Indentation tectonics in nature and experiment. 2. Central Asia.

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We review existing geophysical and geological data bearing on the Cenozoic deformation history of Central Asia since the collision of India with Asia some 50 Ma ago.

The pre-Cenozoic history is marked by the successive accretion of continental blocks and terranes, with intervening sutures reactivated in the Cenozoic.

The Central Asian Triangle is an area about 3 000 Km wide and 4 000 Km long where topography exceeds 1 Km. The long axis of the triangle trends NE from a point midway along the Himalayan arc. From estimates of Moho depth for China and adjacent regions, crustal thickness exceeds 40 Km throughout much of the Central Asian Triangle. About its long axis, there are elements of mirror symmetry, but also significant deviations. The main element of symmetry is in the NE: a long topographic trough (Gobi) is flanked by lateral strips of high land, that fall abruptly to the Chinese and Russian plains. The main deviations from symmetry are (1) the difference in elevation and width of the two lateral strips and (2) the different areal extents of the Tibetan and Pamir plateaux, partly separated by the Tarim basin. The NW lateral strip has en échelon E-W mountain ranges (Hindu Kush, Pamir, Tien Shan, Altai, Sayan) suggesting convergent left-lateral wrenching along the strip. The Central Asian Triangle has two southerly prongs, the Burmese and Suleiman ranges.

Historical and current seismicity is concentrated in the Central Asian Triangle, especially its boundary strips and southerly prongs. Currently active faults include thrusts (mainly bounding the plateaux), wrenches (mainly within the lateral strips and southerly prongs) and rifts (mainly in the northern parts of the lateral strips and in the Tibetan plateau). Fault plane solutions and seismic moments are interpreted to show that the Central Asian Triangle is moving northeastward with reference to Siberia and China, while shortening in the same overall direction.

Satellite imagery, geological maps and regional descriptions have been used to compile a map showing the traces of faults known or inferred to have been active sometime in the last 50 Ma. This map shows that the current velocity field has been active with minor modifications over the Quaternary and much of the Tertiary. The Central Asian Traingle has moved NE relative to Siberia and China, while contracting in the same direction upon major thrusts bordering and within the high plateaux. From the Gulf of Oman to Lake Baykal and beyond, the NW lateral strip is a left-lateral wrench zone, convergent in the SW, divergent in the NE. Similarly, the SE lateral strip is a right-lateral wrench zone, strongly divergent in the NE, now convergent in the SW. Much of the deformation in the wrench zones is accomplished by synthetic and antithetic strike-slip faults. Blocks between antithetic faults have rotated by a domino mechanism. A reconstructed displacement field for the last 10 Ma shows how compatibility has been maintained between the various fault blocks as they have rotated and translated rigidly, bounded by thrusts, wrenches or rifts.

Of the experimental models described in Part 1, three show major features comparable with those in Asia, especially the plateau region, and the main left-lateral wrench zone. The experiments suggest that the Cenozoic northward motion of India has been taken up by crustal thickening and by eastwards lateral escape, in roughly equal proportions, although thickening has been dominant.

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Introduction

In the first paper of this series, we reviewed existing mechanical models of continental indentation and presented our own experimental results scaled for gravity. The experiments confirm the observations made by Argand (1924), Molnar & Tapponnier (1975) and other authors since then, that indentation can result in deformation well within an indented continent. Furthermore, the experiments suggest that the relative proportions of crustal thickening and lateral escape depend primarily upon the degree of lateral confinement, but also upon other factors, such as lithospheric rheology and the relative dimensions of indenting and indented continents.

With these results in mind, we now examine geophysical and geological data on Central Asia. We have tried to take a balanced view of various kinds of data, without pretending to cover them all: the subject is vast. First, we consider the accretionary history of Central Asia and India. Second, to obtain some idea of crustal thickening, we follow England (1982) in examining current topography; but we also discuss available estimates of Moho depths. Third, we turn to current seismicity and active faulting for a view of the present day velocity field. Fourth, we examine faults known or inferred to have been active sometime in the last 50 Ma, with a view especially to detecting lateral escape.

With these data at hand, we attempt to reconstruct the displacement field within Central Asia for the last 10 Ma. Finally, we compare the data and our reconstruction with the experiments described in Part 1.

Acceretionary history of Central Asia and India

During Cenozoic indentation by India, Central and Eastern Asia already consisted of a mosaic of blocks and intervening sutures accreted during the Paleozoic and Mesozoic. The blocks probably had differing resistances to deformation. Hence, their distribution may be important for understanding the Cenozoic deformation history.

During the Appalachian-Hercynian-Uralian orogeny, Africa, Central Europe, the Russian platform and the Kazakhstan block, became welded together (Ziegler et al. 1979). China now consists of three main Precambrian blocks, the Sino-Korean (North China) block, the Yangtze (South China) block and the Tarim block (Zhang et al. 1984). On the basis of tectonic, stratigraphic and paleontological data, the Sino-Korean and Tarim blocks appear to have coalesced with the Siberian platform by the Permian. Recent paleomagnetic results for the Tarim block confirm this conclusion (Bai et al. 1987). In contrast, paleomagnetic data suggest that Mongolia was part of the Sino-Korean block in the Permian, but that this composite block had not yet coalesced with the Siberian platform at that time, although it certainly had done so by the Cretaceous (Pruner 1987). The Yangtze block appears to have been isolated at low latitudes until the Mesozoic (Opdyke et al. 1987).

The Tibetan plateau, along the Golmud-Lhasa traverse, appears to be made of three micro-continental fragments, the Kunlun, Qiangtang and Lhasa terranes, separated by the Jinsha and Banggong sutures (Chang et al. 1986). Lower Carboniferous fauna in the Kunlun terrane is of Laurasian affinity and so accretion may have occurred earlier than for the Tarim block. In the Qiangtang terrane, Permian flora are of Cathaysian affinity. Rifting and separation from Gondwana probably occurred before the Permian, followed by collision with the Kunlun in the late Triassic to early Jurassic. Finally, fauna and a possible glaciomarine mixtite suggest a Gondwanian origin for the Lhasa terrane. Rifting and separation from Gondwana probably occurred in the Triassic, followed by collision with the Qiangtang terrane in the Jurassic.

In the NW Himalayas, Afghanistan and Pamirs, there are also several sutures separating accreted terranes (Tapponnier et al. 1981a, Coward et al. 1986). The southernmost terrane in the NW Himalaya is the Kohistan-Ladakh island arc, generated in the Cretaceous. South of this is the Indian plate itself.

The Indian and Asiatic plates currently meet in the Himalayas at the Indus-Tsangpo suture. South of this, the Main Central Thrust and other subsidiary thrusts have caused a thickening of the Indian crust (Seeber et al. 1981, Coward et al. 1986, Mattauer 1986). The Indian plate collided with Asia some 50 Ma ago. Since then it has moved northward some 2 500 Km at an average rate of about 50 mm per year (Molnar & Tapponnier 1975, Minster & Jordan 1978) and has also rotated counterclockwise some 20° or so (Klootwijk et al. 1985, Patriat & Achache 1984).

Current topography and crustal thickness

Current distributions of crustal thickness provide excellent indications as to where and how vertical tectonic movements have outpaced erosion and sedimentation. This is especially so in Central Asia, where deformation has been relatively rapid over the past 50 Ma and current slip rates on active faults are unusually large. The value of examining elevation has been recognized in this context by England (1982) and England & Houseman (1986). For comparison with viscous numerical models, England (1982) used a topographic map of Asia smoothed by regional averaging in quadrangles 1°×1° square. For comparison with our own experimental models and

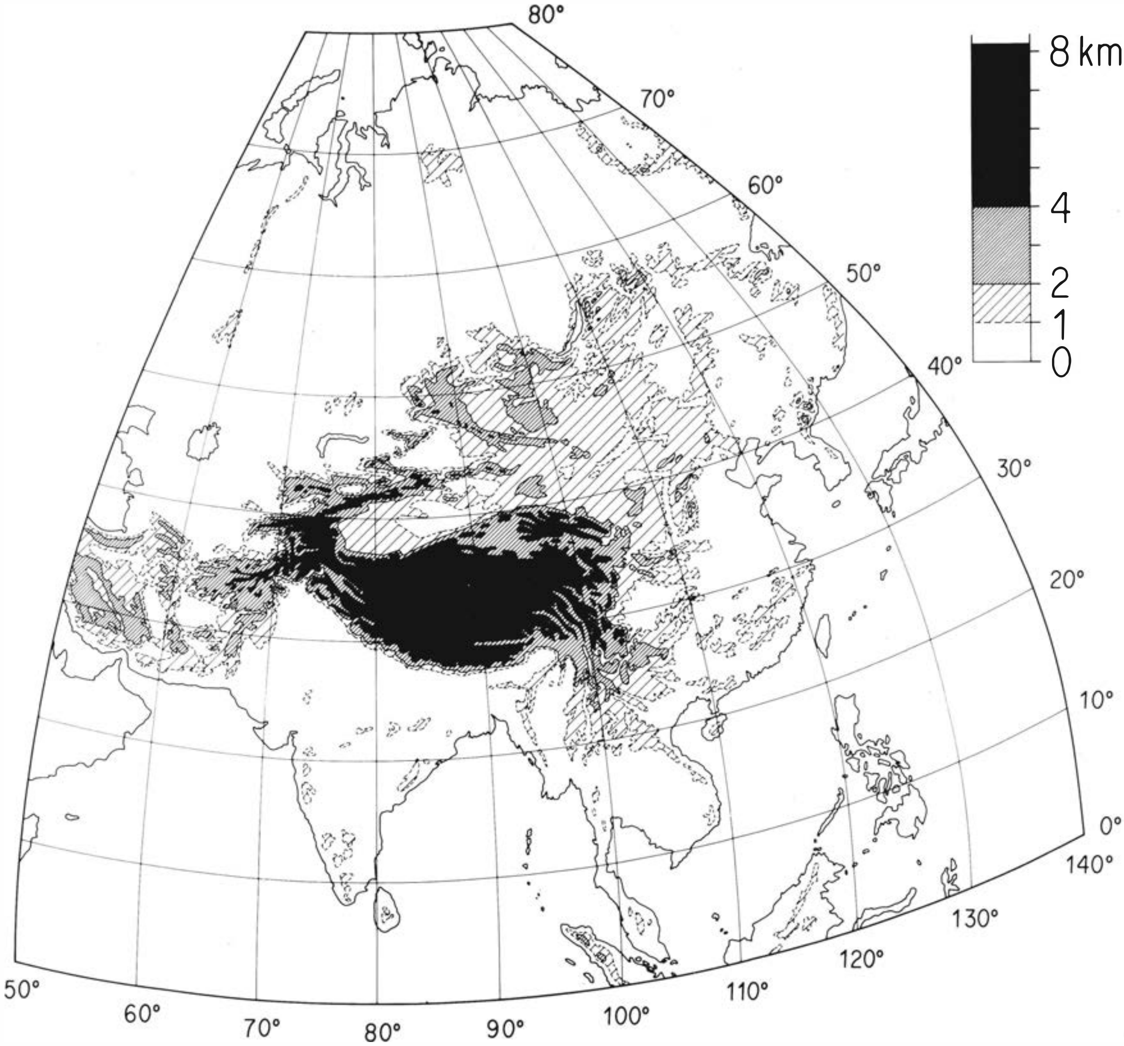

Fig. 1. Current topography, contoured in Km (see key). Bonne projection (modified conic).

to help identify major faults, we prefer less smoothing (Fig. 1).

Estimates of crustal thickness have been made for various parts of Asia, on the basis of gravity data and wide-angle seismic refraction. A map of Moho topography is thus available for China (Yuan et al. 1986). Sparser data have been consulted for specific areas within and outside China, notably Tibet (Chen & Molnar 1981, Romanowicz 1982, Molnar & Chen 1984, Hirn et al. 1984a, 1984b, Lyon-Caen & Molnar 1983, 1984, Jobert et al. 1985, Lyon-Caen 1986), the Tien Shan (Volvoskii 1973) and the Himalaya-Pamir-Hindu Kush region (Kaila 1981).

All these data indicate that surface topography exceeds 1 Km and crustal thickness probably exceeds 40 Km throughout almost all of a roughly triangular area, about 3 000 Km wide and 4 000 Km long, whose long axis trends NE-SW. This area we refer to as the Central Asian Triangle. We now examine in more detail the distribution of topography and estimated crustal thickness, paying attention to its overall location, shape and symmetry, as well as to the distribution of local features, such as plateaux, basins and ranges.

Continental India is a flat area of normal elevation (0–1 Km) and crustal thickness (less than 40 Km) (Kaila 1982). Immediately to the North is the Himalayan arc (between 72°E, 36°N and 97°E, 28°N), where topography rises from near sea-level to peaks over 6 Km high in a distance of only about 100 Km. Further North again are two high (over 4 Km) plateaux, the large Tibetan plateau in the East and the smaller Pamir plateau to the West (about 73°E, 38°N). The location of the Himalaya and of these two plateaux immediately to the North of India is evidence for continental thickening resulting from northward motion of India. So too is the position and width of the remainder of the Central Asian Triangle. This area is roughly symmetric about an axis running NE-SW through the centre of the Himalayan arc; but we draw attention to an element of asymmetry that may be significant. Running along the NW margin of the Triangle is a strip about 400 Km wide, marked by a series of mountain ranges. The major ones, including the Hindu Kush (35°N), the northern Pamir (39°N), the Tien Shan (43°N) and the Altai (48°N), typically reach heights of about 4 Km and are about 100 Km wide at 2 Km elevation. Roughly speaking, they trend E-W and are spaced en-échelon at 500 Km intervals. Each range is underlain by thick crust, decreasing from about 70 Km in the Pamirs to about 50 Km in the Altai. Between the ranges are intermontane basins where topography and crustal thickness are almost normal. If these mountain ranges indicate crustal thickening, their en-échelon distribution suggests convergent left-lateral wrenching along the NW margin of the Central Asian Traingle. To examine this possibility is one of the main objects of this paper.

In contrast, the SE margin of the triangle (between 28°N and 33°N) shows no such mountain ranges distributed en-échelon at that scale. Instead the Tibetan plateau drops to the Chinese plain along a relatively straight margin, broken only in the South by the ranges of SE Asia. These and the intervening river valleys (Irawaddy, Salween, Mekong, Red, Yangzi) are closely spaced (about every 50 Km), trend NW-SE in arcuate fashion, and, in fact, follow major faults and lithological boundaries distributed en-échelon with respect to the SE margin. They will be discussed later. Further North, the SE margin of the triangle reaches heights of about 2 Km.

Thus both lateral margins of the Central Asian Triangle are marked by local topographic highs, reaching 4 Km or more in the NW, but only 2 Km or so in the SE. Between them, along the central axis N of the Tibetan plateau, is the Gobi trough, about 1 500 Km long and 1 Km in elevation (between 102°E, 42°N and 115°E, 47°N). There are also two major intermontane basins: at 82°E, 40°N, the Tarim basin (separating Tibet from the Tien Shan), where elevation and crustal thickness are only slightly larger than normal; and at 86°E, 46°N the Dzhungarian basin (separating the Altai from the eastern Tien Shan), where elevation and crustal thickness are about normal.

Finally, we notice that on both sides of India are mountainous strips: to the W, the Hindu Kush and Suleiman ranges (about 68°E); to the E, the Indo-burman ranges (about 93°E). These southerly prongs of the Central Asian Rectangle show, once again, a certain symmetry, although the western prong is higher and wider than the eastern prong.

To summarise, the pattern of topography shows major elements of mirror symmetry about an axis running NE-SW; but there are also significant departures, especially the distribution of major plateaux and basins and the difference in elevation between NW and SE margins of the Central Asian Triangle.

Current seismicity, faulting and velocity field

By current seismicity, we mean what is in the historical records. For most of Asia, such records cover the last hundred years or so, which is small compared with the recurrence times of earthquakes on individual faults. Hence, the available data are not really sufficient to give us a balanced view of current acitivity (Molnar & Deng 1984). They are of course even less likely to reflect what has happened for the last 50 Ma and cannot be extrapolated backwards over such a period with much confidence.

There are many ways of examining current seismicity. One of the simplest is to locate epicentres geographically (Fig. 2). Clearly the seismicity on land is more diffuse than it is at mid-ocean ridges or at subduction zones. On the other hand, it is virtually restricted to the Central Asian Triangle, expecially the boundary strips, the Tibetan plateau and the southerly prongs. This suggests that the Triangle is undergoing internal deformation by slip on a multitude of faults, whereas the surrounding areas are not. The concentration of epicentres in the boundary strips suggests that relative motion, between the deforming Triangle and the surrounding rigid areas to NW and SW, is concentrated in the boundary strips.

Fault traces

Satellite imagery has been of great help in locating the traces of faults active currently and in the Quaternary (Molnar & Tapponnier 1975, 1977, 1978, Tapponnier & Molnar 1976, 1977, 1979). Major active faults are concentrated in the boundary strips of the Central Asian Triangle, on its southerly prongs and around the Tibetan plateau (Fig. 2). The frontal Himalayan thrusts currently consume the northern margin of the Indian continent. Other ma-

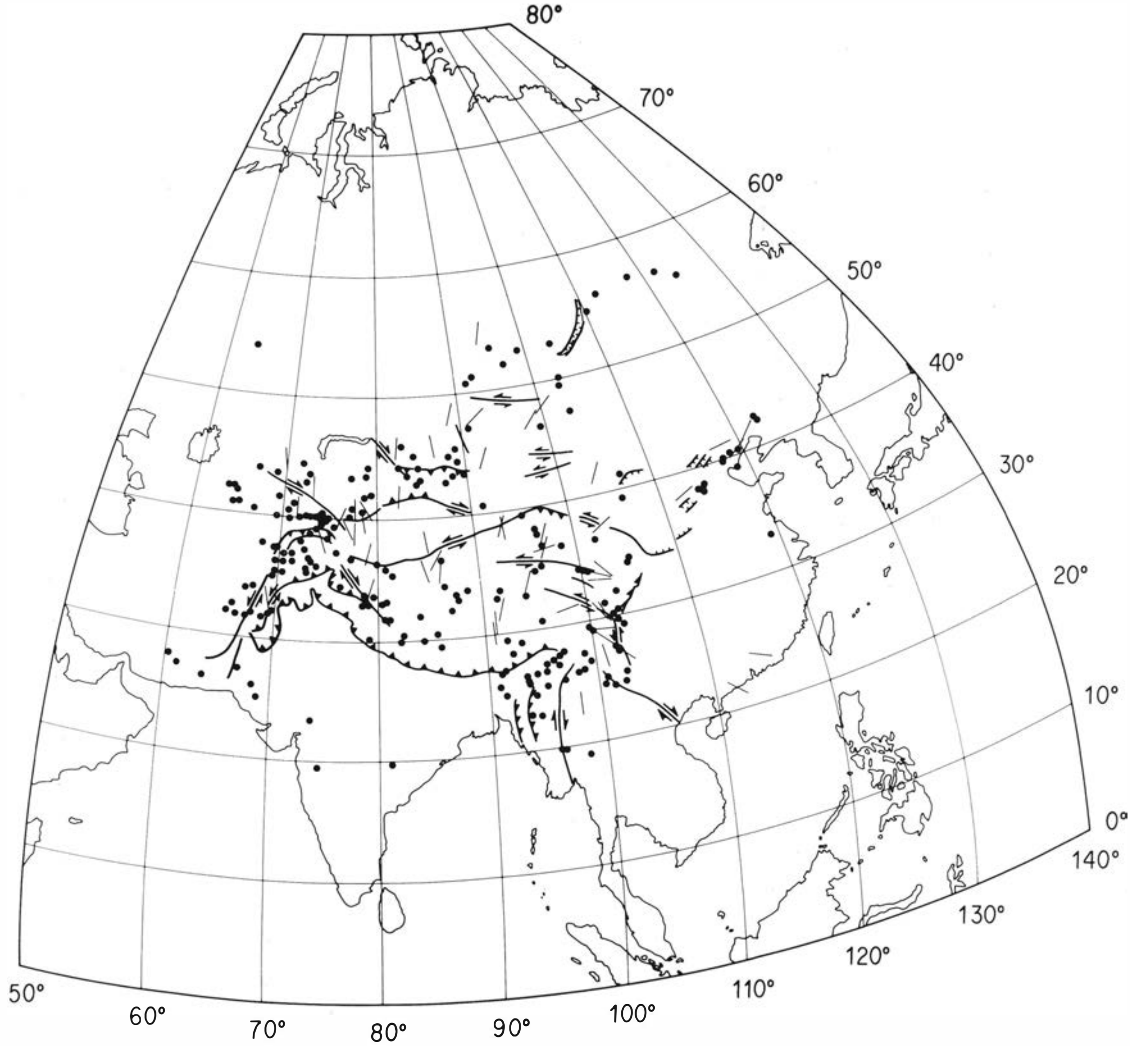

Fig. 2. Current sesmicity and principal active faults. Black dots indicate epicentres of earthquakes reported by at least 50 stations in the period 1961–1977 (after England 1982). Bars are P-axes from fault-plane solutions, where such axes are nearly horizontal (after England & Houseman 1986). Thick lines are fault traces (mainly after Molnar & Deng 1984). Faults are classified as strike-slip (pairs of arrows showing senses of slip); reverse faults or thrusts (black triangles pointing in underthrusting direction); or normal faults and rifts (ticks on downthrown side). Bonne projection (modified conic).

jor thrusts are active in the Pamirs, Tien Shan, northern edge of the Tibetan plateau and southerly prongs (Suleiman and Indoburman ranges). Normal faults are active in the Baykal region (108°E, 53°N); in China between Shansi (110°E, 38°N) and the coast; and within the Tibetan plateau. Elsewhere, wrench faults appear to dominate. Although we agree with England & Houseman (1986) that satellite imagery probably favours recognition of wrench faults and normal faults, rather than thrust faults, there is no doubt that wrench faulting is currently of great importance in Central Asia. We do notice however that wrench faults are not distributed evenly across Central Aisa, as one might expect from the theory of slip-line fields; rather they are concentrated in the boundary strips previously mentioned. We will discuss this observation later.

Fault-plane solutions

Seismic data and information on fault orientations have been used to obtain fault-plane solutions in Central Asia and China (Molnar & Tapponnier 1975, 1977, 1978, Tapponnier & Molnar 1977, 1979,

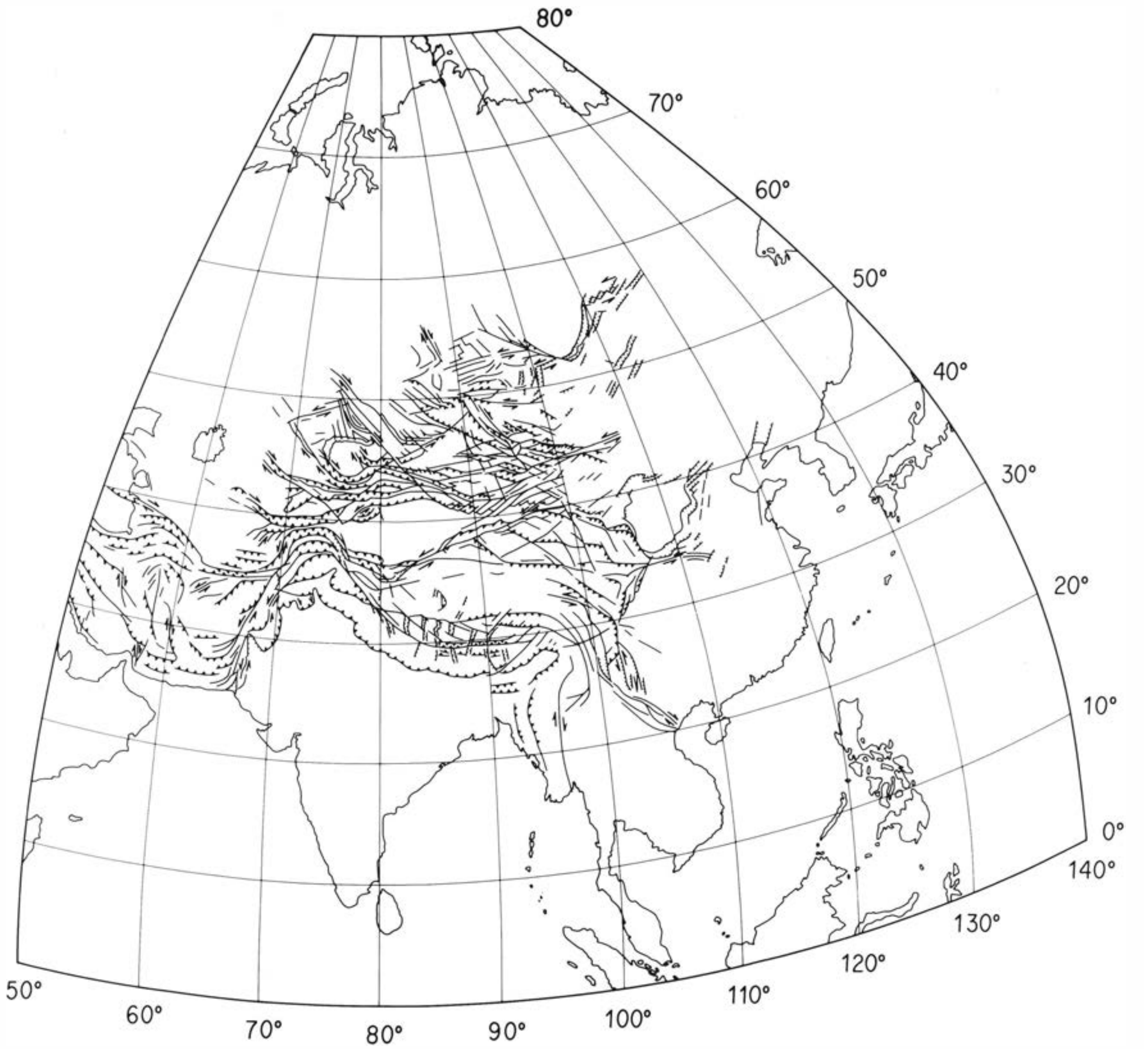

Fig. 3. Faults active sometime in the last 50 Ma. Same fault symbols as in Fig. 2. Sources of data given in text. Bonne projection (modified conic).

Molnar & Chen 1982, 1983, Le Dain et al. 1984, Baranowski et al. 1984). The solutions confirm the satellite observations that NS or NE-SW thrusting is common in the Central Asian Triangle, especially near its base; wrench faulting is common throughout, especially near the lateral boundaries; whereas normal faulting predominates near the apex, in the plains of eastern China and in Tibet. Leaving aside the normal faults, it is possible to plot on a map the trend of the nearly horizontal P-axes obtained from fault-plane solutions of individual thrusts, reverse faults and wrench faults (Fig. 2). As noted by Molnar et al. (1973), these axes are nearly NE-SW along the centre line of the Central Asian Triangle and therefore parallel to it; NS on its northwestern flank, EW on its southeastern flank. Thus they show a degree of symmetry about the centre line. We cannot agree with England & Houseman (1986) that the P directions lie everywhere parallel to the steepest gradients of crustal thickness and topography, except if we exclude strike-slip faults.

Current velocity field

So far, direct measurements of current velocities in Central Asia have not been made, but estimates of velocity gradients have been obtained using earthquake data. Molnar & Deng (1984) considered a number of subareas and made an inventory of all large earthquakes known to have occurred in the last 80 years. Using fully asymmetric moment tensors (Molnar 1983), they calculated an average velocity gradient due to fault slip in each subarea. Such an asymmetric tensor can be expressed as the sum of a symmetric tensor (the stretching) and an orthogonal tensor (the spin). The principal directions of the stretching tensor are weighted averages of P,T axes determined for individual faults. Hence the principal directions of stretching, calculated for Central Asia by England & Houseman (1986), using the data of Molnar & Deng (1984), have a similar distribution to that of P axes for individual earthquakes (Fig. 2) and we do not reproduce them here. The spin tensor obtained from an asymmetric moment tensor expresses the rate of rigid rotation (vorticity) associated with fault slip. We call this spin the internal spin. The internal spin is a maximum if there is only one family of spaced parallel faults in a given subarea; it is zero, if there are conjugate families with equal activities. In addition to the internal spin, obtainable from seismic data, there may be an external spin, due to rigid rotation of the entire subarea, including faults and fault blocks, with respect to some external reference frame. The external spin may have great importance in some situations. For example, in a domino mechanism, external spin is greater than internal spin and of opposite sense (see Jackson & McKenzie 1983). How can an external spin be measured or estimated? For rotations about vertical axes, one way is by paleomagnetic studies, but these are lacking for Central Asia. Another indirect way is via the compatibility equations for velocity gradients, which express certain requirements of material continuity. Thus slip on faults should not lead to the appearance of unwarranted gaps or overlaps between fault blocks. A study of the velocity field in Central Asia using these principles is currently underway and will not be described here. We wish to point out however that when these principles are applied to marginal strips on the NW and SW margins of the Central Asian Triangle, they lead to results not mentioned by Molnar & Deng (1984). The stable platforms (Chinese and Russian) outside these strips are currently almost aseismic. Hence components of simple shear upon antithetic NW-SE strike-slip faults (left-lateral in the SE strip, right-lateral in the NW strip) cannot occur without leading to external spins by a domino mechanism. In other words, the marginal strips include components of shear (right-lateral in the SE, left-lateral in the NW) which allow the axial parts of the Central Asian Triangle to advance towards the NE, relative to China and Russia, while contracting in the same direction. The motion is thus similar to that observed for plateau regions in front of indenters in the experimental models previously described (Part 1), as well as in numerical models (Houseman & England 1986).

Faults active sometime in the last 50 Ma

Just as currently active faults provide a good indication of how indentation is proceeding, so we believe that faults known to have been active sometime in the last 50 Ma reveal how indentation has accumulated since collision. We have therefore compiled a map showing such faults (Fig. 3). Our Cenozoic fault map is provisional and also somewhat schematic at the scale of Central Asia. Further work will probably reveal many faults that we have omitted, because of lack of data, or because of our unfamiliarity with existing data. In particular, we admit great ignorance of the Russian and Chinese languages, in which many key papers have been written.

Our principal sources of data are geological and tectonic maps of Asia (Academia Sinica 1971, 1975, Akademiya Nauk 1964, 1973, U.S. Geological Survey 1967, Terman 1974, Ministry of Geology 1980, Li et al. 1982, Zhang 1983). Satellite photographs and mosaics have been published, together with very useful references to regional geological descriptions, by Tapponnier & Molnar (1977, 1979), Molnar & Tapponnier (1978), Gallagher (1981), Le Dain et al. (1984) and Armijo et al. (1986). We have consulted the pioneering descriptions of Argand (1924), Berkey & Morris (1927) and Norin (1937, 1941, 1946), as well as more recent geological descriptions in English (Chang 1959, Gansser 1964, 1980, Wellman 1966, Florensov 1969, Burtman 1975, Curray et al. 1978, Logachev & Florensov 1978, Ni 1978, Sherman 1978, Trifonov 1978, Ni & York 1978, Lawrence & Yeats 1979, Desio 1979, Sarwar & De Jong 1979, Kravchenko 1979, Bally et al. 1980, Lawrence et al. 1981, Mitchell 1981, Burg et al. 1983, Zhang et al. 1984, Allègre et al. 1984, Coward et al. 1986, Chang et al. 1986, Tapponnier et al. 1986, Molnar et al. 1987a, 1987b).

The regional descriptions reveal that many faults, especially those in the Hindu Kush-Baykal strip, have a long history of activity, starting in Paleozoic or Mesozoic times and continuing through part or all of the Cenozoic. In some instances, we have found no reference to documented Cenozoic activity, but we have inferred it on the basis of pronounced differential relief across given fault traces. Some of our inferences have been verified during the revision stages of this paper (Molnar et al. 1987a, 1987b).

The Cenozoic fault map (Fig. 3) distinguishes between reverse, normal, strike-slip and oblique faults, but not between major and minor faults. Furthermore, no attempts have been made to classify faults according to when they were active during the Cenozoic time span.

The Cenozoic fault map shows many faults concentrated in the Central Asian Triangle, with the exception of the Tarim basin and Central Tibet. The Tarim area, with its Precambrian basement, may have undergone little Cenozoic deformation; much of it is in any case covered by recent sediments. Central Tibet is insufficiently explored and also covered in part by sediments. Elsewhere, the fault density may be sufficient to warrant a continuum description for some purposes (see England 1982); but we prefer a more detailed description in terms of fauls and fault blocks, for better comparison, either with other geological and geophysical data, or with scaled experiments.

The Cenozoic fault map (Fig. 3) shows a spatial distribution of reverse faults, normal faults and strike-slip faults that is broadly similar to that for currently active faults (Fig. 2); except of course that less faults are active now. In particular, Cenozoic thrusts and reverse faults occur at the bases of almost every mountain range that exceedss 2 000 m in elevation (Fig. 1), with the exception of the southern Sayan (near Lake Baykal) and the Hangayn Nuruu in Mongolia (100°E, 48°N). The reverse faults mostly dip towards the centres of the ranges, which therefore form pop-up structures at exposure.

We now outline major features of the fault network in Central Asia, area by area, and make local interpretations in terms of finite deformation.

SW boundary (base) of triangle (Himalaya)

The well-known frontal thrusts of the Himalaya (Main Boundary Thrust and Main Central Thrust) are northerly dipping at exposure and have arcuate traces parallel to the mountain front (Gansser 1964). The Main Central Thrust was apparently active 20 Ma ago (see Allègre et al. 1984), but current motion is mainly on the Main Boundary Thrust, or between the two thrusts. Fault-plane solutions indicate current thrusting on surfaces dipping northwards, or reverse faulting on surfaces dipping steeply southwards (see summary by Molnar & Chen 1982, Baranowski et al. 1984). The former better fits the surface geology. The inference is that the Indian plate underthrusts the Himalaya at least to depths of 10–20 Km, where most epicentres lie. The direction of underthrusting varies, from NE in the NW Himalaya, to NNW in the E. Himalaya: thus it is roughly radial with respect to the Himalayan arc. The current rate of convergence across the Himalaya is estimated to be 15 ± 5 mm a^{-1} (Lyon-Caen & Molnar 1985). Radial convergence at this rate implies an arc-parallel extension of about 10 ± 3 mm a^{-1} in the hangingwall, if only the hanging wall deforms. This is compatible with the estimated rate of about 10 ± 6 mm a^{-1} of E-W extension in Tibet (Armijo et al. 1986).

The current velocity field seems to have operated in the Himalaya over much of the Cenozoic as well. In the Greater Himalaya, north of the Main Central Thrust, Indian crustal material is about double normal thickness (Hirn et al. 1984a), notwithstanding considerable erosion and probable arc-parallel extension as well. Hence there may be as much as 750 Km–1 000 Km of convergence accumulated across the Himalaya in the last 50 Ma.

The curvature of the Himalaya and the associated radial motion probably have a long Cenozoic history. Paleomagnetic vectors around the arc have been rotated perhaps as much as 55° out of initial parallelism (Klootwijk et al. 1985), indicating oroclinal bending. This rotation appears to have accumulated since the Miocene.

SW prong (Pakistan)

Near the margin of India, the Chaman fault, a left-lateral wrench, runs NNE from the Gulf of Oman (67°E, 26°N) to Kabul (69°E, 35°N) (Lawrence & Yeats 1979, Lawrence et al. 1981). The minimum displacement on this fault is estimated to be 200 Km. On the Indian side is a festoon of arcuate thrust and fold belts, separated by lateral wrenches and Tertiary rift basins (Sarwar & De Jong 1979, Seeber & Armbruster 1979). Overthrusting has been towards the SSE, with some extension at right angles indicated by the rift basins. On the Asian side of the Chaman fault, a series of northerly dipping thrusts can be traced eastwards until they curve into the Chaman fault itself (Lawrence et al. 1981). All these features indicate a left-lateral wrench zone that is convergent, in the sense that there has been some contraction across it.

Further north, the western Hindu Kush is an area where elevation reaches 4 Km. The left-lateral Chaman fault intersects EW right-lateral strike-slip faults in the Kabul area. Triangular fault blocks at restraining and releasing intersections are visible on geological maps (e.g. Academia Sinica 1975). From these we deduce a finite contraction direction that is NW-SE and a horizontal NE-SW extension direction, as well as crustal thickening due to motion on reverse or oblique faults. These bulk strains are compatible with left-lateral shear along the W margin of India.

Presumably the SW prong has registered something like 2 500 Km of left-lateral displacement in the last 50 Ma, although the field evidence for such a displacement magnitude does not seem clear to us.

SW corner of Triangle (Pamirs)

In the region of the Karakorum-Pamirs (72°E, 37°N) is a remarkable crustal structure, the Pamir plateau, where elevation reaches 6 Km and crustal thickness is estimated to be 75–80 Km (Kaila 1981). Except in the northern Pamirs, the plateau is bounded by the right-lateral Karakorum wrench fault to the E (with some 200 Km of Cenozoic displacement) and a left-lateral wrench zone to the W. Within the plateau is a series of arcuate thrusts and high-angle reverse faults, some dipping N, others S (Desio 1979, Kravchenko 1979). Individual ranges seem to be pop-ups between conjugate reverse faults or thrusts. The current elevation of the plateau is attributable to Cenozoic motions on these faults, mainly since the Oligocene. Basement rocks, Paleozoic and older, are exposed on the plateau, indicating considerable erosion. The direction of finite contraction (estimated at 300–400 Km in the Karakorum) is almost N-S (Coward et al. 1986), but some E-W extension is responsible for the narrow Mustagh Ata rift valley at the northern end of the Karakorum fault (76°E, 38°N).

Many faults in the Pamir plateau are currently active. Small earthquakes are widespread in the area, fault-plane solutions indicating a mixture of thrust, strike-slip and normal faulting (see review by Molnar & Chen 1982). In general, the P axes are about N-S. Activity seems to be greatest at the southern edge of the plateau, where the Indian plate is subducted northwards, and at the northern edge, where there is southward underthrusting of the Kazakhstan foreland. The presence of inclined zones of intermediate-depth seismicity (150–300 Km) suggests that there has been subduction of mantle lithosphere.

Both the current activity and the finite bulk strains are compatible with regional left-lateral NE-SW wrenching, or with regional right-lateral NW-SE wrenching. The former seems more likely, if only to ensure continuity with the SW prong.

NW boundary strip (Tien Shan-Baykal)

Along this strip, the various mountain ranges already mentioned (Northern Pamirs, Northern and Southern Tien Shan and Altai) are basically crustal pop-ups between conjugate reverse faults, but strike-slip faults are also present, more rarely in the south (Tien Shan), more frequently in the north (Altai). Aspects of the active tectonics, but also of the Cenozoic tectonics, have been reviewed by Tapponnier and Molnar (1979) and Molnar and Chen (1982).

In the Tien Shan (42°N), the general EW trend and most of the current topography and elevation can be attributed to Cenozoic reverse faulting and shortening in a NS direction (Krestnikov 1982). High-angle reverse faulting affects the basement, which is currently at exposure in many areas, indicating considerable erosion. Folding and thrusting of Cenozoic age are common within Paleozoic, Mesozoic and Cenozoic sediments. Currently there is a high level of seismicity and most fault-plane solutions show thrust or reverse faulting with P-axes oriented nearly N-S. Dips of fault planes are mostly steep (30°–60°). The Tien Shan is not, however simply a linear fold and thrust belt. Segments of ranges intersect one another obliquely, enclosing almond-shaped intermontane basins. This structure results from strike-slip and oblique faulting. Most prominent are right-lateral strike-slip faults trending NW-SE, including the well-known Talasso-Fergana fault (72°E, 42°N) for which Cenozoic displacement may total several tens of kilometers and the Dzhungarian fault (83°E, 43°N) with about 7 Km displacement since the Pliocene. However there are also left-lateral faults trending ENE-SSW, such as the active Tchonkemina fault (77°E, 43°N). Some of the high-angle reverse faults seem to have registered components of left-lateral strike-slip, an example being the Kuruk Tagh fault system (87°E, 41°N). At their western extremities, the northern Pamirs and the Tien Shan ranges bifurcate into conjugate fault systems, trending NW-SE and NE-SW. The motions on these have been dominantly strike-slip (indicating NS contraction and EW extension).

In the Altai and Gobi-Altai, strike-slip faulting seems to have been dominant in the Cenozoic, although clear thrusts, high angle reverse faults and oblique faults also occur (notably in the Barkol Tagh, 94°E, 43°N). Of the strike-slip faults, left-lateral ones trending about NW-SE seem to dominate in the Altai (90°E, 48°N), whereas right-lateral ones trending ENE-SSW (including the active Bogdo fault) dominate in the Gobi Altai (100°E, 45°N). These two families intersect at about 94°E, 46°N, with spectacular thrusts in the restraining quadrants. The finite contraction direction is NNE-SSW. The elevation of the Altai (about 3 Km) is probably mainly due to Cenozoic crustal thickening, resulting from reverse faulting and oblique components on the main left-lateral wrench faults.

In contrast, the uniform elevation (about 3 Km) of the Hangayn massif (100°E, 48°N) is not obviously due to Cenozoic crustal thickening. Some thrusts, some strike slip faults and some normal faults of Cenozoic age exist within the massif. To the north, the right-lateral Hangayn fault (48°N) trends EW for about 500 Km. Further north still the Sayan (51°N) appears to show less Cenozoic deformation, although some Paleozoic faults appear to be reactivated, mainly as strike-slip faults, but with some high-angle reverse motions. At its NE edge, the Sayan drops from about 2 Km elevation to less than 500 m in the Siberian plain W of Lake Baykal. We infer a component of reverse faulting at this edge.

Between 98°E and 120°E, normal faulting predominates. Here is the Baykal rift system, conveniently considered as 3 segments. From SW to NE, these are the Hövsgol and Upper Yenisei Graben (around 100°E, 50°N), the Baykal and Barguzin graben (around 108°E, 54°N) and the Muya-Udokan en-échelon graben (56°N). The first two are linked by the left-lateral Tunka transform fault (52°N), which has some 11 Km of Neogene-Quaternary displacement. The Baykal rift system started to form in the late Oligocene, or possibly earlier (Florensov 1969), accompanied by trachy-basaltic vulcanism; but the main normal faulting appears to be Pliocene and Quaternary. Currently, the rift system shows more seismic activity than either the East African rift system or the Rhine-graben. Strike-slip faulting, mainly left-lateral on EW planes, is subordinate to NE-SW normal faulting. Since the Oligocene, basement rocks are offset by as much as 7 Km on major normal faults bounding southern Lake Baykal (Florensov 1969). The lake itself is the deepest in the world (up to 1 620 m). Southeast of Lake Baykal, northeast trending graben (110°E, 50°N) are not currently active, but apparently formed in the Cenozoic.

SE prong (Burma)

The active tectonics of this area is compatible with northward motion of India (Le Dain et al. 1984). Much of this motion appears to be concentrated on the Sagaing-Andaman Sea-Sumatran fault system (96°E). Fault plane solutions indicate right-lateral slip. Curray et al. (1978) and Mitchell (1981) have estimated some 460 Km of cumulative right-lateral slip. Molnar and Deng (1984) estimate a current slip rate of several cm a^{-1}.

In the Andaman arc, fault-plane solutions imply a moderate eastward subducting of the India plate. Similar underthrusting has occurred in the Indoburman ranges, apparently since the Late Cretaceous, although the major period of folding and thrusting was Oligocene-Miocene. Quaternary and recent folding has also occurred. For earthquakes of intermediate depth, foci are distributed along a single inclined zone dipping about 45°E, but P axes of fault-plane solutions are mostly parallel to strike (NS to NNE-SSW). Shallow earthquakes have similar P axes and indicate strike-slip.

In the Eastern Highlands of Burma, fault-plane solutions also indicate NS compression, but Tertiary folding and faulting suggest EW shortening (Le Dain et al. 1984, Tapponnier et al. 1986).

Hence the current tectonics of Burma are compatible with northward motion of the Indian plate, whereas the Tertiary tectonics seem to indicate EW shortening and convergence between India and Indochina. For Tapponnier et al. (1986), the Tertiary record involved a southeastwards extrusion of SE Asia, but direct evidence for this seems to be lacking.

SE Corner (Assam-Yunnan)

The Cenozoic tectonics of this area are not well understood, partly because they are complex, partly because of problems with exposure and access. The current tectonics are clearer (Tapponnier & Molnar 1977, Le Dain et al. 1984). In Assam, the eastern end of the Himalaya trends ENE-WSW and fault-plane solutions indicate nearly NS thrusting. At the northern end of the Indoburman ranges, current shortening is also NS, but extension is EW. Further E, in Yunnan, the major 900 Km long Red River fault (105°E, 22°N) trends NW-SW. Right-lateral Quaternary displacements accumulated at about 2–5 mm a^{-1} (Allen et al. 1984). To the N of the Red River fault are the NS rifts of Yunnan (103°E, 25°N), filled with Quaternary sediments. Fault-plane solutions for the area and seismic moments indicate NS shortening, some crustal thinning and some EW extension. Thus the entire SE corner currently suffers NS shortening and has probably done so throughout the Quaternary.

We do not feel that current knowledge enbles us to say much about Tertiary motions in this area. Tapponnier et al. (1982, 1986) have suggested that the Red River fault was left-lateral during the Tertiary, but the evidence for this does not seem conclusive.

SE boundary (Sichuan to North China basin)

From eastern Tibet to western Sichuan (30°N), geological maps (Ministry of Geology 1980, Academia Sinica 1975) show a series of concentric, highly arcuate faults and intervening fold belts that curve around the Assam syntaxis. Currently, several of these faults are active as left-lateral wrenches (Tapponnier & Molnar 1977, Molnar & Deng 1984); but in the Tertiary they may have been thrusts and reverse faults responsible for crustal thickening. The main currently active wrench is the Xianshuihe (Kangting) fault (102°E). The regular spacing of these wrenches implies that the region is undergoing EW shortening and NS stretching (Molnar & Deng 1984), but not necessarily a southeastwards expulsion. Instead the wrenches and intervening blocks may have rotated (and be rotating) clockwise, domino fashion, giving a component of right-lateral wrenching along the SE boundary. As far as we know, there is no plaeomagnetic evidence for such local rotations. Possible structural evidence is the occurrence of NS rifts in Yunnan (see previous section), but not in Sichuan. The transition from EW stretching in Yunnan to EW shortening in Sichuan, implies a current clockwise bending of material to the W of the Xianshuihe fault, with respect to the stable Chinese platform to the E.

To the NE of the Xianshuihe fault are the NE trending traces of the Longmen Shan thrusts (105°E, 32°N). Here there is a large drop in elevation, from about 4 Km at the eastern edge of the Tibetan plateau, to only a few hundred metres in the Sichuan basin. The thrusts put Paleozoic rocks on top of Quaternary alluvium and appear to be currently active (Tapponnier & Molnar 1977). Fault-plane solutions indicate oblique (left-lateral) thrusting (Tapponnier & Molnar 1977, Molnar & Deng 1984).

Further to the NE, the Longmen and several other fault systems appear to converge and continue eastwards into the Qinling Shan (110°E, 34°N). Here EW faults have been reactivated in the Cenozoic. The present level of seismicity is low, but field observations show that the faults are active (Peltzer et al. 1985). Quaternary displacements are a combination of normal and strike-slip components. Strike-slip has been left-lateral since the Eocene.

Further N are the normal and strike-slip faults of the Shansi rift system (105°E–115°E, 34°N–41°N). The normal faults trend NE and are quite regularly spaced, en-échelon, along the margins of the rhombohedral Ordos block. Both current seismicity and field observations indicate that the margins of the block have undergone divergent wrenching, left-lateral on the EW trending margins, right-lateral on the NS trending margins (Tapponnier & Molnar 1977). These motions seem to have operated during much of the Quaternary. We infer stretching, crustal thinning and some NE-SW shortening. As well as this, right-lateral wrenching in a NNE direction appears to have overshadowed left-lateral wrenching in an EW direction, on the basis of both current seismicity (Molnar & Deng 1984) and the finite rift pattern.

At 120°E, 40°N, right-lateral and left-lateral wrenching, NW-SE stretching and crustal thinning also appear to be the current mode of deformation in the North China basin (Molnar & Deng 1984, Ye et al. 1985). Cenozoic rifting began in the middle Eocene, continued during the Tertiary and terminated, at the end of the Tertiary, with a period of denudation, followed by regional subsidence (Ye et al. 1985), Hellinger et al. 1985). The present phase of rifting and wrenching initiated in the Quaternary.

Tibetan plateau

Current deformation in the Tibetan plateau seems to be concentrated on its margins, although the interior is not totally inactive. In contrast, significant Cenozoic deformation is recorded well within the plateau (Chang et al. 1986).

The southern margin of the plateau is part of the Himalayan arc, already described. Along a surfacce transect from S to N across the plateau, current deformation shows a number of rapid changes. Southward overthrusting in the southern Himalaya gives way to EW rifting in the high Himalaya and southern Tibet (Tapponnier & Molnar 1977, Molnar & Tapponnier 1978, Ni & York 1978, Tapponnier et al. 1981b, Molnar & Deng 1984, Armijo et al. 1986, Mercier et al. 1987) and then again to strike-slip faulting, with EW stretching and NS shortening, in northern Tibet (Armijo et al. 1986). Field studies show that rifting in southern Tibet did not start until the Pliocene (Mercier et al. 1987). Before that, this same region experienced folding (50–40 Ma) and reverse faulting (25–16 Ma), indicating NS shortening and crustal thickening. The change in tectonic style probably occurred in Southern Tibet during the Late Miocene (10–5 Ma); but it seems quite possible that rifting is currently propagating southwards, behind the serially propagating thrust front of the Himalaya. The rate of EW extension due to rifting is about 10 % per Ma (Armijo et al. 1986).

Along the Lhasa-Golmud highway in central Tibet (between 91°E, 30°N and 95°E, 37°N), the current tectonics are dominated by left-lateral EW trending strike-slip faults. These indicate NE-SW shortening and NW-SE stretching; but there may also be block rotations. The Xidatan fault (36°N) shows a Quaternary left-lateral displacement of some 30 Km (Chang et al. 1986).

Near the Kunlun (36°N), Pliocene strata are folded about EW axes, indicating a component of NS shortening in the Quaternary. Evidence for Tertiary NS shortening is clear along much of the Lhasa-Golmud section (Chang et al. 1986). Paleogene redbeds are folded and thrusted, indicating something like 40 % shortening. If this value is representative of the whole Tibetan plateau, it is enough to account for most of the crustal thickness of Tibet. Further N, in the Qaidam basin (38°N), fold axes trending NW-SE, and associated thrusts, are active today and probably have been so for much of the Quaternary (Tapponnier & Molnar 1977, Molnar et al. 1987a, 1987b). They indicate NE-SW shortening.

The NE margin of the Tibetan plateau shows rapid decreases in elevation (for example, from about 5 Km in the Qilian Shan, to about 1 500 m in the Gansu corridor). The Gansu corridor (102°E, 38°N) is a narrow popdown basin, filled with about 1 Km of Quaternary sediments, between northward overthrusts of the Qilian Shan in the S and southwards overthrusts of the Longshu Shan in the N. Current motion is mainly reverse faulting (Tapponnier & Molnar 1977, Molnar & Deng 1984). This apparently started at the end of the Tertiary. Further E, the main currently active fault at the edge of the plateau is the NW-SE Haiyuan (Kansu) fault (106°E, 36°N). This is a left-lateral strike-slip fault, with some reverse components (overthrusting to the NE). It has a loing history (Burchfiel et al., work in progress).

At is NW margin, the Tibetan plateau also shows a very rapid drop in elevation, from about 4 Km in the Altyn Tagh ranges (90°E, 38°N), to 1 Km or less in the Tarim basin. Just over the edge of the plateau is the remarkable Altyn Tagh fault system whose ENE trending trace can be followed about 1 200 Km, from the Karakorum (80°E, 35°N) to the Nan Shan (97°E, 40°N). This fault clearly has had a long history of left-lateral displacements. Currently, it is almost aseismic (Molnar & Deng 1984), but recent field evidence points to large earthquakes having occurred in the last few hundred years, with a left-lateral slip of some 10 m in some localities (Molnar et al. 1987a, 1987b). This suggests a slip rate of some 30 ± 20 mm a^{-1}. There is no knowing how long this may have continued; but such a rate, if maintained for 50 Ma, would result in a finite displacement of 1 500 ± 1 000 Km. We think such a displacement is possible, for two reasons. First, the fault system, has geometric features similar to those of other major strike-slip faults, such as the San Andreas system of California, or indeed the Chaman system already described. Second, left-lateral displacements of the order of several hundreds of kilometres are required to account for the difference in crustal thickness between the Tibetan plateau and the Tarim block. In this sense, the Altyn Tagh must be of transform type (Mattauer 1986), transferring NNE contraction from Tibet in the E, to the Karakorum in the W. The current topography of the Altyn Tagh and nearby ranges (Akato Tagh, Chiman Tagh) is satisfactorily explained by recent field observations of reverse fault scarps at the base of each range (Molnar et al. 1987a, 1987b). Thus the composite current motion on the Altyn Tagh zone is one of oblique left-lateral thrusting. This has probably occurred over much of the Cenozoic.

Finally, the eastern margin of the Tibetan plateau has already been described, as part of the SE boundary of the Central Asian Triangle.

Inferred Cenozoic displacement pattern

From the data already presented, especially the current elevation, finite fault pattern and current velocity field, we draw tentative conclusions concerning the pattern of Cenozoic displacements (Fig. 4). We regard this pattern as a working hypothesis, to be tested in the future using new data and other methods, including paleomagnetism and geometrical reconstructions. In the following section, we present a reconstruction covering the last 10 Ma only.

On our map (Fig. 4), we distinguish areas of dominantly coaxial crustal thickening (such as the Himalaya), from areas of convergent wrenching (such as the Hindu Kush-Pamirs-Tien Shan), pure wrenching (Altai), or divergent wrenching (Baykal). On this basis, simple crustal thickening appears to be confined to the Tibetan plateau. Elsewhere, wrenching would appear to be a significant component of the deformation history. In a sense this is not surprising, because crustal thickening cannot diminish laterally without coexistent wrenching. The important question is how, where and to what extent wrenching has occurred.

Structures typical of wrench tectonics have been reviewed before (Wilcox et al. 1973, Tchalenko 1970, Christie-Blick & Biddle 1985, Naylor et al. 1986); but in our discussion of Central Asia we attempt to be more rigorous. We list the following conditions to be satisfied.

1. The area of wrenching is a strip, long and narrow, where deformation is relatively intense.
2. In each of a number of subareas, faults of all kinds have mutually compatible displacements and the inferred principal directions of finite strain are oblique to the strip, in plan.
3. Belts of crustal thickening or thinning are compatible with the principal strain directions derived from fault patterns.
4. Within the strip, there are not only horizontal contractions, but also horizontal extensions, in mutually orthogonal directions.
5. A. Synthetic strike-slip faults are dominant, with respect to antithetic strike-slip faults; or, B. anti-

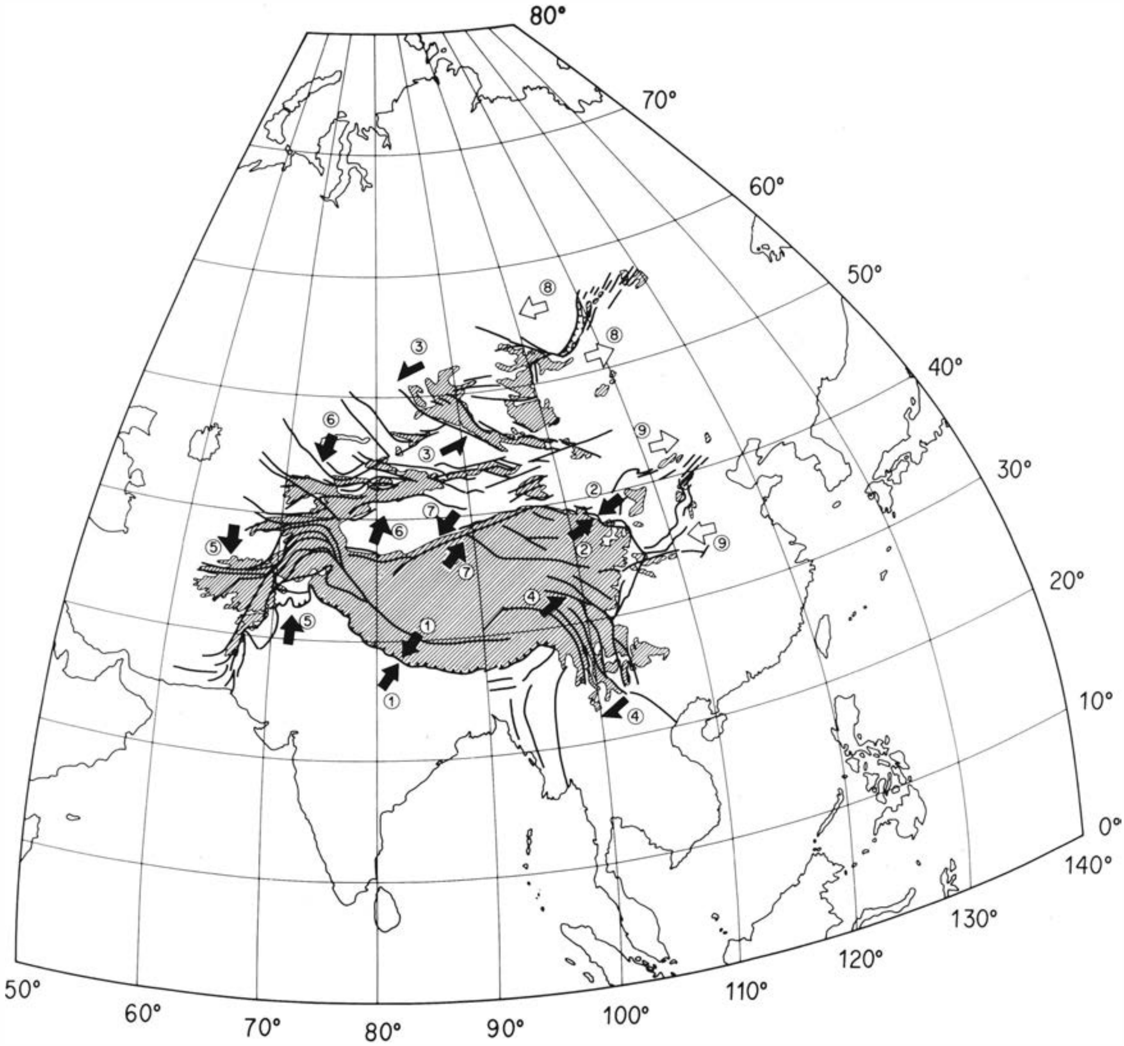

Fig. 4. Inferred Cenozoic displacement pattern. Traces of major faults are superimposed on areas with elevation greater than 2 Km (hatched). Pairs of arrows indicate horizontal displacement gradients (black for contractional, white for extensional). Opposing symmetric black arrows indicate that simple contraction dominates in Himalaya (1) and northern margin of Tibetan plateau (2); black half-arrows, dominant wrenching in Altai (3) and eastern Tibet (4); asymmetric black arrows, convergent wrenching in Hindu Kush (5), Tien Shan (6) and Altyn Tagh (7); asymmetric white arrows, divergent wrenching in Baykal (8) and Shansi (9).

thetic faults and intervening blocks show evidence for finite rotations in the appropriate senses.

Conditions 2, 3 and 4 concern the finite strains. Together with condition 1, they ensure that the finite deformation has a component of simple shear parallel to the strip (Ramsay & Graham 1970). Condition 5 ensures that this simple shear has accumulated progressively in the required sense. Thus conditions 1 to 5, taken together, form a powerful set. Their satisfaction is more than enough to identify a wrench zone.

The most difficult condition to satisfy is condition 5B. Paleomagnetism is potentially a powerful method for this purpose; but for Central Asia, paleomagnetic data are so far insufficient. We therefore turn to structural data. In particular, we look for minor faults that demonstrate relative rotations between major fault blocks. To our knowledge, such a method has not been applied before at a large scale.

In our interpretation (Fig. 4), there are 3 major wrench zones in Central Asia: (1) the western margin of the Tibetan plateau, (2) the SE marginal strip of Central Asia, including the eastern margin of the Tibetan plateau and (3) the NW marginal strip of Central Asia, from Pakistan to Lake Baykal. Of these, the first requires little discussion, because conditions 1 to 5A are met and the tectonics are dominated by a single synthetic strike-slip fault, the Altyn Tagh. The other two wrench zones require deeper discussion.

NW strip

The NW strip is some 5 000 Km long. Conditions 1 to 4 are met at all points and the finite strains are compatible with left-lateral wrenching. Synthetic (left-lateral) strike-slip faults, at low angles to the strip, are dominant in both the S (Pakistan) and the N (Baykal area). In central areas, antithetic strike-slip faults are numerous. Is there structural evidence for anticlockwise rotation of intervening fault blocks? We believe there is, as follows.

1. On the southwestern sides of antithetic strike-slip faults, there frequently are local fold-and-thrust belts with almost orthogonal (NE-SW) trends. Major examples occur in the northwestern Pamirs (38°N, 68°E) and western Tien Shan (Chatkal range, 42°N, 71°E), Minor examples in the Altai (50°N, 88°−90°E) have been described by Tapponnier and Molnar (1979, Fig. 12 and page 3438). Although the contraction across these local belts clearly absorbs some of the right-lateral displacements on the antithetic strike-slip faults (where the latter terminate or approach the Kazakhstan platform), we believe these local belts are also evidence for rotation of fault blocks. The key observations are (1) that local belts of contraction are almost orthogonal to strike-slip faults; (2) that local belts do not span entire fault blocks, between one strike-slip fault and the next, but instead span only part of the distance; and (3) that the amount of contraction, indicated by current topography, depth of erosion or the width of the belt, diminishes southwestwards, away from the associated strike-slip fault. *If strike-slip displacements on major antithetic faults and contractions across local belts are simultaneously restored, the major fault blocks rotate, domino-fashion, with respect to the Kazakhstan platform.*
2. As traces of major antithetic faults are followed southeastwards, they tend to turn. From initial SE trends at the edge of the Kazakhstan platform, they bend progressively to the E within major mountain belts, becoming principally reverse faults. Other reverse faults bend to the SE, as they leave the mountain belts, becoming antithetic strike-slip faults. The Talasso-Fergana fault, as it enters, crosses and leaves the northwestern Tien Shan (43°N, 71°E), has a somewhat sigmoidal trace. Other major strike-slip faults cannot easily be followed across entire mountain belts.
3. Belts of uplifted and eroded basement rocks, lying alongside major faults, also have curved or even sigmoidal trends. Good examples occur in the Tien Shan (Academia Sinica 1975, Akademiya Nauk 1964).

For all these reasons, we believe the NW strip is a zone of left-lateral wrenching, convergent in the SW (Pakistan), divergent in the NE (Baykal). The relative motion of India and Asia would suggest that left-lateral displacement is something like 2 500 Km in Pakistan. Clearly this must diminish northeastward, to something like 10−20 Km near Lake Baykal. This decrease requires major associated crustal thickening, as observed in the Hindu-Kush, Pamirs, Tien Shan and Altai. We notice also that the trend of the NW strip varies from nearly NS at the Gulf of Oman, to nearly EW beyond Lake Baykal. This curvature implies annular wrenching, about a pole located somewhere in SE Asia.

SE strip

Compared with the NW strip, the SE strip is shorter (some 2 500 Km). The finite strains (conditions 2−4 above) are everywhere compatible with right-lateral wrenching. Synthetic (right-lateral) strike slip faults are dominant in the S (Burma) and N (Shansi); but in the central zones, antithetic faults are numerous. The structural evidence for clockwise rotation of fault blocks, domino style, is as follows.

1. In NE Burma, Yunnan and Sichuan, all major faults and intervening folded geological formations are strongly arcuate (Academia Sinica 1975, Ministry of Geology 1980), in the required sigmoidal sense.
2. The northward change from EW Quaternary extension in Yunnan, to EW Quaternary contraction in Sichuan, implies clockwise bending and rotation of the strip with respect to the Chinese platform.

We also notice that strike-slip motions and domino rotations are common at the sides of arcuate thrust blocks in indentation experiments (Davy & Cobbold, Part 1). This may account for the domi-

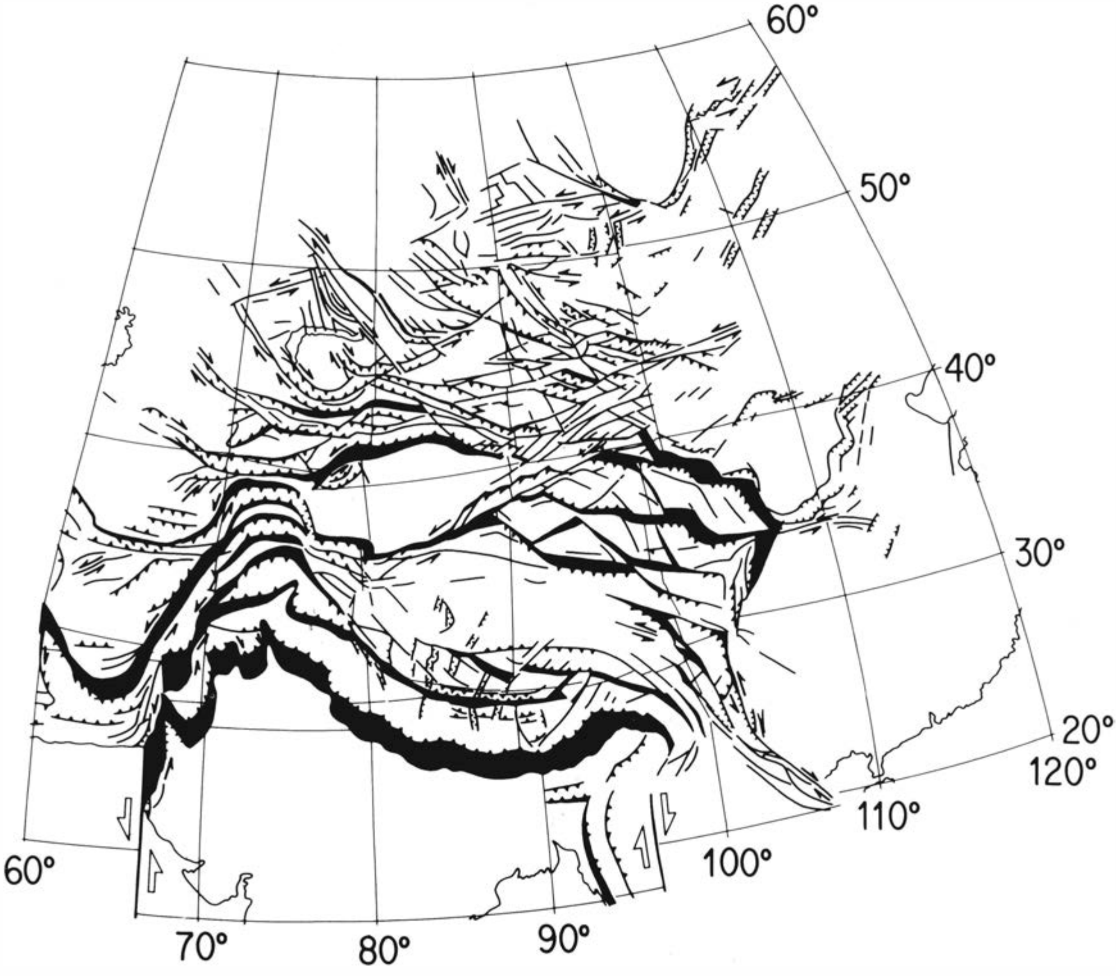

Fig. 5. Reconstruction of displacement field for last 10 Ma of indentation. Starting with current deformed state (Fig. 3), estimated displacements of India (white arrows) and of faults in central Asia, have been reversed. The lines of latitude and longitude of Fig. 3 have been treated as material lines during reversal of deformation. Reversal of thrust displacements causes gaps (black areas) to appear between fault blocks. Rift valleys become narrower. Bonne projection (modified conic).

nance of left-lateral faulting at the eastern margin of the Tibetan plateau.

Reconstruction covering the last 10 Ma

To check the ideas discussed in the previous sections, especially the wrenching along the lateral strips of the Central Asian Triangle, we have attempted to reconstruct the displacement field for the time-period 0–10 Ma (Fig. 5). The data used are (1) the Cenozoic fault map (Fig. 3), (2) current rates of slip, where these have been estimated (e.g. Molnar & Deng 1984), (3) directions and senses of slip, where these are known but rates are not, (4) boundary motions of India and China. We also assume that blocks between faults are rigid (or at most a little flexible) and that no unwarranted gaps or overlaps appear during block displacement. We emphasize that the uncertainties involved are rather large and that our solution is certainly not unique. However we have verified, by trial and error, that the range of possible solutions is not unduly great. This is mainly because Central Asia is surrounded by stable platforms, that we assume rigid, and because the relative motion of India and Asia is rather well constrained. Nevertheless, because we rely rather heavily on the current velocity field, we have made no attempt to extrapolate this over more than 10 Ma. In fact, we assume that current material velocities were constant over this period.

In this first attempt at a reconstruction, our method is purely manual. We first take the Cenozoic fault map and cut along each fault trace, using a dissecting knife, leaving a minimum of connectivity, so as to avoid fault blocks dropping out of the array. Because of the density of faults, and hence of cuts, the dissected area of Central Asia becomes extremely easy to deform in a large number of ways, without much distorting the fault blocks themselves. Thus we verify that the large-scale behaviour is that of a continuum, whereas the small-scale behaviour involves rigid fault blocks.

To obtain the pattern of Fig. 5, we first withdrew India southwards by 50 $mm.a^{-1} \times 10$ Ma = 500 Km. Next we withdrew Indochina southeastwards about 200 Km along the Red River fault. For simplicity, we assumed the relative motion between India and Indochina to be distributed as 300 Km of pure strike-slip on the Sagaing fault and about 100 Km of thrusting in the Indoburman ranges (reversal of thrusting is represented in Fig. 5 by black gaps). Similarly, we reversed an estimated 200 Km of thrusting in the Himalaya, 150 Km in the Pamirs and Karakorum, 100 Km in the Tien Shan and about 200 Km in northern Tibet. Elsewhere we closed rifts and reversed strike-slip faults, following as closely as possible the velocity field estimated for subareas of Central Asia by Molnar and Deng (1984). To maintain continuity and avoid unwarranted gaps and overlaps, we found it necessary to allow additional external spins for those fault blocks lying between antithetic strike-slip faults, in both the NW and SE strips. In this way, the strips acted as wrench zones. In the SE strip and SE corner, we also found it necessary to straighten the narrow arcuate fault blocks between antithetic strike-slip faults. Partially straightened as well, in Fig. 5, is the Himalayan arc.

Most of the necessary fault slips were obtained with little difficulty, by simply pulling the Himalayan front of the dissected map southwards. This also resulted automatically in domino rotations in the boundary strips. In fact, we recommend this procedure as an instructive practical exercise for anyone interested in patterns of fault slip and continental deformation.

Our reconstruction suggests that Quaternary indentation of Central Asia has occurred mostly by crustal shortening in the Himalaya, Pamirs, Tien Shan and Tibetan plateau. Two major wrench zones accommodate the difference in NS contraction between the undeformed platforms and Central Asia. The left-lateral NW zone has an arcuate trace from the Gulf of Oman to Lake Baykal and beyond. It is strongly convergent in the SW, weakly divergent in the NE. The right-lateral SE wrench zone has a straighter trend, from Burma to the North China basin. It too is convergent in the S, divergent in the N. Contraction across both shear zones takes place at the expense of WNW-ESE extension in the major plateaux. The left-lateral shear displacement across the NW wrench zone decreases rather steadily and slowly from 500 Km at latitude 20°N, through 250 Km at about 40°N (Tien Shan), to less that 10 Km in the extreme NE. In contrast, right-lateral displacement across the SE wrench zone decreases more rapidly, from 500 Km at 20°N, through a major jump at the SE corner (28°N) to a value of about 300 Km, then a rapid decrease at 35°N to less than 10 Km displacement.

The reconstruction also indicates that rigid rotations of fault blocks about vertical axes have been significant in certain areas, especially the Tarim block (15° clockwise since 10 Ma), central Tibet (15° anticlockwise), eastern Tibetan plateau (20° clockwise) and western to central Tien Shan (15° anticlockwise). These areas are potential targets for paleomagnetic studies, which may be able to provide a check on the reconstruction.

Tertiary displacements

Zhao and Morgan (1985) have reconstructed the entire Cenozoic history of displacements in central and eastern Asia, using similar data to those reviewed in this paper, but with less detailed constraints from the finite fault pattern. In their reconstruction, they have incorporated a southeastwards expulsion of Indochina during the Tertiary. We feel that available Tertiary data for SE Asia are not yet good enough to closely constrain any reconstruction and therefore we have not yet attempted to do one.

The only area where Tertiary faulting is reasonably well documented is the NS strip. The earliest activity on some of the major faults appears to be as follows: Karakorum and Talasso-Fergana right-lateral system (mid-Tertiary), Tien Shan folds and thrusts (Oligocene), Dzhungarian right-lateral fault (Pliocene), block faulting in Mongolia (Pliocene), Baykal rift system (Oligocene). In general, important Cenozoic deformation seems to have started in the late Oligocene and to have become more intense in the Pliocene. As there is no documented evidence for major changes in the senses of displacement on these faults, we imagine that the NW strip may have functioned as a left-lateral wrench zone since the Oligocene, if not before.

Crustal thickening in Tibet also appears to have a long Cenozoic history. Wrenching at the margins thus seems to be a necessity. So far, we can only conclude that there is no hard evidence for the displacement field having been very different in the Tertiary, from what is was in the Quaternary. This agrees with the prediction of both experiments (Davy & Cobbold, Part 1) and calculations (England & Houseman 1986).

Comparison of Asia with experiments and discussion

We now compare the deformation pattern in Asia with those in our experiments (Davy & Cobbold, Part 1). The object is to see which model provides the best fit and how good this fit is.

The easiest features to compare are probably the finite fault patterns and the distributions of crustal thickness. We proceed by elimination. The experiments with totally constrained eastern continental margins (Models 7, 8 and 9) show too many thrusts, not enough strike-slip faults and rifts and a pattern of crustal thickening that is too symmetric about a NS centre line. Model 6 has similar deficiencies, although there are a few strike-slip faults. In contrast, model 2 has too few thrusts and not enough crustal thickening. This leaves models 1, 3, 4 and 5 for closer comparison with Asia.

Models 3, 4 and 5 all show a single major left-lateral wrench zone, convergent in the SW, where it joins the corner of a single major plateau. Asia has the same basic pattern, except that the plateau area is interrupted by a major basin (the Tarim), bounded on its SE by a prominent left-lateral wrench fault (the Altyn Tagh). Model 5 (stage 2) shows a secondary left-lateral wrench fault in the appropriate position, but no basin equivalent to the Tarim. In both models 4 and 5, the major wrench zone shows a degree of complexity that begins to approach what is visible in Asia. Model 4, in particular, shows en-échelon thrusts in the SW (due to strong convergence across the wrench), giving way in the NE to synthetic and antithetic wrench faults, the latter separating domino blocks. This pattern is comparable with the transition in Asia from the Tien Shan to the Altai. In contrast, the wrench zone in model 3 appears to be too simple.

Models 4 and 5 do however have defficiencies when closely compared with Asia. They do not show rifts in the North, either along the main left-lateral shear zone, or prolonging to the N the eastern margin of the plateau. In contrast, model 1 does show a long eastern right lateral wrench zone, marked by rifts in the N; although the western left-lateral wrench zone is too short and strikes too northerly.

In summary, none of the experimental models has a fault pattern identical with Asia, but models 4, 5 and 1 have patterns which show similarities with it. A better fit might be obtained using a model where confinement decreases northward along the eastern continental margin. Such a condition might mimic the present distribution of forces across the eastern margin of China, from relatively large compression at Taiwan, to relatively small compression behind the Japanese arc.

Meanwhile, the closeness of fit between Asia and models 4, 5 and 1 leads us to several tentative conclusions. First and foremost, models 4 and 5 suggest that lateral escape has indeed occured in Asia, but not to the extent favoured by Tapponnier et al. (1986). Second, the models suggest that indentation has been taken up dominantly by crustal thickening, as concluded by England and Houseman (1986). However, the relative proportions of lateral escape and thickening are hard to estimate. On the basis of model 4, escape might account for something like 45 % of the indentation; whereas in our reconstruction for the last 10 Ma, lateral escape accounts for only about 20 % of the indentation. This discrepancy will perhaps be resolved when new data become available, especially for northern regions.

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