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Preliminary conclusions of the Royal Society and Academia Sinica 1985 geotraverse of Tibet

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The 1985 Chinese/British expedition to the Tibetan Plateau attempted to solve the question of the origin of the very thick crustal rocks in this region. Continuing northwards movement of the Indian plate over the past 38 Myr has given rise to severe folding and thrust faulting, causing crustal thickening by internal deformation. Previous collisions of microplate terranes derived from Gondwanaland occurred during Mesozoic times but the Kun Lun terrane of northern Tibet was already part of Laurasia by the Carboniferous.

THE Tibetan Plateau along the traverse route is underlain by at least three continental fragments successively accreted[1-6] to the southern margin of Asia. On fossil and sedimentary evidence the Lhasa Terrane came from Gondwanaland; the Kunlun Terrane was part of Laurasia in the Carboniferous. The deformation and derivation of Cenozoic deposits suggest that thickening of the Tibetan Plateau crust can be explained by internal shortening and do not support the idea of long-distance underthrusting of the Tibetan Plateau by Indian continental crust. Neotectonic features along the northern half of the route consist of active east-west trending strike-slip faults, thrusts and folds, while along the southern half the previously reported N-S trending normal faults are most prominent.

We present here the preliminary fieldwork results of a geological traverse across the high Tibetan plateau during June and July 1985 which followed the 1,150-km-long Lhasa-Golmud highway. The purpose was to investigate the origin and chronology of successive collisions of continental fragments with Laurasian or Gondwanian provenance, and to determine how the crust of Tibet was thickened. Final interpretation of our work must await the results of palaeomagnetic, geochemical, geochronological, palaeontological, sedimentological and structural laboratory work. High-quality topographic maps at 1:100,000 scale were used, supplemented by LANDSAT and Metric camera satellite imagery. The pre-Cenozoic geology of the region is described from north to south; we divide it here into the Kunlun, Qiangtang and Lhasa Terranes, separated by the Jinsha and Banggong Sutures (Fig. 1).

The Kunlun Terrane

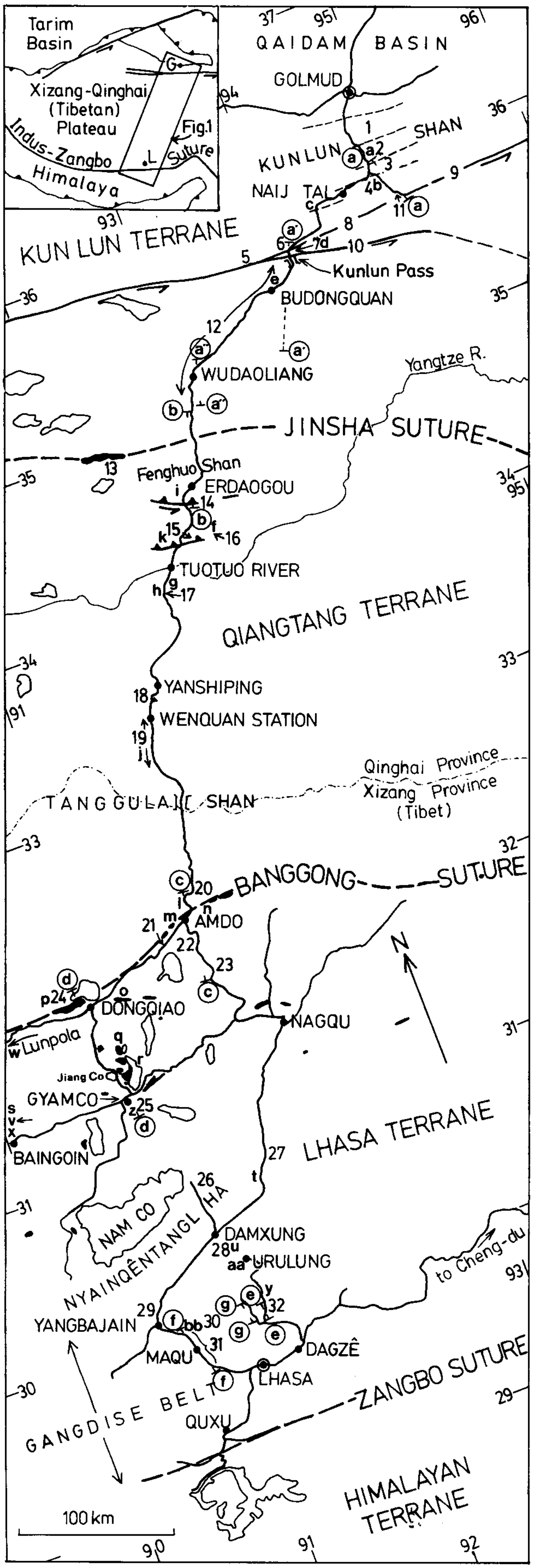
We treat the area north of the Jinsha Suture as a single tectonic unit, the Kunlun Terrane. Based on the presence of an ophiolite belt of late Palaeozoic or Triassic age in the A'nyêmaqên Shan 300 km to the east-southeast, the Kunlun Terrane was previously thought to be made up of two units, separated by the South Kunlun Suture[2]. However, in the geotraverse area, there seems to be lithological and structural continuity across this zone. The oldest fossiliferous rocks seen by us in the central Kunlun, are a thick sequence consisting of turbidites, slates with horizons of graded limestone conglomerates, limestones and minor silicic volcanics (Fig. 1, locality 3). The limestones yield both a Lower(?) and an Upper Ordovician fauna. Further north in the Kunlun are sequences, >1 km thick, of calc-alkaline basaltic, andesitic and rhyolitic lavas (Fig. 2, column *a*), associated with fluviatile redbeds. These are overlain by Lower Carboniferous (Upper Dinantian) carbonate-clastic cycles of marine deltaic origin, which yield Laurasian coral and brachiopod faunas (Fig. 2, *a*).

Apparently unconformable on the Lower Palaeozoic sequence, although faulted against it in the central Kunlun, is a thick, coarse conglomerate containing granite and other boulders. The granites resembles those of the North Kunlun batholith (Fig. 1, locality 1). The conglomerate passes up into a mainly clastic (Fig. 2, column *b*) and volcaniclastic Permo-Triassic sequence, which locally includes 2 km or more of basaltic lavas and tuffs (Fig. 1, locality 4 and Fig. 2 column *c*) and probably originated in a rift. These are succeeded by a thick carbonate succession which ranges up to late-middle Triassic in age.

To the south, between the Kunlun and the Jinsha Suture, there is a wide zone with finer-grained, deeper-water Triassic sediments (Bayan Kala Group), consisting mainly of mudstones with graded wackes (Fig. 1, locality 12 and Fig. 2 column *e*). These are thought to represent an accretionary prism made up of turbidites and contourites, but it is possible that part of the sequence may have been deposited on a passive margin continental rise.

In the northern Kunlun, a prominent feature is an east-trending calcalkaline batholith (Fig. 1, locality 1). Early intrusions are foliated and of a more mafic, dioritic to tonalitic, composition. Later intrusions are undeformed and cut by garnetiferous pegmatites which suggests some crustal melting. This batholith intrudes, but may be cogenetic with, local Upper Palaeozoic volcanics. North of the Xidatan Fault (Fig. 1, locality 8), there is an east-trending belt of calc-alkaline orthogneisses (Fig. 1, locality 6). Around Naij Tal there are several large post-tectonic high-level granites.

Structures in the Kunlun Terrane can be separated into an early Mesozoic and a Palaeogene or younger set. We found no



evidence of major late Palaeozoic compressional deformation. The attitude and scale of the folds (Fig. 3*a*); the nature and intensity of the cleavage; and the magnitude of finite strains in the Lower Palaeozoic and Permo–Triassic rocks appear similar. Pebbles of Upper Ordovician limestone in the Permo–Triassic basal boulder conglomerate show no evidence of predepositional strain. Although all contacts seen are tectonically modified, the thick, Permo–Triassic basal conglomerates and the local absence of Devonian and Carboniferous rocks indicate a substantial unconformity. We believe this unconformity is caused by extensional tectonics. Therefore, the southern limit of strong Late Palaeozoic compressional deformation lies to the north of this transect.

North of the Middle Kunlun Faults (see Fig. 3*a*), strata are affected by open to closed folds and lack an axial-surface cleavage. Between the Middle Kunlun Faults and the Xidatan (locality 8), the very thick sequence of Permo-Triassic sediments, lavas and volcaniclastics is tightly folded, cleaved and shows internal thrusting. The structures are generally upright, but are occasionally overturned to the north. An east-west zone of post-tectonic metamorphism, locally reaching garnet grade, is superimposed on these structures. In the southern Kunlun, the most conspicuous feature is a north-dipping phyllonite zone (locality 7), probably a major detachment (Fig. 3*a*), which contains south-vergent shear sense indicators. South of the Kunlun Pass, steeply dipping to vertical grey-green turbidites, which young to the north, show zones of intense deformation and thrusts almost parallel with bedding. They seem to be part of a heavily imbricated thrust package. Near Budongquan, tight upright folds are seen. South of Wudaoliang, southwards facing originally recumbent refolded folds with an axial-surface cleavage are developed in Triassic flysch (Fig. 3*a*). They vary in orientation around upright folds with a steep axial-surface cleavage. These, in turn, are folded by more open, upright structures. These complexly deformed, well-foliated Triassic rocks are overlain unconformably by folded, but not foliated Palaeogene redbeds. A folded but not foliated sequence of possible Jurassic, locally red, clastics with coal seams, occurs in an intermontane basin (Fig. 1, locality 11) in the south Kunlun (Fig. 3*a*). The basal breccia of this sequence rests uncomformably on marble of probable Permo-Triassic age.

The time of deformation in the Kunlun Terrane is not tightly constrained by direct evidence. However, the prominent north-derived molasse of mid- to late Jurassic age in the Qiangtang Terrane to the south (see below) brackets the event more closely. The main deformation affecting the Permo-Triassic section in the southern Kunlun seems to have begun in the late Triassic or early Jurassic.

The Jinsha Suture

This is represented in the traverse area by an inlier of ultramafics and gabbros (Fig. 1, locality 13), supposedly ophiolitic[2,7], which is surrounded by Palaeogene redbeds. The outcrop, located 60 km west of the road, could not be reached. However, other ophiolites, associated with radiolarites, have been recognized along strike far to the east-southeast and to the west[2,7].

Part or all of the Triassic flysch sequence south of the Kunlun Pass, can be regarded as occupying the suture zone. The overall arrangement of the structures in the Kunlun Terrane (Fig. 3*a*), the southward facing recumbency in the south and, in particular, the north-derived Jurassic molasse south of the Jinsha Suture indicate that the suture dips northwards.

Fig. 1 (left) Map of the traverse routes. Numbers along the routes locate features referred to in the text. Lower case letters, sites of stratigraphic sections shown in Fig. 2. Lines of cross-sections in Fig. 3 are shown by a T at each end with letters in circles adjacent. Black, areas of ophiolite suite outcrop (from ref. 7). Location of map shown in the inset (L and G in this inset are the positions of Lhasa and Golmud).

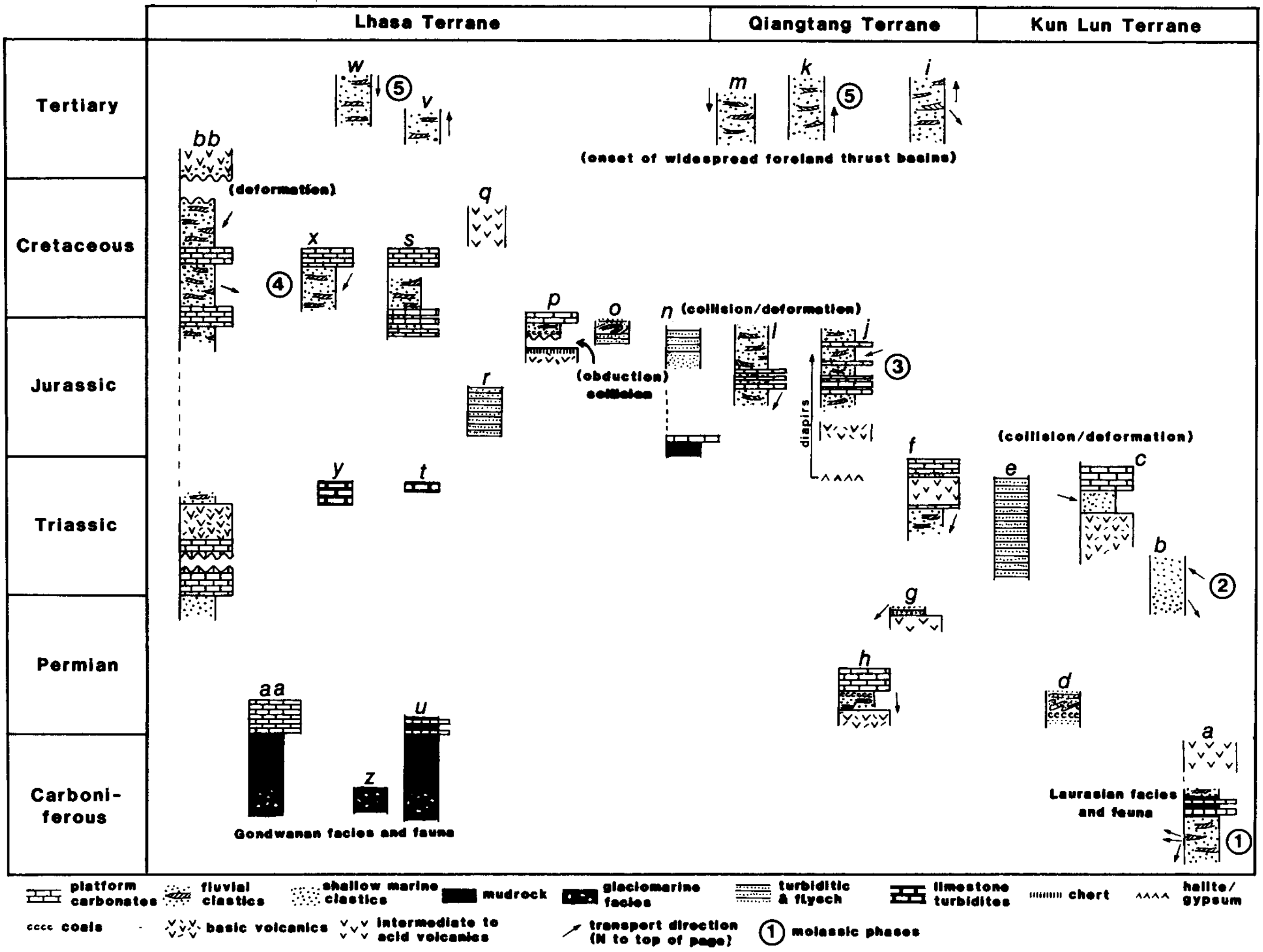


Fig. 2 Schematic sections (no vertical scale of thickness) of the more important stratigraphic sequences examined on the geotravese. Letters (*a–z*, *aa*, *bb*) indicate locations, shown on Fig. 1. Ordovician sections discovered in the central Kunlun are omitted for clarity. Numbers in circles refer to phases of continental molasse sedimentation.

The Qiangtang Terrane

This terrane extends over 300 km, from the Jinsha Suture to the Banggong Suture. The oldest rocks are Permain. In the north, these include fluvio-deltaic clastics with coals and fusulinid-bearing limestones (Fig. 1, localities 15 & 17; Fig. 2 columns *g* & *h*). The flora includes *Gigantopteris*, which is typical of the Cathaysian flora. Associated basalt flows are of transitional to alkalic composition, with silicic centres marked by agglomerates and dacite-rhyolite flows. Both subaerial and submarine volcanics are present and probably indicate a rift setting. Thick Triassic fluviatile gravels, derived from the north, are overlain by plagioclase-pyroxene-olivine phyric flows thought to be part of the basalt-andesite-rhyolite Batang Group which outcrops to the east of the geotraverse (16, *f*). Their mineralogy is consistent with a volcanic arc origin. Preliminary palaeomagnetic results from these lavas show a Northern Hemisphere palaeolatitude close to that expected for the southern margin of Asia in the Triassic. The central and southern parts of the Terrane are dominated by a thick (>2.5 km) mid to late Jurassic fluvial redbed sequence particularly well exposed near Wenquan Station (Fig. 1, locality 19; Fig. 2, column *j*), which interdigitates to the south with an increasingly marine facies of shallow subtidal clastics, calcareous muds and limestones deposited in an offshore shelf basin. Strongly altered mafic lavas occur locally within the Jurassic succession northwest of Wenquan Station. This great northeast derived clastic wedge (molassic phase 3 on Fig. 2) clearly records the unroofing of the newly uplifted Kunlun Terrane.

Jurassic and older rocks of this Terrane are affected by mostly upright southeast- to east-trending folds. In the north, isolated areas of late Palaeozoic to Mesozoic rocks show upright, locally north-verging, open to tight folds lacking, or with, weak cleavage. Near Yanshiping, Jurassic redbeds are locally imbricated and folded above low angle thrusts, which probably decouple on evaporites. A large gypsum diapir has risen in an anticline ~10 km southwest of Yanshiping (Fig. 1, locality 18) and smaller examples were seen elsewhere. South of the Tanggula Shan, the folds are tighter, with a better developed axial-surface cleavage. But nowhere along the traverse in the Qiangtang Terrane are there any intensely-deformed and metamorphosed Mesozoic rocks.

The folding may be of early Cretaceous age. Locally, flat-lying red clastics of possible late Cretaceous or Tertiary age unconformably overlie folds north of Amdo (Fig. 1, locality 20; Fig. 2, column *m*). Near the Tuotuo River (Fig. 1, locality 15; Fig. 2, column *k*) folded Palaeogene red beds unconformably overlie Permian and Triassic rocks.

The Banggong Suture

Isolated outcrops of thrust-bounded ophiolites are distributed over ~180 km in the northern half of the Lhasa Terrane[7,8,9]. The northern limit of the array is a well defined east-west line which is thought to represent the Banggong Suture between the

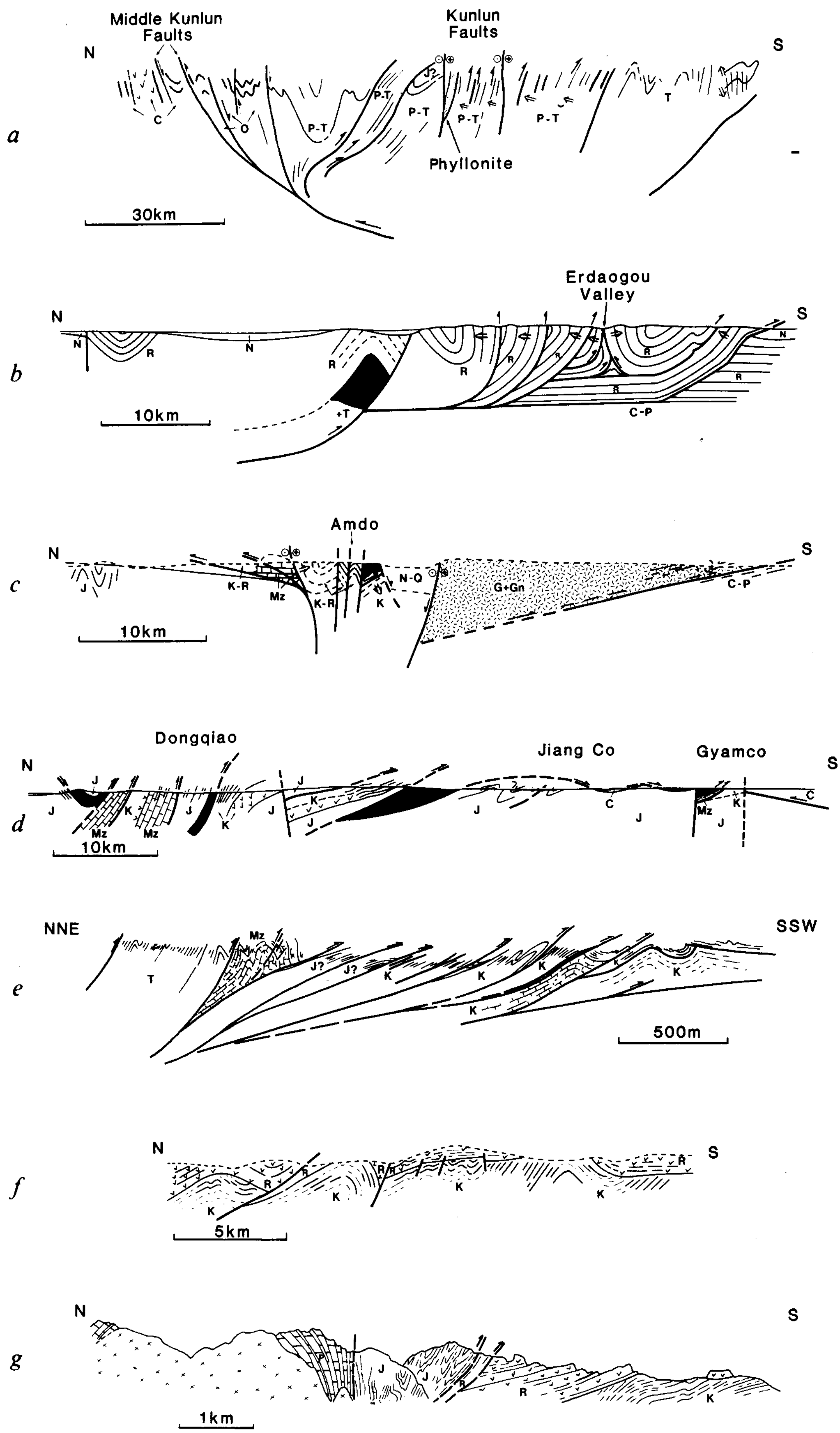


Fig. 3 Selected cross-sections of portions of the geotraverse routes. Locations shown on Fig. 1. O, Ordovician; C, Carboniferous; P, Permian; T, Triassic; J, Jurassic; K, Cretaceous; Mz, Mesozoic; R, Palaeogene; N, Neogene; Q, Quaternary; G, granitic rocks; Gn, gneisses; x, granite; v, volcanics; black, ophiolites; double-shafted arrows, younging directions.

Qiangtang and Lhasa Terranes (Fig. 1). South of the suture, between Dongqiao to Gyamco (~70 km apart), the ophiolite outcrops are closely spaced and probably represent part of a single nappe which is now disrupted (Fig. 3*d*). South of Gyamco, the rarer outcrops of ophiolite are gently dipping and are part of the same ophiolite nappe. Thus, the array of ophiolites represents a single flat sheet, obducted at least 180 km southwards from the suture.

The ophiolites are dismembered[8] but are made up of a harzburgite mantle sequence, a dunite–wehrlite–gabbro–trondhjemite plutonic complex, a sheeted dyke swarm (well exposed south of Amdo (Fig. 1, locality 22)) and basalt pillow lavas. The sequence of crystallization and preliminary geochemical data support a supra-subduction zone origin. The pillow lavas are covered by Upper Jurassic deep-sea sediments.

East of Gyamco, ophiolites, originally obducted in the late Jurassic, early in the collision between the Qiangtang and Lhasa Terranes, are locally thrust over red clastics, of probable Cretaceous age. The timing of collision and ophiolite obduction is marked by a Middle and Upper Jurassic flysch sequence consisting of cleaved black mudstones with limestone turbidites which pass upwards into a thick sequence of distal clastic turbidites, and southwards into interbedded limestones and brackish clastics. This sequence (Fig. 2, phase 4) represents flexural subsidence caused by ophiolite obduction and thrust loading in the north. A few kilometres west of Dongqiao (Fig. 1., locality *p*) (24, p), harzburgite is unconformably overlain by soil horizons formed in a seasonally humid climate. These underlie coastal plain clastics which are overlain by cross-bedded chromite-rich fluvial sandstones. *Cladocoropsis* patch reefs of late Upper Jurassic age cap this sequence. West of Dongqiao, a calc-alkaline granodiorite/diorite pluton gives a preliminary isotopic age of ~130 Myr.

The Lhasa Terrane

This terrane extends over ~350 km, from the Banggong Suture southwards to the Indus–Zangbo Suture, which is the northern limit of exposure of the Indian continental crust. The age of basement in the Lhasa Terrane is indicated by a zircon age of 530 Myr from high-grade anatectic gneisses south of Amdo (Fig. 1., locality 23) and inherited zircon ages of ~2,000 Myr from the Yangbajain granite[10]. The gneisses near Amdo show a complex deformation history. An initially intense tectonic fabric was isoclinally folded in amphibolite facies, the isoclines were reoriented by later east-west folds which were carried south on major biotite-grade shear zones and later brittle thrusts (Fig. 3*c*). Only the later stages of fold and thrust deformation are recognized in the adjacent Mesozoic rocks. No stratigraphic contacts between the gneisses and younger sediments were seen.

The oldest fossiliferous sediments in the Lhasa Terrane (Fig. 2) are Upper Carboniferous and contain a low-diversity Gondwanan fauna which includes brachiopods, bryozoans and solitary corals. Other sediments include a mixtite, containing pebbles of various granites, feldspar-phyric felsite, quartzite and other exotics in a matrix of silty mudstone which is finely laminated in places. Striated pebbles were found in two localities. Pebbles penetrating siltsone laminae must be dropstones. This mixtite, previously known[11] near Urulung about 70 km north of Lhasa, has now also been recognized east of Damxung (Fig. 1, locality 28; Fig. 2, column *a*) and near the northern margin of the Lhasa Terrane, ~10 km south-southeast of Gyamco (Fig. 1 locality 25, Fig. 2 column *Z*). We believe it represents a glaciomarine shelf-basin deposit (contrary to some previous opinions[12]). This interpretation and the nature of the fauna lead us to believe that the Lhasa Terrane was derived from Gondwanaland. The late Carboniferous glaciomarine deposits are overlain by shallow sub-littoral sandstones and by Permian shelf carbonates. The Permian fauna is dominated by solitary corals and contains none of the typical Tethyan fauna. This suggests that this Terrane was still part of Gondwanaland in the early Permian.

Thick Triassic platform carbonates contain emersion surfaces, slight internal unconformities and Fe/Mn encrustations. Elsewhere, platform breakup is indicated by limestone turbidites. In the southern part of the terrane, northwest of Lhasa, Triassic(?) mainly basaltic lavas (Fig. 1, locality 30; Fig. 2, column *bb*) a few hundred metres thick, provide evidence for a submarine rift, which we relate to detachment of the Lhasa Terrane from Gondwanaland. Late Triassic and Jurassic reef limestones and clastics[13] overlie the volcanics (Fig. 2, column *bb*) but no intact stratigraphic sections were observed passing down into the Triassic(?) lavas. A very thick (>2 km) sequence of early Cretaceous fluvio-deltaic clastics were later deposited from the north. Abundant granitoid clasts and debris are seen locally towards the north of the Terrane, around Baingoin. A widespread late Aptian–Albian transgression deposited carbonates with orbitolinids[11,13], and local rudist reefs. In the southern part of the Lhasa Terrane, upper Cretaceous fluvial redbeds, derived from the north, are intercalated upwards with volcanics[12,13], which become dominant in the unconformably overlying Palaeogene Linzizong Formation[14].

In the north of the Lhasa Terrane, near Amdo, Cretaceous porphyritic granites (with lower intercept zircon ages of 140–120 Myr[10]) are associated with andesites and rhyolites of Aptian–Albian age (Fig. 1, locality 22). Both plutonic and volcanic rocks are probably post-collisional, and associated with the late Jurassic Banggong Suture. Alternatively, they may be related to northwards subduction under the southern edge of the Lhasa Terrane. Further south is a belt of two-mica anatectic granites (Fig. 1, locality 27) which has given a monazite age of 120 Myr from one pluton at Baingoin[10].

The southern margin of the Lhasa Terrane is dominated by the east-trending 40–90 Myr calc-alkaline Gangdise batholith[12,14] and its associated 1.5 km-thick volcanic sequence (Fig. 1, locality 31; Fig. 2, column *bb*) of late Cretaceous and Palaeogene andesite-rhyolite lavas and pyroclastic rocks, interbedded with continental sediments[15,16]. The northern edge of the Gangdise Belt lies just north of Yangbajain, where a sequence of potassic lavas (Fig. 1, locality 29) was identified. Most of the Gangdise Belt traversed is attributed to magmatism at an active continental margin above a northward-dipping subduction zone[1,2,12]. The Nyainqêntanglha Range exposes a biotite orthogneiss in contact with staurolite, garnet and andalusite bearing metasediments. The zircon age[10] of <50 Myr from the orthogneiss suggests that it may represent uplifted deeper levels of the Gangdise batholith.

Most of the Mesozoic sediments and volcanics north of the Zangbo suture have upright folds, occasionally overturned and south-vergent. The steep cleavage is cut locally by a later gently dipping crenulation cleavage, but we found no evidence of the earlier structures reported by Burg *et al.*[17]. Mesozoic strata to the south of the Zangbo suture are intensely deformed with complexly refolded recumbent folds, unlike equivalent age strata of the Lhasa Terrane[17]. Representative sections for this terrane are shown in Fig. 3*d–g*.

At three localities in the terrane, fluvial clastics containing limestone were observed to overlie older deformed rocks with angular unconformity. Near Dongqiao (Fig. 1, locality 24; Fig. 2, column *p*) pre-Cretaceous obduction of the Banggong Suture ophiolite is demonstrated by this relationship[8]. In the Nyainqêntanglha range north of Damxung Fig. 1, locality 2, Cretaceous redbeds with thick basal breccias lie unconformably on strongly foliated calc-phyllites of possible Jurassic age. In both these examples, the clastics overlying the unconformity are themselves well folded and affected by thrusts, but are not cleaved to any significant extent. At Maqu (Fig. 1, locality 31) farther south near Lhasa, Upper Cretaceous red clastics with volcanics are folded, but not strongly cleaved, and are unconformably overlain by Palaeogene volcanics which are not significantly folded

(Fig. 3*f*). No demonstrable structural break has been found between the little foliated Upper Cretaceous redbeds seen at Maqu and the generally strongly-cleaved older Mesozoic rocks near Lhasa. If this contrast reflects different structural levels of the same deformation, the pre-60 Myr, pre-Indian collision deformation[18] of the late Cretaceous at Maqu could be either a younger stage (by ~75 Myr) of collisional deformation still migrating south from the Banggong Suture, or be caused by compressional tectonics in the back-arc region of the Gangdise-Andean Arc. Alternatively, if the contrast results from an (undetected) pre-late Cretaceous unconformity (as seen in the northern Lhasa Terrane), the folding of the late Cretaceous at Maqu is probably a back-arc event for the Gangdise Arc. This late Cretaceous-early Palaeogene folding event in the southern Lhas Terrane, if separate from the Banggong Suture-related deformation, might also include folds and thrusts that affect the mostly Cretaceous–Palaeogene redbeds in the northern area. However, some or all of these structures in the northern Lhasa Terrane may be post-Indian collision in age. In much of the Lhasa Terrane, it is not yet possible to separate structures formed before and after the beginning of the Indian–Asian collision.

Palaeogene crustal shortening

Intermediate and silicic volcanics are dominant in the Palaeogene Linzizong Formation in the southern Lhasa Terrane. Farther north, thick Tertiary fluvial redbeds fill thrust bounded foreland-type or intermontane basins. Near Baingoin, orbitolinid-rich clasts in the redbeds are derived from a north-facing thrust-scarp of Mesozoic rocks. In the nearby Lunpola basin[19] (Fig. 1) northern-derived Eocene-Oligocene redbeds are strongly folded and are thrust, from the north, over more gently folded Pliocene lake beds.

Near Amdo, thrusted and folded late Cretaceous(?) and Tertiary northern-derived redbeds rest unconformably on more tightly folded Jurassic rocks (Fig. 1, locality 20; Fig. 2, columns *l, m, n*) of the southernmost Qiangtang Terrane and on rocks of the Banggong Suture zone. In the northern Qiangtang Terrane, and overlapping the Jinsha Suture zone onto the southern edge of the Kunlun Terrane, strongly folded Palaeogene redbeds form a belt north of the Tuotuo River (Fig. 1, locality 15; Fig. 2, column *k*) (15, k) and another around and north of Erdaogou (the Fenghuo Shan) (Fig. 1, locality 14; Fig. 2, column *i*). Much of the red arenite and conglomerate forming these thick (>2 km) fluviatile sequences in the northern Qiangtang Terrane is derived from the south, but a proportion has northerly provenance. The existence of these foreland-type and ramp valley basins, as well as the deformation of the sediments is evidence for lithospheric loading and shortening.

At Maqu (Fig. 1, locality 31) the Palaeogene volcanics are gently warped (Fig. 3*f*), suggesting[11] that the post-Eocene deformation is negligible. However, in this general area (Fig. 1, locality 32), prominent southwards thrusting[11,17] of Jurassic rocks over the Palaeogene section was confirmed (Fig. 3*f, g*). Other post-Palaeogene thrusts, some with a component of strike-slip displacement, occur across the entire plateau, notably near Baingoin, bordering the Lunpola basin west of Amdo (locality 21), and locations 10 km and 40 km south of Erdaogou (Fig. 1, locality 14). The Palaeogene redbeds have been strongly folded across the whole of their exposure. In the Fenghuo Shan (Fig. 1, locality 14), the shortening from folding alone (Fig. 3*b*) is estimated to be ~40% over 30 km. A comparable shortening is seen in the Palaeogene redbeds exposed both 30 km further north near Wudaoliang, and 40 km south near the Tuotuo River. If the deformation in these fairly extensive, but isolated, redbeds is representative of the whole, the Tibetan Plateau has been shortened by at least 40% in post-Eocene times. This order of magnitude allows all the crustal thickening of the Tibetan Plateau to be explained by distributed shortening[20,21] within the Tibetan crust. If there were no post-Eocene shortening between the Palaeogene outcrops, the estimate of overall shortening caused by folding would be ~12%; insufficient to explain all the thickening. Because this estimate ignores large-scale thrust faulting, 12% shortening is considered to be an extreme lower limit. The low metamorphic grade of the rocks exposed along the traverse suggests that there would have to be many small displacement thrusts if thrusts contribute significantly to crustal shortening and thickening. Thrusts which are known to have moved after the start of the Indian collison (Fig. 3*b, c, e, f, g*) are consistent with this idea.

If large-scale underthrusting of Asia by Indian crust is proposed to explain crustal thickening[22–26], a systematically migrating elevation front generating southern-derived molassic sediments might be expected. We found no evidence for such systematic migration and derivation of the Palaeogene and Neogene sediments. Previous palaeomagnetic studies[27–29] and our preliminary results imply large amounts of crustal convergence within the southern part of Asia since the Indian collision began. The question of how this is divided between north–south shortening and tectonic escape on strike-slip faults is still to be resolved.

Neotectonics

Concordant summit levels, with rare peaks standing somewhat above that level, are a conspicuous feature of the landscape of the Tibetan Plateau. This morphology may be the product of erosion surfaces formed by scarp retreat (pedeplains). In the south, near Nagqu, such a surface seems to be locally overlain by Pliocene[30] deposits. In the north, near Wudaoliang, Pliocene[31] beds also overlie eroded Palaeocene and older rocks, but the Pliocene strata here have also been involved in folding with the development of new local erosion surfaces. In most places, the ages or relative extents of these surfaces are not known, and it cannot be assumed that the surfaces are of the same or similar ages everywhere. The existence of these surfaces does not preclude significant north–south shortening by folding and/or faulting of the substrate in the Neogene—note the folded (and perhaps actively folding) Pliocene strata near Wudaoliang, and in the Lunpola Basin—nor do they imply any hiatus in convergence between India and Asia since the collison began.

The Tibetan Plateau is a region where active seismicity and faulting has influenced much of the present topography. In central and southern Tibet most of the recent structures are north-trending. Normal faults and strike-slip faults mostly trend either WNW or ENE. As demonstrated by previous work[32–34], these structural trends are consistent with a presently dominant east–west crustal extension in Southern Tibet and the northern Himalaya. We saw no evidence of north–south normal faults north of Wenquan Station, located half-way across the Plateau (Fig. 1). North of that point, a large east–west strike-slip fault zone (described below) is the most prominent structure, but evidence for north–south compression by thrusting and folding of late Cenozoic sediments was also seen. North and south of Wudaoliang (Fig. 1), Neogene strata are warped or gently folded over an extensive area and, near Erdaogou (Fig. 1, locality 14), seem to be overthrust by Palaeogene redbeds. Probable antecedent drainage across this thrust suggests that it was active in the Neogene, and possibly the Quaternary. Farther south, in the region of the active normal faulting, young thrusting is suggested by strongly antecedent drainage across the redbed range at Amdo (Fig. 1, locality 21). Folding of Pliocene lake beds in the Lunpola basin also requires at least local north–south shortening in this southern area in recent geological time[35].

Two strands of the strike-slip fault approach each other near the Kunlun Pass at the southern edge of the Kunlun. Evidence for Recent slip on the Kunlun Pass Fault (Fig. 1, locality 10) is visible from near the pass to at least 25 km to the east. Small stream valleys from mountains to the north are offset left-laterally ⩾50–135 m. Large streams are offset more than smaller ones. An active glacier is deflected 70 m and its terminal moraine and eastern lateral moraine more than 100 m If the valleys were formed in the Holocene, as their morphology suggests, the slip rate is probably 5-10 mm yr^{-1}.

The Xidatan Fault (Fig. 1, locality 8) is a more important structure and continues for several hundred kilometres to the east, where it is clearly active[36,37]. In both the Xidatan, and the Dongdatan (Fig. 1, locality 9) the fault zone is marked by prominent pressure ridges, large tension gashes (up to 2 m deep) and left-lateral offsets of small streams and fans by up to tens of metres. The large scale and the steep sides of the tension gashes imply that a large earthquake occurred on this fault within the past few hundred years. This inference is supported by the length of the zone of disruption which was observed in two segments each ~35 km in length located 35 km apart. The average displacement for this earthquake based on the offset of drainage features was as much as 10 m.

Evidence for substantial left-lateral slip on the Xidatan Fault during the Quaternary is clear. South of the Xidatan and north of the Kunlun Pass (Fig. 1, locality 7), the mountains are covered by a moraine containing boulders of Triassic slates and phyllites, granite, pyroxenite and hornblende gabbro. The moraine is overlain by imbricated stream gravels which have a northeasterly source. These gravels are overlain by varved lake sediments, northern-derived gravels and sands and an upper moraine which lacks pyroxenite and gabbro clasts. This sequence dips southwards at 10-15°. The moraines apparently came from the north[38], probably from mountains now located further west, north of the fault. West of the Kunlun pass and north of the fault, granite and Triassic slates and phyllites outcrop extensively. At one locality only, 30 km west of the eastern edge of the moraine, exposures of hornblende gabbro and pyroxenite were found (Fig. 1, locality 5). We infer that the moraine was left by a glacier that flowed southwards across this pyroxenite and was subsequently displaced.

The age of the lower moraine is probably Late Pliocene, or Pleistocene. From magnetostratigraphy of the overlying lake beds, it has been inferred[39] that the age of the moraine is ~2.8 Myr. This implies an average Quaternary slip rate of at least 11 mm yr^{-1} for the Xidatan Fault. If both fault strands moved throughout the Holocene, a total rate of 20 mm yr^{-1} for both in this interval seems a likely lower limit.

Conclusions

The pre-Tertiary geology of the Lhasa-Golmud traverse route defines three micro-continental fragments, the Kunlun, Qiangtang and Lhasa terranes, separated by the Jinsha and Banggong sutures. Faunal assemblages and a glaciomarine mixtite indicate a Gondwanian origin for the Lhasa Terrane. Rifting and separation from Gondwana probably took place in the Triassic. Permian flora in the Qiangtang Terrane has Cathaysian affinities. Rifting and separation from Gondwana probably occurred in the pre-Permian. Lower Carboniferous fauna in the Kunlun is Laurasian. Pre-late Palaeozoic metamorphic basement was seen only in the Lhasa Terrane but is predicted (from the largely shelf-type sediment sequences) to underlie both the other terranes. The micro-continents were successively accreted to the southern Eurasian continental margin[1-6]. Major deformation and detrital sedimentary wedges indicate the beginning of the collision of the Qiangtang and Kunlun Terranes in the late Triassic-early Jurassic, and of the Qiangtang and Lhasa Terranes in the middle-late Jurassic.

No evidence of late Palaeozoic compressional deformation was found in the Kunlun Terrane, which indicates, together with the fauna, that it was already part of Eurasia by the Carboniferous. Thick sequences of Palaeogene fluvial redbeds deposited in thrust-bounded intermontane basins are found at intervals across the Plateau. Strong folding and thrusting of these sequences suggests that much, if not all, of the thickening of the 70-km-thick Tibetan Plateau crust can be explained by shortening. The provenance, deformation, and distribution of these redbeds provide no support for models calling for extensive underthrusting of the Plateau by the Indian crust.

North-south normal faults and associated strike-slip faults allowing east-west crustal extension are restricted to the southern half of the traverse route. The northern half of the route reveals evidence for late Cenozoic north-south shortening and eastward tectonic escape along left-lateral east-west trending strike-slip faults. We found a Quaternary left-lateral displacement of 30 km on the Xidatan Fault and estimate a Holocene total slip rate of 10-20 mm yr^{-1} across both strands of the Kunlun strike-slip fault.

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