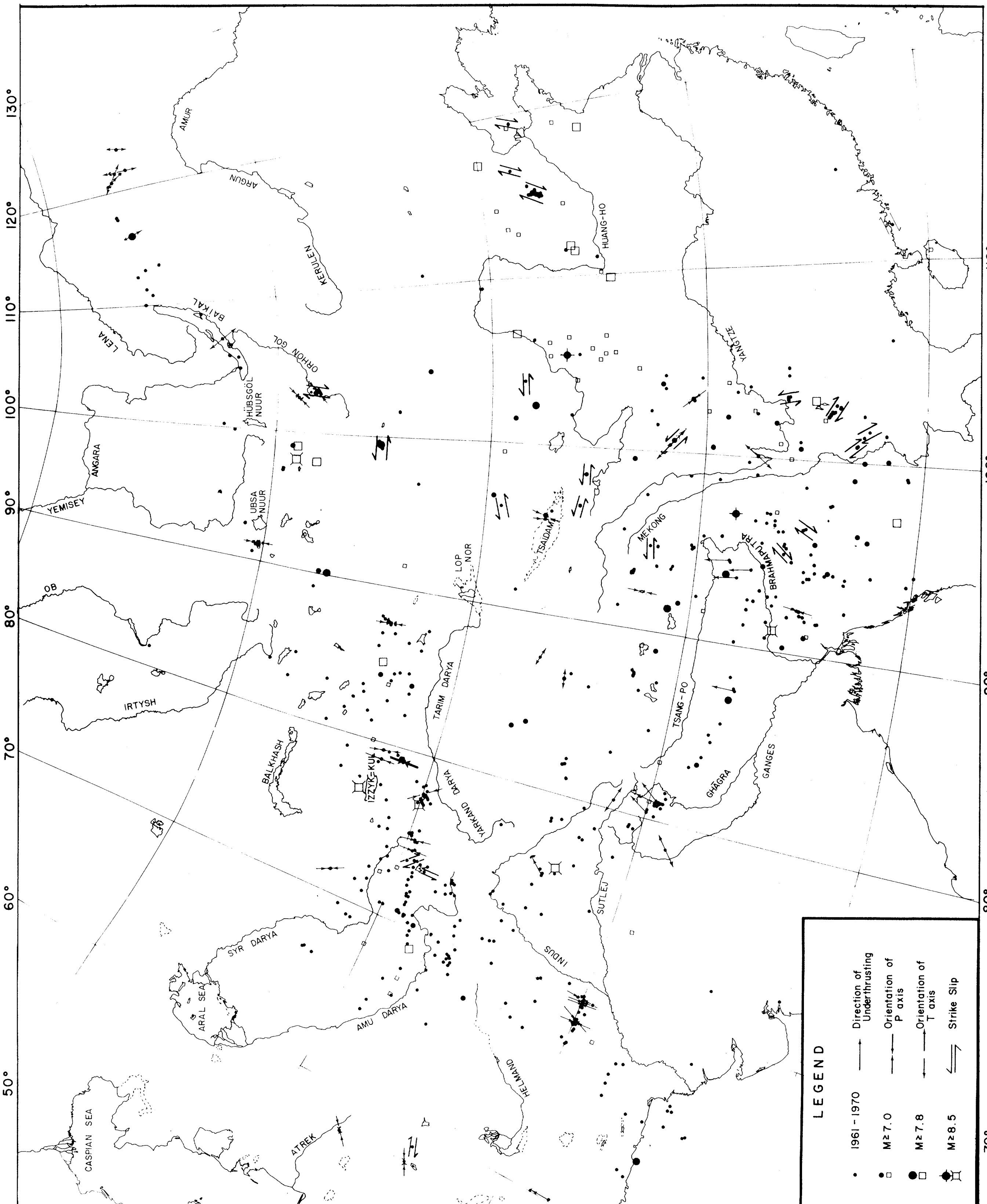


Fig. 3. Seismicity and fault plane solutions in Asia. Closed circles indicate events more recent than 1920, and open squares events before 1920, often based on intensities only. Data include well-located events between 1961 and 1970 (*6*), events with magnitude greater than 7 since 1897 [epicenters are from (*15*) for events before 1920 and were relocated after 1920], and events with magnitude greater than 7 in China located by historical reports of intensity (*42*). Arrows show fault plane solutions used in (*6*) and more recent unpublished data. Single arrows show direction of underthrusting; antiparallel arrows show sense of motion for strike-slip faulting; pairs of arrows pointing toward (or away from) each other show orientations of P (or T) axes for thrust (or normal) faulting.

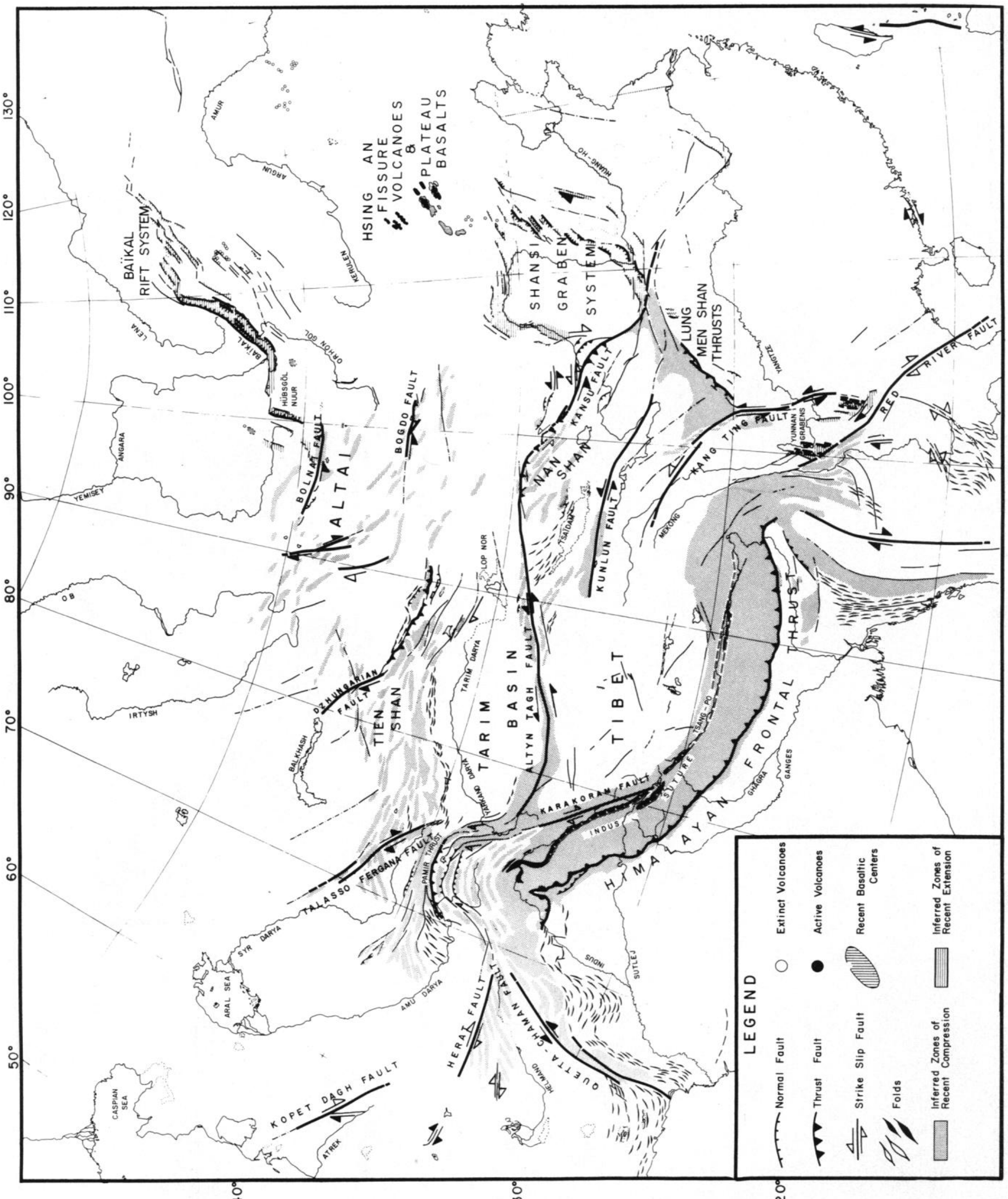


Fig. 4. Preliminary map of recent tectonics in Asia. Bold lines represent faults of major importance—usually seismic and with very sharp morphology. Bold arrows indicate sense of motion, corroborated by fault plane solutions or surface faulting of earthquakes (*6, 30, 33, 34*). Open arrows indicate sense inferred from analysis of photographs. For Tertiary folding bold symbols indicate more prominent, more recent folds. The dotted areas indicate region of inferred recent vertical motion associated with thrust faulting and compressional tectonics. Areas shaded by dashed lines are covered by thick recent alluvial deposits and are dominated by horizontal extension and subsidence (*14*). Contours in the northeast China basins and recent volcanic centers, except for the Hsing An fissure basalts, are from Terman (*43*). This map is preliminary; coverage by ERTS photographs is not complete, and surely many features relevant to the understanding of Asian tectonics have not yet been recognized or were not plotted. The names of faults are not official names but purely for reference in this article.

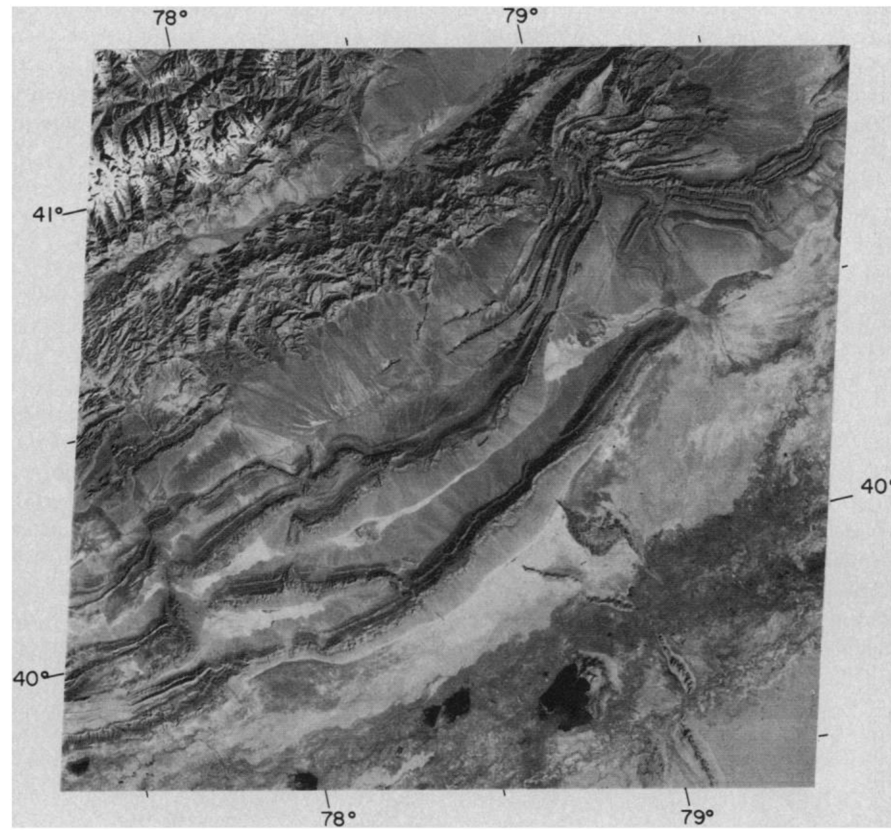
more easily throughout Tibet by folding and thrusting without such a giant underthrust (*5*). Evidence of folding can be recognized on the ERTS photographs of Tibet, especially in southern Tibet, but this deformation could be as old as Cretaceous (*14*). Moreover, the large, simply dispersed short-period Rayleigh waves that cross Tibet without pronounced multipathing imply that a thick, relatively continuous layer of sediments covers Tibet and are consistent with only mild tectonic activity there (*20*). Fault plane solutions of earthquakes in Tibet indicate normal faulting on north-south striking faults (*6*). Thus we cannot exclude the possibility that a few hundred kilometers of shortening occurred within Tibet in the early stages of the collision, but if this shortening did occur it has now stopped.

Perhaps the high altitude of Tibet results from thermal processes and magmatic activity involving the lower crust and upper mantle (*5*), as probably is the case in the Altiplano in the Andes. The abundant evidence for volcanism supports this contention (*5, 21*), and the absence of the seismic phase *Lg* on seismograms for paths crossing Tibet is easily explained by high attenuation due to high temperature in the Tibetan crust (*22*). Thus, although it is difficult to prove, we consider it likely that the combination of underthrusting of the Indian subcontinent beneath Tibet and deformation distributed throughout the Tibetan crust do not amount to more than 300 or 400 km.

Crustal Shortening in the Pamirs and Tien Shan

The geology of the Pamirs (*13*) and the intermediate depth earthquakes with an associated zone of high seismic velocity beneath the southern portion of the Pamirs (*23*) can be accounted for (although less convincingly than in the Himalayas) by a southward underthrusting of an old piece of oceanic lithosphere attached to the Eurasia plate (*6, 23, 24*).

In the Tien Shan, fault plane solutions (*6, 25*) and surface deformation associated with large historic earthquakes (*26*) imply that the predominate mode of deformation is thrust faulting (Fig. 3). However, the deformation cannot easily be ascribed to one side of the belt underthrusting the other as in the Himalayan and Pamir regions, but occurs over the entire zone of elevated topography. Folds and faults recognized on the ERTS photographs are consistent with this pattern and suggest the existence of major thrust faults on the north and south sides of the Tien Shan (Figs. 4 and 5). Particularly on the south side, clearly folded sedimentary formations (Fig. 5) are probably related to thrusting in the underlying



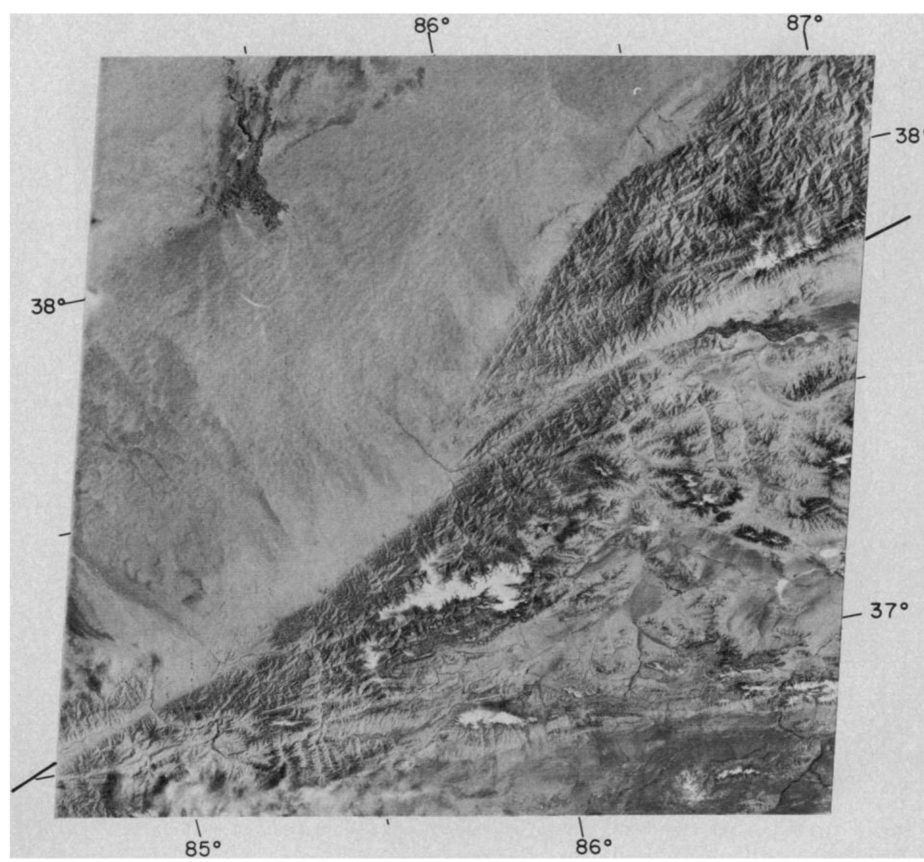


Fig. 5 (top). Frontal folds and thrusts, southern edge of Tien Shan. [ERTS photograph E-1458-04571-5] Fig. 6 (bottom). Altyn Tagh (Astin Tagh or A erh chin Shan) fault. Lines at the edges of the photo show trend of fault. [ERTS photograph E-1308-04262-5] basement rocks. It appears that the thrusting, distributed over a broad zone, manifests itself in a thickening and shortening of the crust (*24*). Seismic refraction profiles show that the crust is thicker than in the more stable platform areas by 20 to 30 km (*27*). From these data, and assuming that the excess crustal thickness is due to crustal shortening, we can estimate the amount of the shortening across the eastern portion of the Tien Shan to be about 200 to 300 km. By this same logic, Ulomov (*24*) estimated a similar amount in the Pamiers and neighboring Tien Shan.

In addition to the predominant thrust faulting, several major northwest-southeast trending right lateral strike-slip faults, most of which are discussed in the Soviet literature (*28*), are clearly recognized in the ERTS photographs. Much of the displacement on them may have occurred before the India-Eurasia collision, but the clear traces seen on the ERTS photographs indicate that they are active today. Right lateral motion along them (*28*) can be inferred from the associated tectonic deformation observed on the ERTS photographs, and is consistent with a horizontal maximum compressive stress oriented roughly north-south. These faults control very strongly the structure of the chain (Fig. 4); the "tectonic fabric" expressed in the orientation and high elevation of recent topographic ridges differs markedly on each side of them. Some appear to continue for a few hundred kilometers into the stable Eurasia platform, but the low seismicity there suggests that they are no longer active. Hence the motion on them must terminate through some distributed mode of deformation, such as asymmetric folding or thrust faulting on both sides of the fault.

Major Strike-Slip Faulting in China and Mongolia

To the northeast of the Himalayan chain, the deformation involved predominantly strike-slip faulting (Figs. 3 and 4). Most of our understanding of continental deformation in Asia stems from a more detailed study (*29*) where several major left lateral strike-slip faults, trending roughly east-west, were recognized in central China. The long linear valleys and adjacent ridges characteristic of active strike-slip faulting are among the most clearly defined features on the ERTS photographs (Figs. 6 and 7). Fault plane solutions of earthquakes (*6, 29, 30*), surface faulting (*31*), and associated en echelon compressive features imply that the sense of all of these faults is left lateral. The three most prominent of these faults (Fig. 4) are herein referred to as the Kang Ting fault (Fig. 6) (west of the Lung-Men Shan thrusts), the Kunlun fault (south of the Tsaidam Basin, within the eastern Kunlun Mountains), and the Altyn Tagh fault (Fig. 7) separating Tibet from the Tarim Basin and passing south of the Altyn Tagh (also called Astin Tagh or A erh chin Shan). Further east, this latter fault connects with a complicated thrust–left lateral fault system along the northeast edge of the Nan Shan. This system, in turn, joins the Kansu fault, which extends southeast about 700 km and seems to die out southeast of the Shansi graben. Part of the displacement on the Kansu fault appears to be absorbed in the Shansi graben system (Fig. 4).

We are not aware of any geologic evidence for the displacement on these faults. Along the most important of them, the Altyn Tagh fault, however, restoration of about 400 km of left lateral motion would place the Altyn Tagh adjacent to the elevated Nan Shan and would leave the Tsaidam Basin open to its northwest end. Although this observation is by no means conclusive, it is also noteworthy that this fault looks at least as prominent on the ERTS photographs as the San Andreas fault in California, for which 300 km of displacement since early Miocene is well documented (*32*). Thus, we consider it likely that a total of at least 500 and perhaps 1000 km of eastward displacement of southeast China occurred on these faults.

Surface deformation associated with the great 1905 earthquakes in northern Mongolia (M = 8.7 and 8.4) and with the 1957 Gobi-Altai earthquake (M = 7.9) resulted from primarily left lateral strike-slip motion on east-west faults (*33, 34*). In contrast to these and to deformation south of this region, faulting associated with major earthquakes west of Mongolia in 1931 (M = 7.9) (*34, 35*) and in central Mongolia in 1967 (M = 7.7) (*34*) caused north-south striking surface faulting. For the latter event, the fault plane solutions show right lateral strike-slip faulting. Some of these and other parallel faults are remarkably conspicuous on the presently available ERTS coverage of western Mongolia. The deformation in Mongolia appears to result largely from conjugate faulting in response to northeast-southwest compressive stress, with the north-south faults dominating in western Mongolia but giving way further east to predominantly east-west faulting similar to that further south in China. As for the Shansi graben, the predominantly

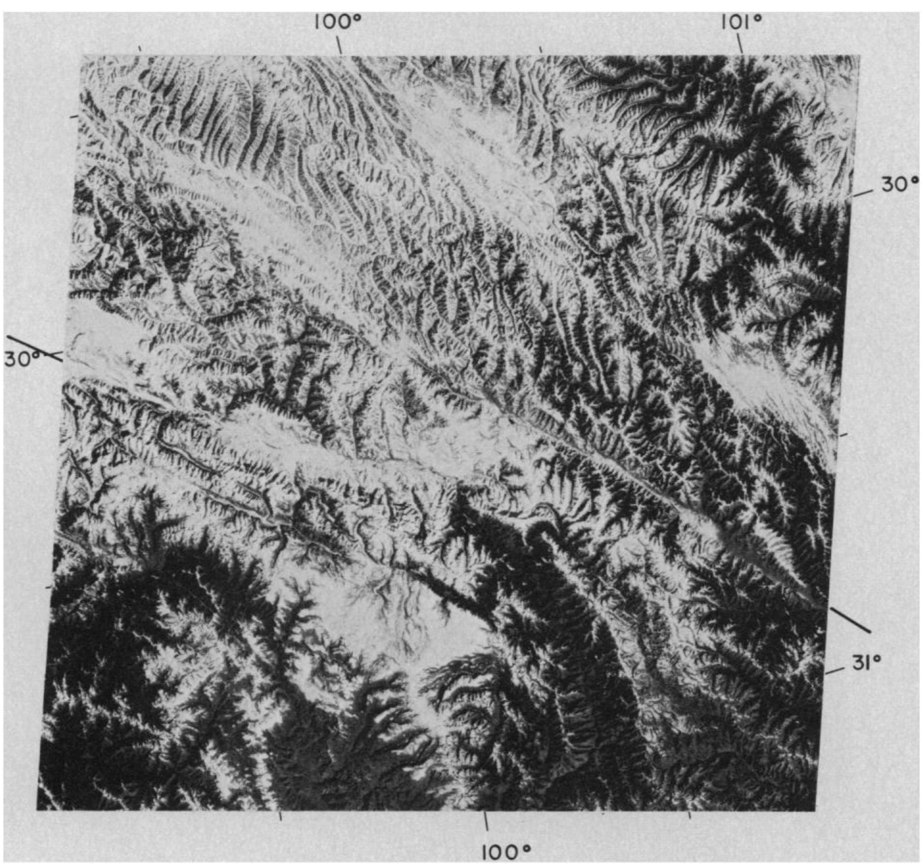


Fig. 7. Kang Ting fault. Lines on east and west edges of photograph show fault trend. Near 31.5°N, 100.0°E the fault seems to be displaced. Fault plane solutions of earthquakes on 30 August 1967 (31.57°N, 100.31°E) and 7 February 1973 (31.46°N, 100.29°E) show normal faulting with northwest-southeast T-axes. The fault plane solution for the 6 February 1973 shock (31.40°N, 100.58°E), which occurred on the Kant Ting fault, showed left lateral strike-slip motion on the fault (*6, 29*). [ERTS photograph E-1513-03214-5]

left lateral strike-slip motion on the east-west faults appears to be absorbed in the Baikal rift zone, a belt of normal faulting caused by approximately northwest-southeast extension (Figs. 3 and 4).

Implications

Much of the deformation north of the Himalayas appears to occur by strike-slip motion. We do not know when these strike-slip faults formed or started to contribute to the overall deformation of Asia, but their seismic activity and clear expression in the ERTS photographs attests to current activity. That the present relief north of the Himalayas and the basins and grabens of eastern China and in the Baikal rift zone all developed since the Eocene (*13, 14*) suggests a comparable date for the initiation or rejuvenation of strike-slip faulting. It is noteworthy that in older orogenies, such as the Hercynian orogeny in northern Africa and western Europe, huge strike-slip faults are found to play an important part even after the main folding phase (*36*). The Cabot fault through Nova Scotia and Newfoundland may be another such example, and the large-scale shearing of the Canadian and other shields discussed by Sutton and Watson (*37*) may be the result of Proterozoic continental collisions. Thus, large-scale strike-slip faulting may be a characteristic feature associated with continental collisions of all ages (*7, 38*).

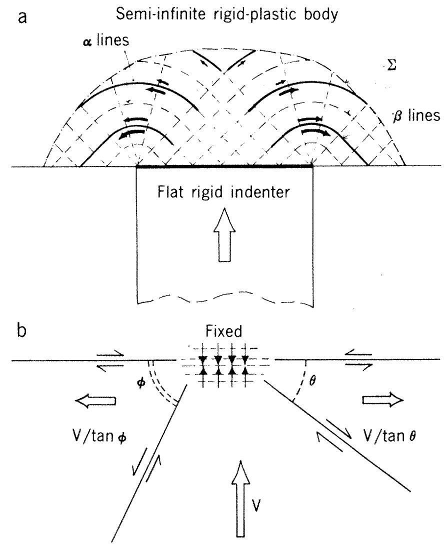


Fig. 8. (a) Slip line field and plastic region at the yield point in the indentation of a semi-infinite medium by a flat rigid die (*44*). This is a plane, nonsteady state motion problem. The symbol Σ denotes the probable plastic boundary at yield point; α and β slip lines are two orthogonal families of curves introduced as "characteristics" to solve the stress differential equations. Principal stresses bisect the small quadrangles delineated by the slip lines. Slip lines experimentally materialize as tangential displacement discontinuities in the plastic material and are shown by arrows (*45*). (b) Shortening and strike-slip faulting [modified from McKenzie (*7*)]. The top block is held fixed. Conjugate faulting allows triangular blocks to move laterally away from the impinging triangular block, at velocities proportional to the velocity (*V*) of the impinging block and depending on the orientations of the boundaries between them.

The distribution and sense of strike-slip faults in Asia bear a striking resemblance to the geometry of slip lines in the well-known plasticity problem of plane indentation (Fig. 8a). The symmetry of plane indentation may be absent in Asia because of the asymmetry of the boundary conditions. Because continental lithosphere in Eurasia provides more resistance to lateral motions than do subduction zones along the Pacific margins, the region between India and the stable parts of the Eurasia plate can move eastward more easily than westward with respect to these plates. As the Himalayas trend northwesterly and the relative plate motion is north-south, the amount of east-west motion on these faults could correspond to a comparable amount of convergence (Fig. 8b).

Thus these strike-slip faults transfer some of the convergence to regions such as the Nan Shan and Lung-Men Shan, where both fault plane solutions and the similarity of the relief observed on the ERTS photographs to that of the Himalayas imply thrust faulting and therefore crustal shortening and thickening, or to regions of normal faulting and crustal extension, such as the Baikal rift zone or the Shansi graben system. We consider the effect of strike-slip faulting on these latter zones to be grossly analogous to the development of tension cracks near the ends of and oblique to shear zones. Thus we interpret both the Baikal rift zone and Shansi graben system as manifestations of the India-Eurasia collision, and therefore driven by the forces causing the collision, not by forces directly beneath the rifts. The Rhine graben and Rough Creek–Kentucky River fault zone may have similar relationships to the Alps and the southern Appalachians.

Deformation is not uniform across Asia, and stress seems to be transmitted across some regions without deformation. Like McKenzie (*7*), we think that the transmission of stress is not necessarily due to the strength of the lithosphere but can also be due to the buoyancy of continental crust, especially if it is hot, as beneath Tibet. Although Tibet may be experiencing only minor deformation at present, because stress differences of several hundred bars are necessary to maintain its elevation in isostatic equilibrium (*39*), it can transmit horizontal compression of this amount from the Himalayas to regions further north. In fact, normal faulting with east-west T-axes in Tibet (Fig. 3) (*6, 29*) may reflect east-west flow of material in the lower crust and upper mantle beneath Tibet to compensate for the pressure imposed by the plate motion. In contrast, the Tarim Basin, which has been stable since the Precambrian (*14*), probably transmits stress to the Tien Shan because it is underlain by strong lithosphere. Further north, earthquakes and deformation then tend to occur in old zones of weakness, such as in the Tien Shan (*6*).

Hence we consider most of the large-scale tectonics of Asia to be a result of the India-Eurasia continental collision, which apparently not only created the Himalayas but also rejuvenated an old orogenic belt (Tien Shan) 1000 km north of the suture zone, caused important strike-slip faulting oblique to the suture zone and as much as 1000 km from it, and perhaps ripped open two rift systems more than 2000 km away. It is no wonder that relative motion between India and Eurasia decreased markedly at the approximate time of the collision (Figs. 1 and 2). This change in rate supports the contention that forces applied to boundaries of plates are an important component in the sum of forces that drive the plates. Nevertheless, that these plates continued to converge at a rate of about 50 mm/year and cause all of this deformation surely must place an important constraint on simple models for the driving mechanism of plate tectonics, which consider only forces equivalent to pushes from ridges and pulls by downgoing slabs.

References and Notes

1. D. P. McKenzie, *Geophys. J. R. Astron. Soc.* **18**, 1 (1969).
2. B. Isacks, J. Oliver, L. R. Sykes, *J. Geophys. Res.* **73**, 5855 (1968).
3. J. F. Dewey and J. M. Bird, *ibid.* **75**, 2625 (1970).

→ W. Hamilton, *Geol. Soc. Am. Bull.* **81**, 2553 (1970).

5. J. F. Dewey and K. C. A. Burke, *J. Geol.* **81**, 683 (1973).

→ P. Molnar, T. J. Fitch, F. T. Wu, *Earth Planet. Sci. Lett.* **19**, 101 (1973).

7. D. McKenzie, *Geophys. J. R. Astron. Soc.* **30**, 109 (1972).
8. A. Gansser, *Geology of the Himalayas* (Wiley-Interscience, New York, 1964).
9. ———, *Eclogae Geol. Helv.* **59**, 831 (1966).

→ C. M. Powell and P. A. Conaghan, *Earth Planet. Sci. Lett.* **20**, 1 (1973).

11. A. Hennig, *Southern Tibet by Sven Hedin* (Norstedt, Stockholm, 1915), vol. 5.

→ A. Sahni and V. Kumar, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **15**, 209 (1974).

13. A. V. Goryachev, *Mesozoic-Cenozoic Structure, History, Tectonic Development, and Seismicity of the Region of Lake Issyk-Kul* (Akademia Nauk, Moscow, 1959); I. E. Gubin, *Regularities of Seismic Effects in the Territory of Tadjikistan* (Akademia Nauk, Moscow, 1960); *Lecture Notes on Basic Problems in Seismotectonics* (International Institute of Seismology and Earthquake Engineering, Tokyo, 1967); A. V. Kozhevnikov, V. E. Savin, A. K. Ufland, in *Geology of the Mesozoic and Cenozoic of Western Mongolia* (Nauka, Moscow, 1970), p. 151; V. N. Krestnikov, *History of Development of Oscillating Movements of the Earth's Crust of the Pamir and Adjacent Parts of Asia* (Akademia Nauk, Moscow, 1962); N. N. Leonov, *Tectonics and Seismicity of the Pamir-Alai Zone* (Akademia Nauk, Moscow, 1961); V. V. Loskutov, in *Neotectonics and Seismotectonics of Tadjikistan* (Donish, Dushanbe, 1969), p. 35; S. A. Zakharov, in *ibid.*, p. 3; *Development of Tectonic*

Ideas in Tadjikistan and the Hypothesis of Zonal Tectogenesis (Donish, Dushanbe, 1970).
14. Chang Ta, *The Geology of China* (U.S. Department of Commerce, Washington, D.C., 1963) (translated from the original 1959 edition).
R. L. Fisher, J. G. Sclater, D. P. McKenzie, *Geol. Soc. Am. Bull.* **82**, 553 (1971); X. Le Pichon, J. Francheteau, J. Bonnin, *Plate Tectonics* (Elsevier, Amsterdam, 1973); D. McKenzie and J. G. Sclater, *Geophys. J. R. Astron. Soc.* **25**, 437 (19 W. C. Pitman III and M. Talwani, *Geol. Soc. Am. Bull.* **83**, 619 (1972).
16. C. F. Richter, *Elementary Seismology* (Freeman, San Francisco, 19 S. J. Duda, *Tectonophysics* **2**, 409 (1965).
17. T. J. Fitch, *J. Geophys. Res.* **75**, 2699 (1970).
18. M. Kono, *Geophys. J. R. Astron. Soc.* **39**, 283 (19 M. N. Qureshy, S. Venkatachalam, C. Subrahmanyan, *Geol. Soc. Am. Bull.* **85**, 921 (1974).
19. P. Evans, *J. Geol. Soc. India* **5**, 80 (1964).
20. W. P. Chen and P. Molnar, *Bull. Seismol. Soc. Am.*, in press.
21. K. Burke, J. F. Dewey, W. S. F. Kidd, *Geol. Soc. Am. Abstr. Programs* **6**, 1027 (1974); W. S. F. Kidd, abstract, *EOS Trans. Am. Geophys. Union* **56**, 453 (1975).
22. Work of Molnar with V. I. Khalturin, I. L. Nersesov, A. I. Ruzaikin, *Dokl. Acad. Sci. U.S.S.R.*, in press.
23. L. P. Vinnik and A. A. Lukk, *Izv. Earth Phys. No. 1* (1974), p. 9.
24. V. I. Ulomov, *Informational Communication 81, Institute of Seismology, Academy of Sciences of the Uzbek S.S.R.* (Fan, Tashkent, 1973); *Dynamics of the Earth's Crust and Prediction of Earthquakes* (Fan, Tashkent, 1974).
25. E. I. Shirokova, *Izv. Earth Phys. No. 1* (1967), p. 22.
26. K. I. Bogdanovich, I. M. Kark, B. Ya. Korolkov, D. I. Mushketov, "The earthquake in the northern part of the Tien Shan of 22 December 1910 (4 January 1911)," *Trans. Geol. Comm. No. 89* (1914); V. I. Kuchai, *Geol. Geophys. No. 101* (1969); I. V. Mushketov, "The earthquake of 28 May 1887 in the city Verny (Alma-Ata)," *Izv. Imp. Russ. Geogr. Surv.* **14** (No. 2), 65 (1888); *Chilik Earthquake of 30 June (12 July) 1889, Materials for the Study of Earthquakes of Russia, I* (1891).
27. I. P. Kosminskaya, N. A. Belyaevsky, I. S. Volvovsky, in *The Earth's Crust and Upper Mantle*, P. J. Hart, Ed. (American Geophysical Union, Washington, D.C., 1969), p. 195; V. I. Ulomov, *Deep Structure of the Earth's Crust in Southeast Central Asia* (Fan, Tashkent, 1966); I. S. Volvovsky, *Seismic Investigation of the Earth's Crust in the U.S.S.R.* (Nedra, Moscow, 1973).
28. V. S. Burtman, *Izv. Ser. Geol. No. 12* (1961), p. 37; in "Faults and horizontal movement of the earth's crust," *Trans. Geol. Inst. No. 80* (1963), p. 128; A. V. Pieve, S. V. Ruzhentsev, *ibid.*, p. 152; A. I. Suvorov, *ibid.*, p. 173; S. V. Ruzhentsev, *ibid.*, p. 113; "Tectonic development of the Pamir and the role of horizontal movement in the formation of their alpine structure," *Trans. Geol. Inst. No. 192* (1968); V. S. Voitovich, *Nature of the Dzungarian Deep Fault* (Nauka, Moscow, 1969).
29. P. Tapponnier, P. Molnar, F. T. Wu, T. J. Fitch, in preparation.
30. A. R. Ritsema, *Geophys. J. R. Astron. Soc.* **5**, 254 (1961).
31. A. Heim, *Bull. Geol. Soc. Am.* **45**, 1035 (1934); B. A. Bolt, *EOS Trans. Am. Geophys. Union* **55**, 108 (1974).
O. F. Huffman, *Bull. Geol. Soc. Am.* **83**, 2913 (1972).
33. N. A. Florensov and V. P. Solonenko, Eds., *The Gobi-Altai Earthquake* (Siberian Department of the U.S.S.R. Academy of Sciences, Novosibirsk, 1963); S. D. Hilko, personal communication.
34. L. Natsag-Yum, I. Balzhinnyam, D. Monkho, in *Seismic Regionalization of Ulan Bator* (Nauka, Moscow, 1971), chapter 4.
35. T. C. Kuo, personal communication.
M. Mattauer, F. Proust, P. Tapponnier, *Nature (Lond.)* **237**, 160 (19 P. Matte and F. Arthaud, *Tectonophysics* **25**, 139 (1975).
J. Sutton and J. W. Watson, *Nature (Lond.)* **247**, 433 (1974).
J. F. Dewey and K. Burke, *Geology* **2**, 57 (1974).
39. E. V. Artyushkov, *J. Geophys. Res.* **78**, 7675 (1973); F. C. Frank, in *Flow and Fracture of Rocks* (American Geophysical Union, Washington, D.C., 1972), p. 285.
40. J. R. Heirtzler, G. O. Dickson, E. M. Herron, W. C. Pitman, X. Le Pichon, *J. Geophys. Res.* **73**, 2119 (1968); J. G. Sclater, R. Jarrard, B. McGowran, S. Gartner, in *Initial Reports of the Deep Sea Drilling Project* (Government Printing Office, Washington, D.C., 1974), vol. 22, p. 381.
41. J. B. Minster, T. H. Jordan, P. Molnar, E. Haines, *Geophys. J. R. Astron. Soc.* **36**, 541 (1974); P. Molnar and J. Francheteau, *ibid.*, in press.
42. W. H. K. Lee, *Earthquakes and China: A Guide to Some Background Materials* (Preliminary open file report, U.S. Geological Survey, Menlo Park, Calif., 1974).
43. M. J. Terman, *Tectonic Map of China* (Geological Society of America, Boulder, Colo., 1974).
44. R. Hill, *The Mathematical Theory of Plasticity* (Oxford Univ. Press, London, 1950), p. 254.
45. W. A. Backofen, *Deformation Processing* (Addison-Wesley, Reading, Mass., 1972), p. 136.
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Selective Silencing of Eukaryotic DNA

A molecular basis is proposed for programmed inactivation or loss of eukaryotic DNA.

Ruth Sager and Robert Kitchin

A diverse set of developmental processes has been described in eukaryotic organisms for which no molecular mechanisms are known. These processes range from the selective (uniparental) inheritance of chloroplast (*1–4*) and mitochondrial (*5–7*) DNA's to chromosome elimination in interspecies somatic cell hybrids (*8–13*), and include the nuclear destruction that follows plasmodial fusion in *Physarum* (*13*), haploidization in barley (*14*), effects of B chromosomes in maize (*15*), heterochromatization and chromosome elimination in insects (*16–34*) and in marsupials (*35, 36*), and X-chromosome inactivation in placental mammals (*37, 38*). These phenomena have in common the selective silencing by inactivation or elimination of specific chromosomes or DNA molecules in the presence of unaffected homologs. We propose that all these phenomena are regulated by the same underlying mechanism: modification and restriction of DNA by enzymes with specificity for particular recognition sites.

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Mechanisms of Modification and Restriction of DNA

DNA modification and restriction (M-R) was discovered in bacterial systems (*39*), where it serves to degrade one DNA, usually of exogenous origin, in the presence of a second DNA, usually that of the host, which remains intact. The molecular basis of this phenomenon, now known for several different bacterial M-R systems (*40*), is the presence of specific nucleotide sequences in DNA, four to eight nucleotides in length, which are recognized by the modification and restriction enzymes. If the modification enzyme acts first, it protects the recognition site by DNA methylation from attack by the restriction enzyme, an endonuclease. If the DNA is unmodified, both strands can be endonucleolytically cleaved by the restriction enzyme at or near the recognition site. Further degradation is then carried out by less specific nucleases. Thus, the M-R system is a powerful means of eliminating particular DNA's (such as invading viral DNA's) in the presence of other DNA's (such as host DNA's) which are preserved. Restriction enzymes have exhibited exquisite precision in their nucleolytic attack on specific recognition sites in DNA, as predicted by Arber and Linn (*40*), and have been used extensively for site-specific cleavage and for sequence analysis of DNA.