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Tectonic framework of the Himalaya, Karakoram and Tibet, and problems of their evolution

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The Himalaya, the Karakoram and Tibet were assembled by the successive accretion to Asia of continental and arc terranes during the Mesozoic and early Tertiary. The Jinsha and Banggong Sutures in Tibet join continental terranes separated from Gondwana. Ophiolites were obducted onto the shelf of southern Tibet in the Jurassic before the formation of the Banggong Suture. The Kohistan–Ladakh Terrane contains an island arc that was accreted in the late Cretaceous on the Shyok Suture and consequently evolved into an Andean-type batholith. Further east this Trans-Himalayan batholith developed on the southern active margin of Tibet without the prior development of an island arc. Ophiolites were obducted onto the shelf of India in the late Cretaceous to Lower Palaeocene before the closing of Tethys and the formation of the Indus–Yarlung Zangbo Suture at about 50 Ma. Post-collisional northward indentation of India at *ca.* 5 cm a^{-1} since the Eocene has redeformed this accreted terrane collage; palaeomagnetic evidence suggests this indentation has given rise to some 2000 km of intracontinental shortening. Expressions of this shortening are the uplift of mid-crustal gneisses in the Karakoram on a late-Tertiary breakback thrust, folding of Palaeogene redbeds in Tibet, south-directed thrust imbrication of the foreland and shelf of the Indian Plate, north-directed back-thrusts along the Indus Suture Zone, post-Miocene spreading and uplift of thickened Tibet, giving rise to N–S extensional faults, and strike-slip faults, which allowed eastward escape of Tibetan fault blocks.

1. Introduction

Central Asia is dominated by the Tibetan Plateau and the mountain ranges of the Karakoram and the Himalaya. The tectonic evolution of these regions took place in three stages. (1) Following northward drift of several plates separated from Gondwanaland, growth of magmatic arcs during closure of Tethys in the Mesozoic–Lower Tertiary. (2) Accretion of these plates and arcs terminated in the collision between India and the amalgamated Asian Block to the north, giving rise to the Indus–Yarlung Zangbo Suture. (3) Post-collisional northward indentation of India since about 40 Ma has given rise to some 2000 km of crustal shortening (on palaeomagnetic evidence) and has caused redeformation of major segments of this accreted collage of plates.

The aim of this paper is to provide a synoptic account of the main tectonic zones and their mutual relations. A variety of tectonic problems are then discussed, because considerable disagreement has arisen concerning the interpretation of some key geological relationships.

2. Tectonic zones

This region of Central Asia is divisible into the following tectonic zones, which retain their coherence and continuity for considerable distances along strike (see figure 1).

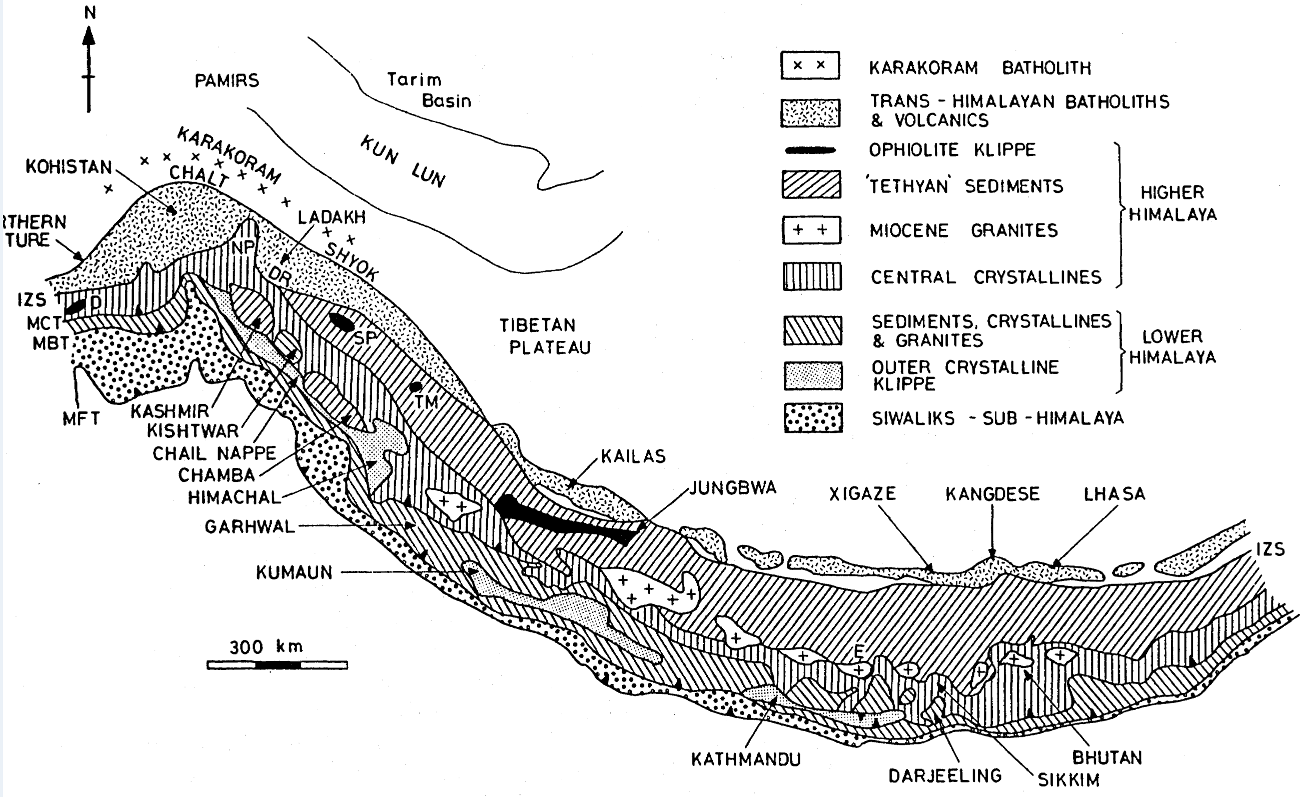

FIGURE 1. Map of the Himalaya showing the main tectonic zones and key localities. D = Dargai ophiolite, Dr = Dras, E = Everest, NP = Nanga Parbat, SP = Spongtang ophiolite, TM = Tso Morari, IZS = Indus–Yarlung Zangbo Suture, MCT = Main Central Thrust, MBT = Main Boundary Thrust, MFT = Main Frontal Thrust. After Windley (1983).

(a) *Tibet*

For the purpose of this description, the Tibetan Plateau is taken to extend from the south side of the Kun Lun Range to the north side of the Trans-Himalayan magmatic belt. This region is divisible into three micro-continental fragments, the Kun Lun, Changtang and Lhasa Terranes separated by the Jinsha and Banggong Sutures (Chang *et al.* 1986). Faunal data suggest that the Kun Lun was already part of Laurasia by the Carboniferous, and that the Changtang and Lhasa Terranes were separated from Gondwana in the pre-Permian and Triassic respectively. These terranes were accreted successively northwards to the southern margin of Asia. The Jinsha Suture formed in the late Triassic–early Jurassic and the Banggong Suture in the late Jurassic–early Cretaceous (Lin & Watts, this symposium). Palaeomagnetic data by Patriat & Achache (1984) and biostratigraphic data by Wang & Sun (1985) indicate that the Lhasa Terrane remained stationary through most of the Upper Cretaceous and Eocene, but that it has moved 20° north since the suturing of India to it in the Eocene. The folding and thrusting of Palaeogene red beds across a wide extent of the Tibetan Plateau allows a minimum estimate of overall shortening of 12% (Chang *et al.* 1986). Remnants of dismembered ophiolites occur along the Banggong Suture Zone and in isolated, gently dipping outcrops over the plateau for at least 200 km south of it (Girardeau *et al.* 1985*a*). They were obducted probably in a single flat thrust sheet over the continental margin of the Lhasa Terrane (Chang *et al.* 1986). Granites of 140–120 Ma within the Lhasa Terrane were probably formed by lower crustal anatexis during intracrustal thrusting and thickening following the collision between the Changtang and Lhasa Terranes (Xu *et al.* 1982).

Neotectonic structures are widespread across the Tibetan Plateau. These are extensional structures which are significantly different in south and north Tibet (Chang *et al.* 1986; Mercier *et al.* 1987). South Tibet (extending to the northern part of the Tibetan-Tethys Zone) has extended in an E–W direction on major N–S-aligned rifts (Tapponnier *et al.* 1981*a*). The rate of Quaternary extension is about 1% Ma^{-1}, corresponding to a 'spreading' rate of 1.0 ± 0.6 cm a^{-1} (Armijo *et al.* 1986). In contrast, north Tibet has been able to escape more easily eastwards and thus has extended along a conjugate set of NW–SE and NE–SW strike-slip faults (Mercier *et al.* 1987).

(*b*) *The Trans-Himalayan magmatic belt*

This Andean-type magmatic belt (Le Fort, this symposium) is situated along the northern margin of the Indus–Yarlung Zangbo Suture. In Tibet, the Gangdese batholith of plutonic bodies is divisible into four simultaneously emplaced units, the predominant rocks of which are adamellites, quartz monzodiorites and granodiorites (Debon *et al.* 1986). U–Pb dates of the intrusives range from 94 to 41 Ma in Tibet (Scharer *et al.* 1984*a*) and from 103 to 60 Ma in Ladakh (Scharer *et al.* 1984*b*). Considering that the India–Eurasia collision took place in the period 50–40 Ma, the Trans-Himalayan plutons were emplaced before and during the period of collision. This may not be surprising in view of the expected time lapse between subduction of oceanic lithosphere and the intrusion of calc-alkaline melts (Zhou 1985).

North of the Gangdese batholith there is a belt of ignimbrites, andesites and alkaline rhyolites belonging to the Lingzigong Formation, which is at least 1500 m thick and which has $^{39}\mathrm{Ar}/^{40}\mathrm{Ar}$ ages of 60 and 48 Ma (Maluski *et al.* 1982; Coulon *et al.* 1986) and Rb–Sr ages of 60 and 56 Ma (Xu *et al.* 1982). These volcanics are widely regarded as the extrusive and comagmatic equivalents of the Gangdese plutonic batholith.

In the western Himalaya the Kohistan–Ladakh Terrane is situated between the Shyok Suture and the Indus Suture. Recent detailed field and geochronological studies of rocks in Pakistan and NW India demonstrate that the magmatic belt in this terrane underwent at least three stages of crustal growth, each separated by phases of deformation, caused by collision tectonics.

1. An island arc (Tahirkheli & Jan 1979; Bard *et al.* 1980), which developed in Tethys from the Jurassic(?) to the mid-Cretaceous, has the following units from top to bottom: (*a*) The Yasin Group of slates, turbidites, volcaniclastics and limestones has an Aptian–Albian microfauna and formed in intra-arc basins (Pudsey *et al.* 1985*b*); (*b*) The Chalt (Pakistan) and Dras (India) volcanics of basaltic tholeiites, andesites, rhyolites, tuffs and volcaniclastic sediments (Dietrich *et al.* 1983; Radhakrishna *et al.* 1984); (*c*) Plutons of tonalite, granodiorite and diorite, which have ages of 103 Ma – U/Pb (Honegger *et al.* 1982), 101 ± 2 Ma – U/Pb (Scharer *et al.* 1984*b*), and 102 ± 12 Ma – Rb/Sr (Petterson & Windley 1985); (*d*) The Chilas Complex (in Kohistan) of layered gabbros and norites (now two pyroxene granulites), which formed in the sub-arc magma chamber (Khan *et al.* 1988); there are comparable rocks in the Kargil Complex in Ladakh (Rai & Pande 1978). All these rocks were deformed and metamorphosed when the arc was accreted to the Karakoram Terrane on the southern margin of Eurasia (Scharer *et al.* 1984*a*, *b*; Coward *et al.* 1986; Debon *et al.* 1987).
2. Subsequent northward subduction of Tethys gave rise to the Andean-type Trans-

Himalayan batholith, which was intruded into the steeply dipping arc volcanics. Dioritic dykes, representing the earliest phase of the calc-alkaline magmatism, have a ^{39}Ar/^{40}Ar hornblende age of 75 Ma (D. C. Rex, personal communication). Plutons of granodiorite and granite have ages of 60.7 ± 0.4 Ma – U/Pb (Scharer *et al.* 1984*a*, *b*), 59 ± 2 Ma – Rb/Sr (Debon *et al.* 1987), 54 ± 3 Ma and 40 ± 6 Ma – Rb/Sr (Petterson & Windley 1985), Rb/Sr and K/Ar mineral ages between 79 and 45 Ma (Honegger *et al.* 1982), ^{39}Ar/^{40}Ar ages of 44 ± 0.5 Ma and 39.7 ± 0.1 Ma (Reynolds *et al.* 1983) and a Rb/Sr age of 40 Ma (Brookfield & Reynolds 1981). These calc-alkaline plutons (Petterson & Windley 1986) are overlain further west by the Dir-Kalam Group of calc-alkaline volcanics and Eocene sediments that are relicts of the roof of the Andean-type batholith. Deformation of these volcanics and sediments took place when the Kohistan–Ladakh Terrane on the leading edge of the Eurasian Plate collided with the Indian Plate in the Eocene.

3. Abundant sheets of garnet/tourmaline-bearing aplite and pegmatite have poorly defined Rb/Sr whole-rock ages of 34 ± 14 Ma and 29 ± 8 Ma (Petterson & Windley 1985). They were intruded in post-collisional times; they formed by partial melting of continental crust thickened by tectonic and magmatic processes.

On the south side of the Kohistan–Ladakh arc-batholith lies the Kamila amphibolite belt, which was interpreted by Bard *et al.* (1980) as a relic of the oceanic crust on which the arc was built. However, the presence of granitic gneisses in the amphibolites led Coward *et al.* (1986) to suggest this is a belt of highly deformed arc-type plutonics and volcanics. It is possible that this is a relic of a second arc within the Kohistan–Ladakh Terrane.

(*c*) *The Indus–Yarlung Zangbo Suture Zone*

This suture zone formed as a result of the collision between India and the Kohistan–Ladakh arc-batholith in the west and Tibet in the central–eastern Himalaya. There are significant differences in the nature of the zone along strike.

1. In Pakistan, west of the Nanga Parbat syntaxis the suture (or Main Mantle Thrust; Bard *et al.* 1980) separates high-grade amphibolites to the north from high-grade gneisses to the south. Key rock units along the suture are (*a*) a 3 km wide thrust belt of blueschists (Shams *et al.* 1980; Majid & Shah 1985) and (*b*) a 200 km^2 tectonic wedge, the Jijal Complex of high-pressure garnet granulites (Jan & Howie 1981), which may have been recrystallized during sub-arc metamorphism, before collision (Coward *et al.* 1986).

2. In India, the suture zone contains the following units. (*a*) The Lamayuru Complex of allochthonous, pre-orogenic basin sediments (Thakur 1981; Searle 1983). They comprise shales, turbidites and deep-water radiolarian cherts and they range in age from Triassic to late Cretaceous. (*b*) Ophiolitic mélanges, which occur in shear zones up to 150 m thick and which contain serpentinized harzburgites and dunites, gabbros, rodingites, sheared volcanics, blueschists, shales and cherts (Frank *et al.* 1977). They commonly border and cut through the Lamayuru sediments and the Dras volcanic rocks. Some granitic rocks of the Ladakh batholith intrude the mélanges, demonstrating that the emplacement of these dismembered ophiolites (Ramana *et al.* 1986) in the Indus Suture Zone occurred in the Cretaceous. (*c*) The Jurassic–Cretaceous Dras volcanics (Radhakrishna *et al.* 1984), which are equivalent to the Chalt volcanics in Pakistan. (*d*) The Indus Group of Eocene to (?)Miocene molasse sediments, which are dominantly fluviatile and lacustrine sandstones and conglomerates, the pebbles of

which contain granitic and volcanic rocks derived from the Ladakh batholith, over which parts of the Indus Group still overlie unconformably.

3. In Tibet, the suture zone (Burg & Chen 1984; Burg *et al.* 1987) contains the remains of three rock units.

The Xigaze Group consists of Aptian–Albian flysch and conglomerates, which contain pebbles of plutonics and volcanics derived from the Gangdese Belt to the north. It probably formed in a fore-arc on the southern margin of the Lhasa Terrane. It was deformed by the collision of the Indian Plate (Shackleton 1981).

The Xigaze ophiolite occurs in several thrust slices along the suture zone. It displays a complete ophiolitic sequence from marine radiolarian cherts and pillow-bearing basalts to 5 km of harzburgites and minor lherzolites. It has few cumulate gabbros and a sill–dyke complex (Nicholas *et al.* 1981; Girardeau *et al.* 1985*b*). It has a U–Pb whole-rock age of 120 ± 10 Ma and overlying radiolarian cherts have Albian–Aptian microfossils (Gopal *et al.* 1984). Dolerite dykes have a constant trend of N080. By assuming that the dykes were injected in tensional fractures parallel to the oceanic spreading axis and by taking into account the 90° anticlockwise rotation of the whole ophiolite determined by Pozzi *et al.* (1984), Girardeau *et al.* (1985*c*) concluded that the Xigaze ophiolite formed in a spreading centre oriented at N160, which is close to the N175 determined by Pozzi *et al.* (1984) from palaeomagnetic data. Low-temperature fabrics suggest a very low heat flow at the spreading centre, which may have been a discontinuous, slowly accreting type located in a small basin (Girardeau *et al.* 1985*d*). The palaeolatitude of the accreting centre was at 10–20° N (Pozzi *et al.* 1984), which was close to the southern margin of Eurasia. Intraoceanic thrusting began at about 110 Ma soon after accretion, and final thrusting was at 50 Ma during terminal collision.

South of the ophiolite is a thrust slice containing turbidites which are equivalent to the Lamayuru complex in Ladakh and which were deposited in a sedimentary apron on the northern continental margin of the Indian Plate (Burg *et al.* 1987), and the Yamdrock tectonic mélange, which probably formed in the subduction zone trench on the footwall of the Xigaze ophiolite (Searle *et al.* 1987).

4. In Nagaland in NE India there are ophiolites (Agrawal & Kacker 1980) and blueschists (Ghose & Singh 1980) in the suture zone.

(*d*) *Tibetan-Tethys Zone*

Extending from Zanskar along the southern edge of Tibet to the NE corner of India is a continuous zone of essentially conformable Palaeozoic and Mesozoic sediments, which are 6 km thick and which were deposited on the northern passive continental margin of the Indian Plate (Gansser 1964; Gupta & Kumar 1975; Fuchs 1979; Thakur 1981; Tapponnier *et al.* 1981*b*). There is an almost continuous succession from the Cambrian to the Eocene (Baud *et al.* 1984; Gaetani *et al.* 1986). The Panjal Group of continental tholeiitic to mildly alkaline basalts in Kashmir and the equivalent Abor volcanics in NE India (Bhat 1984) formed in Carboniferous–Permian rifts which evolved into the passive continental margin of Neo-Tethys. In general, the Mesozoic sediments pass northwards from Triassic to middle-Jurassic shelf carbonates to late-Jurassic shales deposited in a widespread transgression, to early Cretaceous shelf carbonates, and to a deeper water Campanian–Maastrichtian flysch facies. Shelf limestones continued to form locally until the Lower Eocene. The sediments have been thrust southwards towards the foreland of the Indian Plate. From balanced cross sections, Searle (1986) calculated a shortening of 126 km across this thrust shelf sequence.

The Tibetan-Tethys Zone also contains Lower Ordovician gneissic porphyritic granites as in the Kangmar dome (Burg *et al.* 1984*a*), that have a Rb–Sr isochron of about 485 Ma. They are similar in type and age to the Central Crystalline gneisses of the Higher Himalaya to the south; their aluminous character and high initial Sr isotope ratios suggest they developed in the continental crust, which was part of Gondwana at the time (Debon *et al.* 1986*a*).

There are two ophiolite complexes that have been thrust onto the Tethyan shelf sediments: Spongtang in Zanskar and Jungbwa in SW Tibet (Gansser 1979). The Spongtang klippe is composed of ultramafic and gabbroic rocks with poorly developed cumulates and dykes in a thrust nappe overlying a mélange unit with volcanics, limestone and chert blocks. The ophiolite rests tectonically on a thrust plane over sediments ranging in age from Eocene to Jurassic (Srikantia & Razdan 1981). Relations between mylonitic and ductile shear zones in peridotites led Reuber (1986) to suggest that the ophiolite formed at a transform boundary. The age of both ophiolites is unknown, but presumed to be Cretaceous. The age of tectonic emplacement of the ophiolites over the shelf sediments of the Indian continental margin is controversial and will be discussed later.

At the base of the Tibetan-Tethys Zone there is a northward-dipping normal fault, along which there has been at least several tens of kilometres movement. It formed by gravity collapse during late-Tertiary spreading of the Himalayan crust, which had been thickened during post-collisional convergence of India and Tibet (Burg *et al.* 1984*b*; Burchfiel & Royden 1985).

(*e*) *The Higher Himalaya*

This 3.5–10 km thick 'Tibetan Slab' of high-grade metamorphic rocks (the Central Crystallines) is bounded on the north by the normal fault referred to above and to the south by the Main Central Thrust (MCT). The rocks have undergone amphibolite facies medium pressure-type metamorphism during Himalayan southward-thrusting, giving rise to widespread pelitic schists, marbles, paragneisses, orthogneisses, amphibolites and migmatites (Burg *et al.* 1987).

Two-mica leucogranites have intruded the Central Crystalline Complex and the northern part of the Tibetan-Tethys Zone sediments. The well-studied Monaslu granite has very inhomogeneous Rb–Sr isotopic compositions; magmatic ages range from 25 Ma (U–Pb) and 18 Ma (Rb–Sr isochron), suggesting that the magmatic activity lasted at least 7 Ma (Scharer *et al.* 1984*a*; Deniel *et al.* 1987). In general, the High Himalayan leucogranites are peraluminous in composition and often contain tourmaline, sillimanite, and garnet, and have very high initial Sr isotope ratios of 0.7800–0.7550 (Le Fort 1981; Dietrich & Gansser 1981; Vidal *et al.* 1982; Searle & Fryer 1986). They were most likely generated by anatexis of lower crustal Precambrian paragneisses comparable to those of the Central Crystalline Complex.

(*f*) *The Lesser Himalaya*

The Lesser Himalayan tectonic zone is bounded to the north by the Main Central Thrust (MCT) and to the south by the Main Boundary Thrust (MBT). It consists of weakly metamorphosed, late Proterozoic (Riphean–Vendian) and Palaeozoic sediments, which have been overridden by thrust nappes of high-grade gneiss derived from the Central Crystallines

(Stocklin 1980; Valdiya 1981; Sinha 1981). Predominant amongst the low-grade sediments are carbonates with Riphean stromatolites, slates, phyllites, quartzites, flysch and Permo-Carboniferous tillites. The rocks have been transported southwards in several thrust slices (e.g. the Krol and Chail nappes).

The MCT is a thrust that has problems of definition (Sinha Roy 1982). It has a displacement of more than 100 km (Andrieux *et al.* 1981). In Nepal it is represented by a 10 km wide ductile shear zone (Bouchez & Pecher 1981). Inverted, 'Barrovian-type' isograds are parallel and genetically related to the northward-dipping MCT (Le Fort 1975). Problems associated with the origin of this reversed metamorphism are discussed later.

The MBT underwent movement in the Pliocene–Pleistocene that folded the overlying nappes.

(*g*) *The Karakoram Terrane*

This tectonic zone is situated between the Pamir–Kun Lun Ranges and the Kohistan–Ladakh Terrane. Early reconnaissance on the geological evolution of the Karakoram was reviewed by Desio (1979). Recent detailed work has only been undertaken in the southern and central sectors of this very high mountain range (Rex *et al.*, this symposium). The central Karakoram is dominated by the composite granitic batholith, which evolved in two major stages. (1) Subalkaline to calc-alkaline hornblende-bearing granitic rocks have a U–Pb age of 95 Ma (Le Fort *et al.* 1983*b*) and a Rb–Sr whole-rock age of 97 ± 17 Ma (Debon *et al.* 1987). These subduction-related granites were intruded as an Andean-type batholith into the southern margin of the Karakoram Terrane. (2) Mildly peraluminous granites were intruded at *ca.* 20 Ma; they formed as a result of crustal thickening and partial melting of crystalline basement (Searle *et al.* 1988; Rex *et al.*, this symposium).

South of the batholith there is a high-grade metamorphic series consisting of sillimanite gneisses, kyanite–staurolite–garnet mica schists, marbles and amphibolites (Searle *et al.* 1988). These represent shales, carbonates and minor volcanics that reached peak metamorphic conditions at 550 °C and 5.5 kbar† at a depth of about 17.5 km. Uplift of these mid-crustal rocks with older components of the Karakoram batholith took place along the hangingwall of the Main Karakoram Thrust, which has been interpreted as a late-Tertiary breakback thrust (Rex *et al.*, this symposium).

(*h*) *The Shyok* (*Northern*) *Suture Zone*

This suture zone is commonly but inappropriately termed the 'Northern Suture' in Pakistan (Pudsey *et al.* 1985*a*; Coward *et al.* 1986; Pudsey 1986), and the Shyok Suture in NW India (Rai 1982, 1983; Thakur & Misra 1984). It joins the late-Palaeozoic shelf sediments in the western part of the Karakoram Terrane with the Cretaceous Kohistan–Ladakh Terrane. In Pakistan the suture is a zone of mélange 150 m–4 km wide which contains blocks of volcanic greenstone, limestone, red shale, conglomerate, quartzite and serpentinite in a slate matrix; the mélange is interpreted by Pudsey (1986) as an olistostrome, largely derived from the arc to the south. In the Shyok Suture in NW India (Rai 1983; Thakur & Misra 1983) there is a dismembered ophiolite with peridotite, pyroxenite, gabbro, intermediate volcanics and chert. The ophiolite is overlain discordantly by a 500 m thick molasse containing pebbles of granite and rhyolite derived from the Ladakh batholith.

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† 1 kbar = 10^8 Pa.

(i) *Foredeep and intermontane basins*

South of the MBT there is an apron of fluvial molasse sediments constituting the Siwalik Group with conglomerates, arkoses, siltstones and shales, which were derived from the uplift and erosion of the Himalayas and which were deposited in a foredeep along the southern flank of the mountain range. Most modern studies of these sediments have been in the western Himalaya. Sedimentation began at least 15 Ma ago (Johnson *et al.* 1981, 1985). Sedimentation rates ranged from 15 to 52 cm per 1000 years in the last 13 Ma; this is comparable to the uplift rates of the Himalayan source areas. Southward migration of thrusts across the foredeep has folded and thrust the Siwaliks. However, although the rate of convergence of the Indian subcontinent with Eurasia appears to have been steady in the time concerned, detailed studies of these sediments show that prolonged periods of tectonic quiescence and uniform molasse sedimentation were punctuated by brief, intense intervals of deformation as the locus of thrust faults encroached in a stepwise fashion across the foredeep (Burbank & Raynolds 1984).

The Peshawar and Kashmir Intermontane Basins are situated just north of the MBT and thus are embedded in the still-developing thrust belt (Burbank & Johnson 1983). They contain up to 1300 m of Plio-Pleistocene synorogenic sediments. Basin sedimentation began by 4 Ma in the Kashmir and 3 Ma in the Peshawar Basin at rates of 16–64 cm per 1000 years (Burbank & Johnson 1983; Burbank & Tahirkheli 1985). During the Pliocene sedimentation patterns were related to the uplift of the Pir Panjal and Attock Mountain Ranges respectively.

3. TECTONIC PROBLEMS

There is considerable controversy about a variety of key tectonic problems, which will now be briefly discussed.

(a) *Models of Himalayan structure*

There are several models for the structure and tectonic evolution of the Himalaya that are based on the concept of the drift and collision of India into Eurasia. These all recognize the Indus–Zangbo Suture as the main collisional boundary formed in the early Tertiary, the progressive southward migration of the locus of thrusting through the Tertiary, and the MCT as a major intracontinental thrust formed in the mid-Tertiary as a result of the thrusting of the mid-crustal Tibetan slab over the upper crust to the south. However, these models differ considerably in their interpretation of the structures formed in the late Tertiary.

An important development in the ideas on Himalayan structure came with the recognition of Seeber *et al.* (1981) (see also Seeber & Armbruster 1984), that in the western Himalaya, earthquake foci indicate the presence of a major detachment surface that dips shallowly to the north. Before this discovery, the MCT had to join the MBT at depth (Powell & Conaghan 1973; Powell 1979). The importance of the detachment surface is enhanced in the model of Ni & Barazangi (1984) in which it extends under the Tibetan slab and under Tibet north of the Indus–Zangbo Suture.

(b) *The deep structure of Tibet*

The Tibetan crust is 60–70 km thick (Hirn *et al.* 1984; Hirn, this symposium). Several models have been proposed to explain this anomalous structure. (*a*) Following Argand (1924), Powell (1979, 1986), Powell & Conaghan (1975), Barazangi & Ni (1982) and Knopoff (1983) suggested that the Indian crust was thrust under Tibet, so doubling the crustal thickness.

According to this model there should be geophysical evidence under northern Tibet of a remnant northward-dipping subducting slab. From palaeomagnetic data, Lin & Watts (this symposium) conclude that since collision at 40 Ma the Lhasa Terrane has moved northwards 2000 ± 600 km; this challenges the underthrusting model for Tibet. (*b*) Dewey & Burke (1973) and Sengör & Kidd (1979) argued that the thick Tibetan crust was caused by intracrustal N–S shortening. The recent geophysical data of Hirn *et al.* (1984) and Hirn (this symposium) and the geological information of Chang *et al.* (1986) support this idea. According to Chang *et al.* (1986) the Tibetan Plateau has been shortened by at least 40% in post-Eocene times, and this allows all the crustal thickening to be explained by internal deformation. (*c*) Mattauer (1986) proposed that the Tibetan crust is of multiple age and origin. It was thickened during collisional tectonics in the Hercynian, the Triassic, the Jurassic and the Cretaceous, before the post-Eocene intracontinental thrusting and thickening. This idea is increasingly appealing as more information is produced about the Kun Lun, Jinsha and Banggong Sutures. Geophysical evidence for the deep structure of Tibet is reviewed by Molnar (this symposium).

(*c*) *Inverted metamorphic isograds*

Along the length of the Himalaya there are major inverted metamorphic zones related to crustal-scale thrusting associated with the MCT (Bordet *et al.* 1981; Lal *et al.* 1981; Sinha Roy 1981; Windley 1983). Historically, problems have arisen concerning the positioning of the MCT in the different parts of the Himalaya, and this in turn has created confusion regarding which isograds lie above or below this thrust (Sinha Roy 1982). The inverted metamorphism passes upwards from the chlorite–biotite zone through a Barrovian-type sequence of garnet, staurolite, kyanite and sillimanite zones. Migmatites and leucogranites are characteristically developed in the sillimanite zone.

The thermal model of Le Fort (1975), according to which the thrusting caused the inversion, formed the influential basis of most later attempts to explain this metamorphic problem. According to these ideas the metamorphic zones are related to the post-collisional intracontinental thrusts which were responsible for crustal thickening and which reached a peak some 20 Ma after collision with formation of the MCT in the Miocene. An alternative model concerns the thrusting of a hot slab of Central Crystalline gneisses over a cold slab of Lower Himalayan sediments; cooling of the former and conductive heating of the latter would give rise to the inverted metamorphism. Isograds formed at such a major tectonic boundary could be inverted by syn-metamorphic or post-metamorphic folding (Harte & Dempster 1987; Searle *et al.*, this symposium). England & Thompson (1984) demonstrated that thrusting was the most efficient means of producing high-grade metamorphism and melting in a thickened crust, and Jaupart & Provost (1985) showed that thrusting variably affects the thermal conductivity of low- and high-grade rocks, and so gives rise to temperature maxima at shallow depths. The position of the rocks within a thrust slice, and the number of thrust units in the nappe pile both affect the generation of P–T–time paths during growth and uplift of thickened crust (Davy & Gillet 1986). Hodges *et al.* (this symposium) make the first attempt to relate segments of the Himalayan P–T trajectory to specific tectonic events.

(*d*) *Timing of suture formation*

There is serious disagreement about the age of formation of the Shyok (Northern) and Indus–Yarlung Zangbo Sutures, and this raises the question: which formed first? Let us start with the Shyok Suture. Did it form in the Eocene–Oligocene (Brookfield & Reynolds 1981; Andrews-Speed & Brookfield 1982; Reynolds *et al.* 1983; Thakur 1987*a*), or in the late Cretaceous–Palaeocene (Petterson & Windley 1985; Coward *et al.* 1986; Pudsey 1986; Sharma 1986; Debon *et al.* 1987; Srimal *et al.* 1987; Searle *et al.* 1987, 1988; Rex *et al.*, this symposium)?

The following are constraints on this problem. From palaeomagnetic data on a granodiorite from Ladakh, Klootwijk *et al.* (1979) and Klootwijk & Radhakrishnamurty (1981) concluded that after the accretion of the Kohistan–Ladakh island arc to India this combined mass moved northwards over 25° of latitude before colliding with Asia along the Shyok Suture at the Eocene–Oligocene boundary. However, the isotopic age of the palaeomagnetically determined samples was not known, and therefore this conclusion is doubtful, especially in view of subsequent isotopic results, which show that the Kohistan–Ladakh arc-batholith underwent an evolution from at least 100 to 40 Ma (Scharer *et al.* 1984*b*; Petterson & Windley 1985).

Andrews-Speed & Brookfield (1982) concluded that the Shyok Suture did not form until the Oligocene or Miocene, and Brookfield & Reynolds (1981) and Reynolds *et al.* (1983) until the Miocene, because they considered that the Karakoram batholith formed in the Palaeocene and Oligocene–Miocene as a result of northward subduction of oceanic lithosphere sited on the eventual Shyok Suture. However, isotopic data by Le Fort *et al.* (1983), Debon *et al.* (1987) and Searle *et al.* (1988) showed that the calc-alkaline part of the batholith was intruded in the period 110–95 Ma. (Miocene isotopic dates are probably from cooling ages related to uplift–erosion, etc. (Searle *et al.* 1988).)

The most cogent evidence for a relatively early age for the Shyok Suture comes from the Naz Bar pluton, which is an undeformed granite, which transects the suture (figure 6 in Pudsey 1986). Nine ^{39}Ar/^{40}Ar ages on biotites from this granite all lie in the range of late Cretaceous–Palaeocene (D. C. Rex, unpublished data), and preclude the possibility that the suture formed in the mid-Tertiary. Furthermore, dioritic dykes near Gilgit, that cross-cut structures correlated with the formation of the suture (Coward *et al.* 1986), have a ^{39}Ar/^{40}Ar hornblende age of 75 Ma (D. C. Rex in Petterson & Windley 1985). These results indicate that the Shyok Suture must have formed before the end of the Cretaceous (Coward *et al.* 1986), and at the latest before the end of the Palaeocene (Debon *et al.* 1987).

Let us now consider the Indus–Yarlung Zangbo Suture, whose postulated age ranges from 55 to 40 Ma. According to Thakur (1987*a*, *b*) the initial collision of India with Tibet and the Kohistan–Ladakh Terrane was in the middle Eocene, and according to Debon *et al.* (1987) it was close to the end of the Eocene. This conclusion was largely based on the fact that the calc-alkaline plutons of the batholith continued to form until the mid–late Eocene. However, a time lapse of at least 10 Ma may be expected between the closure of an ocean and the final calc-alkaline magmatism (Zhou 1985). More reliable information is provided by a combination of continental palaeomagnetic data and Indian Ocean magnetic anomaly data, which suggest that initial contact between India and Asia occurred at about 55 Ma (Besse *et al.* 1984; Klootwijk 1984; Patriat & Achache 1984). This age is supported by the change from marine to continental (molasse-type) sedimentation in the suture zone after the Lower Palaeocene (Searle *et al.* 1987).

The question arises: did collision take place at different times along the Himalayan belt? From palaeomagnetic data, Klootwijk *et al.* (1985) concluded that anticlockwise rotation of India allowed progressively eastward suturing from about 62–60 Ma in the NW Himalaya to 55 Ma in Tibet; suturing was completed by the end of the Palaeocene. U–Pb radiometric dating of plutons in the Trans-Himalayan batholith led Xu *et al.* (1982) to suggest that collision of India with the Tibetan block occurred at 60 Ma in Ladakh and at 40 Ma in Tibet. However, more recent Rb–Sr isochron dates on plutons in Ladakh (Reynolds *et al.* 1983) and Kohistan (Petterson & Windley 1985) indicate that the plutonic activity continued until 40 Ma, and in turn, this suggests a similar age for the terminal intrusion of calc-alkaline plutons along the Himalayan range.

In conclusion, the best evidence currently available indicates that the Shyok (Northern) Suture formed in the mid–late Cretaceous, and the Indus–Yarlung Zangbo Suture in the Lower–Middle Eocene.

(*e*) *Timing of ophiolite obduction*

Baud *et al.* (1984) and Thakur (1987*a*, *b*) argued that, because the Spongtang ophiolite rests on fossiliferous early Eocene sediments, it must have been thrust southwards onto shelf sediments in post-early Eocene times. Because such a well-preserved slab of ocean floor can only have been emplaced onto the continental margin before the continent–continent collision, this age would imply that Tethys could not have closed until the mid-Eocene. However, such an age contradicts the biostratigraphic and palaeomagnetic data. In contrast, Brookfield & Reynolds (1981) and Brookfield (1981) proposed that the ophiolite was thrust over the shelf sediments in the late Cretaceous and that the formation of the Indus Suture was complete by the Maastrichtian. The problem lies in the interpretation of the thrust history and geometry. Searle (1983, 1986) and Searle *et al.* (1987, this symposium) emphasized the complexity of the three-stage sequence of thrust events (during ophiolite emplacement, during continental collision, and in post-collisional times). Many of the thrusts currently observed formed in the second and third stages, such as breakback thrusts that reversed the earlier stacking order of the thrust sheets. Only the most detailed structural studies will reveal the position and geometry of the stage-one thrusts responsible for the emplacement of the ophiolites.

In summary, a combination of palaeomagnetic, structural and stratigraphic studies indicate that ophiolite obduction could not have been in the post-early Eocene, because Tethys was closed by that time, but rather in the late Cretaceous – early Palaeocene during collapse of the continental shelf and formation of a foredeep, as documented by Brookfield & Andrews-Speed (1984).

4. Conclusions

The Himalaya, the Karakoram and Tibet were assembled by the accretion of continental and arc terranes to Asia. Following the terminal collision of India with the accreted collage to the north, the continued convergence and indentation of India gave rise to some 2000 km of intracontinental shortening. The structural history can be divided into pre-collisional thrusts and obduction of ophiolites, syn-collisional thrusts and suture formation, and post-collisional thrusts and extensional faults. Neotectonics is dominated by extensional structures and related intrusions and extrusions, as a result of thrust-controlled crustal thickening, consequent weakening of the quartz-dominated lower crust, and spreading and stretching of the upper crust.

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