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The structure of the 1985 Tibet Geotraverse, Lhasa to Golmud

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With an appendix by Zhang Hu

The structures of Tibet were generated during the accretion on to the Asian plate, firstly of the Qiangtang Terrane during the Triassic, then the Lhasa Terrane during the Jurassic–Cretaceous and finally the Indian continent during the Palaeogene. The southern Kunlun mountains show intense deformation associated with the accretion of deep water sediments on to an active plate margin. The deformation was essentially by footwall propagation of thrusts, though there was pronounced out-of-sequence thrusting with the deformation of basins above the main thrust zone, and the back steepening and backthrusting of earlier structures. The Jinsha Suture probably represents the southern edge of this zone.

The Banggong Suture between the Qiangtang and Lhasa Terranes is characterized by pre-collisional ophiolite obduction for over 100 km to the south across the Lhasa Terrane, plus local intense intracratonic deformation of parts of the Lhasa Terrane. However, for this collision there is now very little evidence for intense deformation along the line of the suture and the Qiangtang Terrane itself remained only weakly deformed throughout.

Post-Middle Cretaceous, pre-Tertiary deformation of the Lhasa region produced upright- to north-verging folds which decrease in intensity northwards. They may have been formed at the margin of the Gangdise batholith, or they may have originated from early collisional phases along the line of the Indus–Zangbo Suture. However this deformation is approximately synchronous with the more intense deformation of the Xigatse flysch on the accretionary prism and is therefore probably subduction-related, predating collision.

Tertiary deformation is relatively widespread across Tibet, producing SSE-directed thrusts across the Fenghuo Shan region of the Qiangtang Terrane and across the northern part of the Lhasa Terrane. Several hundred kilometres shortening can be estimated to have occurred during this deformation, probably reworking older Mesozoic structures. However this shortening is insufficient to provide all of that estimated from palaeomagnetic work or from a study of displacement rates of the Indian plate, and much of the displacement of India into Asia during the Tertiary must be taken up on strike-slip faults in Tibet or on thrusts and strike-slip faults in central Asia north of the Tibetan Plateau. The Tertiary shortening cannot account for all the thickening of the Tibetan crust.

1. Introduction

The structural history of Tibet involves the accretion of several crustal blocks on to the Asian continent (Li *et al.*, 1979; Bally *et al.* 1980; Chang & Pan 1981; Sengör 1984; Zhang 1984; Chang *et al.* 1986). The earliest sutures formed in the region of the Tien Shan–Junggar Basin during the late Palaeozoic (Zhang 1984; Watson *et al.* in press), accreting what is here termed the Kunlun Terrane on to the Asian Plate. On the section line covered by the 1985 Geotraverse, however (figure 1), only the sutures south of the Kunlun Terrane were examined; these developed in sequence from north to south (see Chang *et al.* 1986). The Jinsha Suture joins the Qiangtang and Kunlun Terranes and formed in the Triassic. The Banggong Suture joins the Lhasa and Qiangtang Terranes and formed in Jurassic–Cretaceous times. The Indus–Zangbo Suture between the Indian and Lhasa Terranes was the last to form in the early Eocene.

Structures were produced during each phase of accretion. Sometimes they represent pre-collisional deformation; elsewhere they may reflect terrane collision or the late to post-collisional shortening of rocks on either side of the suture. Sometimes accretion formed only narrow zones of deformation, but in the collision which produced the Indus–Zangbo Suture, during the accretion of the major Indian continent, there was late to post-collisional deformation for a large distance across the Indian sub-continent to the south, and across much of central Asia to the north. Apart from these structures which can be tentatively related to continental or microcontinental collision, there are also several enigmatic phases of deformation whose origin is uncertain.

To attempt to unravel this complex history, the structures will be described from north to south, in approximately their sequence of development. The descriptions rely on cross sections, which have been produced from the geological maps made on the Geotraverse (Kidd *et al.*, this volume), stratigraphic information produced by Yin *et al.*, Leeder *et al.* and Smith & Xu. (all this volume) and detailed field observations by the authors. As the traverse strip was narrow and essentially two-dimensional, these cross-sections cannot always be supported by parallel sections, as should be done in any detailed tectonic study of a fold-thrust belt. The cross-sections also have to rely on limited surface data, as generally it was impossible to map sufficient area to produce downplunge projections. Because of the line of traverse, it was often impossible to draw the sections parallel to the thrust transport directions and so material must have moved in or out of the planes of section and they cannot be considered as having undergone plane strain. Furthermore, the fault transport direction was not constant during the deformation. Many regions show a history of deformation involving more than one thrust phase and many of the later thrusts breach earlier thrusts or are cut by later normal or strike-slip faults. Thus it is impossible to produce any truly balanced cross sections through the region (c.f. Dahlstrom 1969; Hossack 1979) and any conclusions concerning the deep structure or the amounts of displacement must be viewed in this light. The conclusions must be considered as educated guesses and hence interpretations will probably change when more detailed and more regionally extensive work is done.

The distribution of terranes and sutures is shown on figure 1, as are the lines of cross-section. The positions of the terrane boundaries follow Chang *et al.* (1986) and rely heavily on the full tectonic interpretation, including stratigraphic, petrological and geochemical data, not just the structural geology.

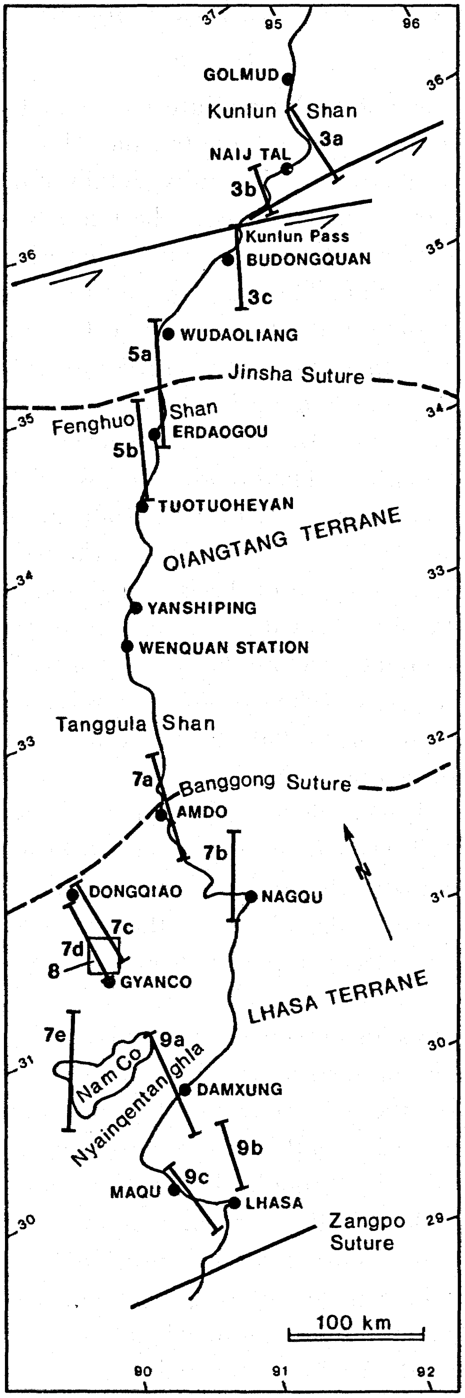

FIGURE 1. Map of the Geotraverse route, showing the terranes and terrane boundaries (after Chang *et al.* 1986) and the section lines described in this paper.

2. STRUCTURE OF THE KUNLUN TERRANE AND THE NORTHERN (JINSHA) SUTURE

(*a*) *General*

In this discussion, the area north of the Jinsha Suture is treated as a single tectonic unit, with structural and stratigraphic continuity across the terrane. Here the stratigraphic sequence is divided into very broad structural-stratigraphic units; details of the stratigraphy are published elsewhere (Yin *et al.*, this volume). In the parts of the main Kunlun ranges traversed there are two older Palaeozoic successions, dated by fossil evidence: one is Ordovician, the other Devonian, Carboniferous and Permian. The sequence consists largely of shales and limestones, though basic volcanics predominate in the Devonian and Carboniferous. To the west of Naij Tal, in the Wanbaogou valley, there is a thick succession of brown-weathering massive limestones which is considered to be Permian in age.

This Palaeozoic succession is overlain by a thick sequence of turbidites, which, especially at the base, are coarse and conglomeratic. The boulders consist of Palaeozoic sediments and also granite rocks which we interpret as probably derived from the Kunlun magmatic arc, dated as end Permian–early Triassic (Harris, Xu, Lewis, Hawkesworth & Zhang, this volume). Hence we consider these turbidites to be of Triassic age and possibly as young as Norian (Leeder *et al.*, this volume). Nowhere was their original stratigraphic contact with the older Palaeozoic rocks seen; the contacts are all faulted or intensely sheared and hence the magnitude of the unconformity between the two successions is conjectural. The turbidites were probably deposited in local basins on the Palaeozoic sediments, but whether the basins were of extensional or flexural origin is uncertain.

Red beds and associated coals were deposited in local basins, probably after much of the deformation. They are dated as Triassic or Jurassic in age by fossil material in the coals. (South of the Kunlun Shan there is a fourth structural-stratigraphic succession, the Bayan Har Group, mainly fine-grained turbidites. No fossil evidence for their age was found from the Geotraverse section, but Triassic faunas have been reported from this zone elsewhere (Yin *et al.*, this volume).)

The distribution of these successions is shown in simplified form in figure 2, as are the lines of section used to describe the Kunlun structure. The sections are (i) in the eastern part of the traverse area, starting north of the area shown in figure 2 along the main valley south of Golmud to Shuinichang (on figure 2) and then up Tuolungou south along the old drovers' road to the Dongdatan valley, and (ii) through the western part of the traverse area from Wanbaogou to the Xidatan valley. Sections through the Bayan Har Group turbidites in the southern part of the Kunlun Ranges are given in figure 3*c*.

The major deformation was Triassic, post-dating the Triassic sediments and predating some early Jurassic granites in the southern Kunlun, which have been dated at about 195 Ma (Harris, Xu, Lewis, Hawkesworth & Zhang, this volume).

(*b*) *The eastern section line*

The eastern section, from about 20 km south of Golmud to the Dongdatan valley, is given in figure 3*a*. In the north, part of the Kunlun batholith, dated as 257 ± 21 Ma (mid Permian) (Harris, Xu, Lewis, Hawkesworth & Zhang, this volume) intrudes openly folded but sometimes steeply dipping Palaeozoic volcanics. Dykes, intruded soon after granite intrusion (Pearce & Mei, this volume), also cross-cut the folded volcanics, indicating that tilting occurred prior to the late Permian–early Triassic.

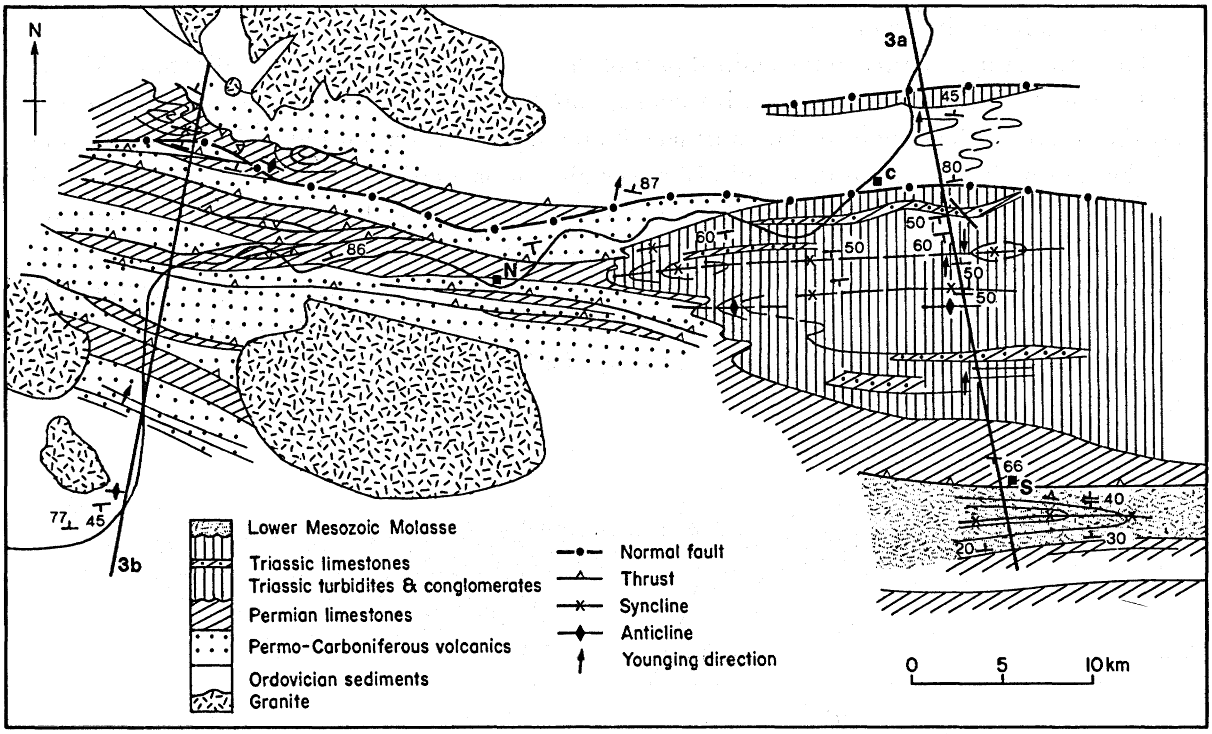

Figure 2. Simplified geological map of the Kunlun Shan, north of the Kunlun Pass, to show the possible correlations between structures shown on the eastern and western cross-sections. Section lines 3*a* and 3*b* are given in figure 4. N = Naij Tal, C = Shuinichang, S = Locality S471.

South of the volcanics and their overlying Carboniferous sediments, there is a series of Upper Palaeozoic fluvial red sandstones, with a weak cleavage and moderately tight upward to northward-facing folds plunging steeply north. The northern boundary of this group of rocks may be a faulted or a normal contact. To the south, most of the rocks carry a penetrative cleavage; the contact marks the northern boundary of the more intense Kunlun deformation. As shown on the section (figure 3*a*), Ordovician shales and limestones are thrust over these Upper Palaeozoic rocks and show tight to isoclinal folding, with axial surfaces which dip steeply to the south, a pronounced cleavage, generally high finite strains and a mineral and stretching lineation with a steep plunge to the south. Triassic conglomerates are downfaulted into this section of Ordovician rocks, in the form of a small wedge, whose master fault occurs on the north side, with a steep southerly dip, similar to that of the thrusts and fold axial planes in the Ordovician rocks. The southern contact of the conglomerates is also tectonic, but is probably close to the deformed unconformity. The finer beds within this Triassic sequence are locally strongly deformed with a strain of similar orientation to that in the Ordovician rocks. Though the contacts between Permo–Triassic beds and older rocks are always tectonic, both groups have a similar deformation history; we saw no evidence within the traverse area for any major phase of folding or cleavage production which affected the Lower Palaeozoic rocks before the Permian, but some of the Permo–Triassic boulder conglomerates contain boulders of limestone of unknown age, which had been deformed before erosion (M. Leeder, pers. comm. 1985).

The map and sections show the fault contacts as essentially thrust or normal faults, however some of the faults crossing this northernmost portion of the traverse route in the Golmud river valley may have Neogene strike-slip components in their overall displacement (see figure 9 of Kidd & Molnar, this volume).

The dominant structure in the central part of the section is a large syncline affecting Triassic rocks, which consist of turbidites with coarse conglomerates, overlain by sandstones in the northern part of the structure. The northern boundary is again a normal fault, downthrowing to the south. The age of this fault is uncertain; it is possible that the fault developed synchronously with the deposition of the turbidites, but it could be a late tectonic structure, post-dating the folding. As the turbidites appear to thicken towards the fault on the section (figure 3*a*), it has some of the characteristics of a growth fault. However, the conglomerates contain boulders of material presumably derived from the Kunlun batholith, over 20 km to the north, that is, they are not locally derived from the fault scarp, as would be expected from a syn-sedimentary fault environment.

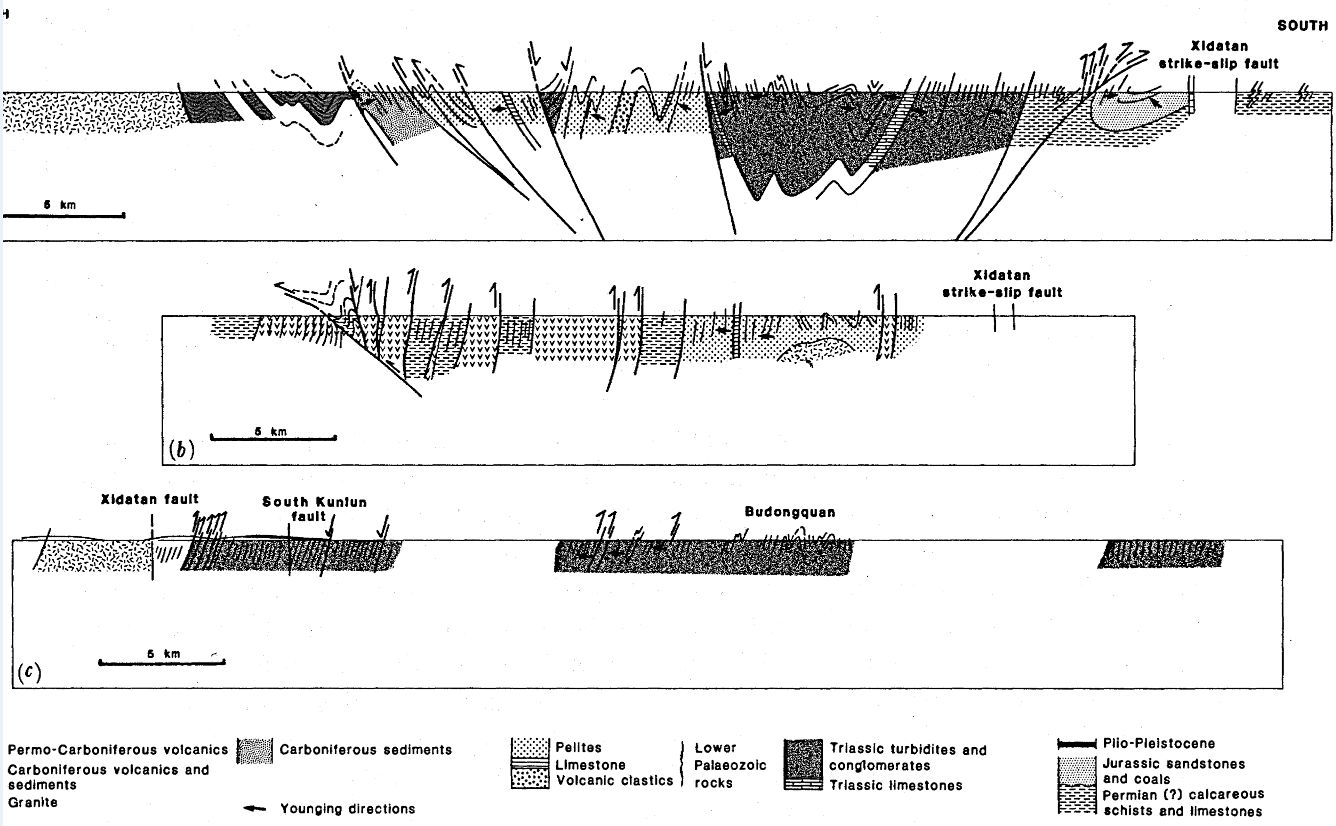

FIGURE 3. Cross-sections through the Kunlun Terrane. Section (*a*) refers to the eastern section of figure 2, Section (*b*) the western section. The location of Section (*c*) is shown in figure 1.

The folds are upright and locally tight, with subhorizontal axes trending east to eastnortheast. Cleavage is well-developed in the medium- to fine-grained rocks, though the pebbles and boulders show variable strains due to the ductility contrast with the matrix. The cleavage is upright, parallel to the fold axial planes and the mineral lineations, where observed, plunge steeply down dip.

To the south, the folds are tighter. The positions of fold axial planes can be determined from changes in bedding-cleavage relations and younging directions, though the exact positions of fold traces are difficult to see as the structures are often isoclinal. A zone, at least 200 m thick, with pebbly horizons (loc. S476), younging north, overlies a zone of intensely deformed shales to the south, with grading indicating that they generally young towards the north. A second-phase crenulation cleavage affects the shales; it dips to the north and is associated with medium-scale south-verging folds and minor shear zones. These folds face downwards to the north or upwards to the south, depending on their position on a first-phase fold. South of the deformed shales there is a zone of intensely deformed slates and limestones, throughout which the bedding and cleavage are parallel, and no clear younging directions were obtained. Mineral lineations plunge to the northnorthwest. The limestone often occurs as discontinuous layers within the shale matrix and appears to be a tectonic melange. Figure 4 shows a sketch map of the structure east of the main track along the Xidatan drovers' trail, (loc. S471, S on figure 2) where the limestone blocks are clearly truncated by a southward-verging F2 shear, which intensifies and locally crenulates the main F1 cleavage. On a larger scale the limestone-shale sequence may be considered as a southerly-directed imbricate zone.

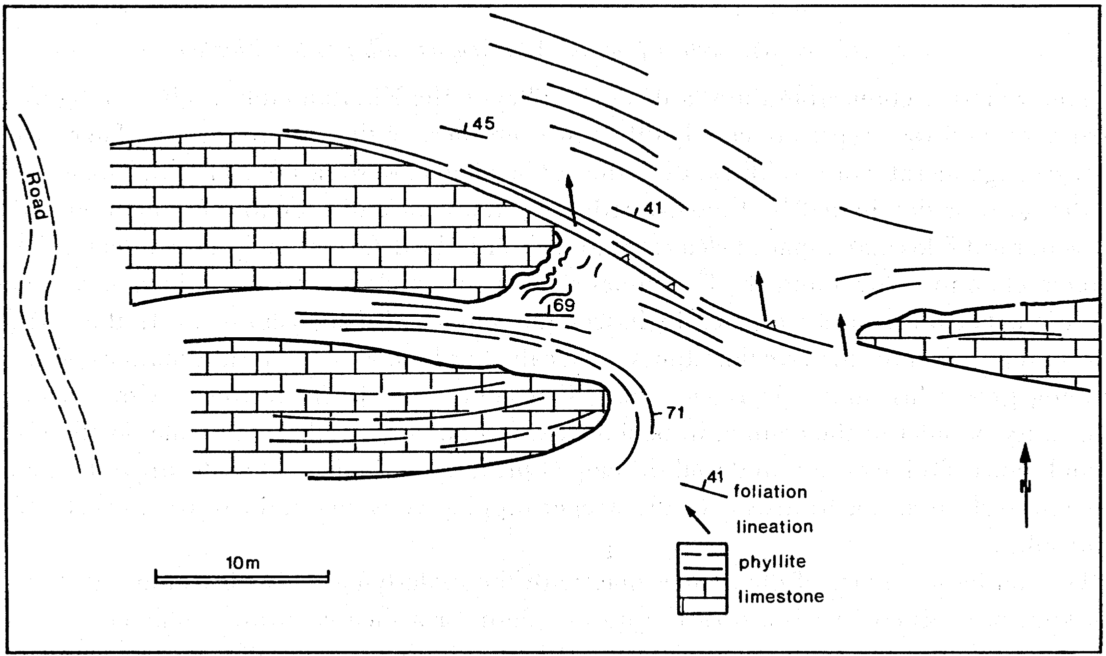

Figure 4. Sketch map of locality S471 on the eastern Kunlun section, to show the shear deformation breaking the structure to give a tectonic melange.

This tectonic melange has been thrust over mudstones, sandstones and conglomerates which are locally red. The deformation intensity and metamorphism are far less in these red molassic rocks than in the slates and limestones to the north, and the basal breccia of this sequence was seen lying unconformably on Permo–Triassic carbonates. Thin shaly coal seams are preserved in places and may be of similar age to thin coals in red beds of late Triassic age in the Xidatan valley farther west, or to Jurassic clastics with coal in the same region (Yin *et al.*, this volume). The dominant structure consists of an inclined south-verging syncline, with an overturned northern limb beneath the footwall of a major thrust, which carries the tectonic melange on its hanging-wall (figure 3*a*).

Beneath the red beds is a series of limestones with a gently dipping tectonic fabric. The limestones are heavily fractured, probably due to the proximity of the Xidatan fault, a major

Neogene to Recent strike-slip fault described fully by Kidd & Molnar (this volume). It disrupts the structural sequence and it is not possible to continue any large-scale structure across the main Dongdatan valley. To the south, the deformation is intense and a main-phase cleavage has been intensely crenulated into south-verging medium-scale folds in limestones and phyllitic sediments.

The overall structure is therefore one of northward-verging folds in the north and upright folds in the central part of the Kunlun, near the Naij Tal valley. These overlie a zone of intensely deformed southward-verging structures in shales and molasse-like red beds which are themselves deformed into a footwall syncline, though they lack the intense cleavage of the rocks on the hanging-wall. The dominant thrusting direction in this southern part of the Kunlun was probably towards the south, as determined from the north-plunging mineral lineations, though there is a slight swing of the lineations to northwest near the Xidatan fault, suggesting a sinistral shear couple. Intense brecciation affects the rocks near this fault, though no small scale kinematic indicators were observed in bedrock.

(*c*) *The western section from the Wanbaogou valley to the Xidatan*

The western section, from the Wanbaogou valley to the Xidatan fault, is given in figure 3*b*. Structures and rock types are clearly different from those of the eastern section. There are no coarse conglomerates or turbidites; these die out in a fold closure east of Naij Tal. The sequence in the north is dominated by brown-weathering limestones, of probable Permian age. They show upright folds and a spaced cleavage; to the south the deformation is more intense, the dip is often close to vertical and the limestones show a strong cleavage with a down-dip mineral lineation. The limestones are generally in tectonic contact with adjacent rocks. In the northern part of the section the massive limestones are locally flat-lying but overlie alternations of steeply dipping greenschist and calcareous schist. This contact is clearly tectonic, with an intense schistosity parallel to the contact in its footwall and hanging-wall. Small-scale north-verging crenulations of this cleavage and well-developed shear bands indicate that the upper limestones have been sheared northwards over the steeper-dipping volcanics and calcareous rocks of the footwall.

The southern contact of these limestones with the underlying schists is tectonized, but it is not known if this contact is a thrust, a normal fault, or a sheared stratigraphic contact. The fabric adjacent to the contact has a steep northerly dip and a down-dip mineral elongation.

To the south, in the Naij Tal valley, there are several alternations of mylonitic limestones and metabasic volcanics. Lithological layering and cleavage are steep and small-scale folds and mineral lineations show a steep plunge to the northnorthwest. The younging directions of these rocks are not known. It is clear that the rocks have been repeated, presumably by thrust imbrication associated with the intense deformation, but it is uncertain which rock has been thrust over which. These lithological repetitions are considered to represent the lateral equivalents of the imbricated tectonic melange zone which occurs in the south of the eastern section (figures 2 and 3*a*, loc. S471).

In the central part of the western section, phyllitic volcaniclastic rocks overlie intensely deformed siliceous pelites and conglomeratic limestones. They have been intruded by sills or dykes of greenstone material, probably related to the overlying volcanic rocks. The conglomeratic limestones are similar to Ordovician conglomeratic limestones which occur near Shuinichang, along the eastern section, and they may be of a similar age. Grading in the overlying volcaniclastics indicates that they young to the north, away from the supposedly Ordovician conglomeratic limestones.

South of the limestones, there is a sequence of arenites and phyllites with locally well-preserved younging directions and angular relationships between bedding and cleavage that enable a structure of upright folds to be discerned, as shown in figure 3*b*. These rocks show a slightly higher metamorphic grade than the others in the Kunlun, possibly up to low amphibolite facies (Harris, Holland & Tindle, this volume).

Though the detailed structure is uncertain, due to the lack of good stratigraphy, the favoured interpretation is one of a sequence of Ordovician limestones and schists, overlain by volcanics and volcaniclastics, possibly of late Palaeozoic age, overlain by brown Permian limestones. These were deformed into a series of upright to south-verging folds and thrusts in this western section, but in the north, later north-verging thrusts carried the Permian limestones over steeply dipping older rocks. The less intensely deformed Triassic turbidites of the eastern section (figure 3*a*) presumably originally overlay the Palaeozoic limestones, shales and volcanics, but disappear to the west, due to easterly fold plunge (figure 2) or, possibly, the edge of the conglomerate–turbidite basin.

The suggested structural correlations are shown on the map of the Kunlun Shan in figure 2, with the major thrust sheets outlined as discussed above. The intense deformation in the Palaeozoic limestones and volcaniclastics of the western section is considered to link with the intense deformation in the tectonic melange in the southern part of the eastern section. The Permo–Triassic turbidites show a less intense deformation and lack the fault repetition. The conglomerates may either (i) predate the intense deformation in the Palaeozoic rocks, but overlie a roof thrust to the intensely deformed structures beneath, or (ii) post-date the intense deformation and hence have formed in a fault-controlled hanging-wall basin above the overthrust Palaeozoic rocks. This latter alternative argues for several phases of superposed co-axial deformation in the Kunlun.

Almost all the deformation predates the intrusion of early Jurassic granites (see Harris, Xu, Lewis & Jin, this volume), which have clearly discordant contacts with the country rock sediments. Along the north side of the Xidatan valley, however, there is an intensely deformed gneissic granite with kinematic indicators suggesting overthrusting to the south. This gneissic granite gives the same radiometric age as the undeformed granites near Naij Tal, supporting the argument for either diachronous or locally superposed deformations.

(*d*) *Kunlun Pass to Budongquan*

South of the Xidatan fault (see figure 3*c*) there is a thick zone of dark grey-black phyllonites which, along much of the Xidatan, adjoin the north side of a tectonically-bounded lens of grey quartzose arenites, slates and olistostromes, with rare silicic tuffs, all intruded pre-kinematically by thick sills and more irregular bodies of altered feldspar and quartz–feldspar porphyry. The arenites are turbidites, which young consistently to the south in steeply north-dipping beds. In one valley, an occurrence of coal yielding a possible Triassic flora occurs near the northern fault boundary. It is unclear if this coal belongs stratigraphically with the turbidites, or is in a structurally isolated sliver along the fault. The coal may be a relict of a basin like that seen farther to the east in the Dongdatan. The fault on the north side of the lens was observed in one locality, where a narrow zone of vertical brittle fault rocks with sinistral strike-slip kinematic indicators was seen. On the south side of the lens, a subvertical fault zone about

150 m wide contains no unequivocal kinematic indicators where seen, although there were questionable structures suggesting south-directed thrusting. This lens is of limited lateral extent, ending eastward before the eastern end of the Xidatan, and to the west where the main road crosses the mountains to the Kunlun pass south of the Xidatan. Beyond these points, the phyllonite is juxtaposed along a steep contact with green phyllitic turbidite arenites and slates (the Bayan Har Group) that extended far to the south.

In the phyllonites, a single strong foliation contains small-scale structures indicating thrusting towards the south, but we have not been able to identify how much shearing and thrust displacement took place on this zone before it was cut by later strike-slip faults. A phyllitic cleavage very nearly parallel, or parallel, to bedding is seen in the grey slate-arenite succession of the tectonic lens and in the green arenites and slates of the Bayan Har Group to the south. In the region less than about 10 km south of the Xidatan and Dongdatan valleys, the foliation in all these rocks, including the phyllonite, is strongly crenulated by folds with gently-dipping axial surfaces and sub-horizontal hinges. These do not have a well-developed axial surface foliation.

The green phyllonitic turbidites are steeply dipping to vertical, young to the north and show phyllonitic zones of intense deformation and thrusts which are parallel to bedding. At least seven zones of intense deformation, considered to be bedding-parallel shear zones, were recognized along the excellent exposures near the Kunlun Pass. Some folds can be identified, but most of the beds dip steeply to the north or south and with few exceptions show cleavage relationships and younging directions which indicate anticlinal closures to the south.

Immediately south of the Kunlun Pass, the structures are masked by Pleistocene glacial deposits, gravels and lake beds and are cut by the Kunlun Pass Fault (see Kidd & Molnar, this volume). However, to the south, there are flags and siltstones with similar structures to those of the Kunlun Pass. The beds are steep, with a cleavage dipping less steeply to the south, indicating anticlinal closure to the south. Local graded bedding shows that the rocks young to the north and occasional cleavage-bearing folds face upwards.

Immediately south of Budongquan, the grey flags and turbidites show a series of tight folds whose axial planes are upright or dip steeply southwards. South of these, there is a region of poor exposure, with local outcrops of well-cleaved slates, but no sign of bedding.

The whole succession of graded flags and shales to phyllonites appears to be over 15 km thick, probably far too thick to be interpreted as an unfaulted sequence. It is interpreted as an imbricated sequence of deep-water sediments, where the beds and the bedding-parallel shear zones and thrusts have been rotated to the vertical by subsequent thrust accretion. From the lineations and folds, the accretion direction was normal to strike, that is north to south; there is no indication of strike-slip deformation before the much younger movements on the Kunlun Pass fault. The amount of shortening is unknown, as there is no undeformed template with which to compare stratigraphic thicknesses. From comparison with other accretionary thrust wedges, the shortening should be at least 50% and from the steepness of the faults and the bedding, and the intensity of the cleavage, it is unlikely to be in excess of 75%.

(*e*) *Budongquan to the Jinsha Suture*

South of Budongquan, the exposure is very poor; most of the deformed rocks are covered by Pliocene to Recent deposits. However, near Wudaoliang there is a set of graded mudstones and siltstones similar to those north of Budongquan. Their structures are shown on the section in figure 5*a*. Three phases of deformation affect the fine-grained turbidites. The prominent folds have axial planes which dip steeply- to moderately-southwards, being folded by a late-phase deformation. There is a main-phase cleavage which is strongly convergent or divergent depending on the competence of the beds and this is deformed by the later-phase crenulation cleavage which dips to the north at a moderate angle; where well developed, it produces a finite pencil cleavage by its intersection with the earlier main cleavage. The main-phase folds show a variation in facing direction. In the northern part of the section they face upwards or northwards, but in the southern part they face downwards, though the main cleavage consistently dips southwards.

The structures, therefore, can be considered in terms of three deformation phases. The first produced a tight to isoclinal fold, with a north-dipping axial plane but no detectable cleavage. The facing direction of this fold is uncertain, but the simplest explanation would be that it faced south. The second, or locally main, phase produced many folds and a well-developed southerly-dipping slaty cleavage, where the folds face upwards on the northern limb of the F1 antiform and downwards on the southern overturned limb. This cleavage was subsequently deformed by north-dipping crenulations.

The age of these structures and their correlation with the structures in the graded siltstones and flags of the Budongquan region is unknown. Immediately south of Wudaoliang, purple sands rest unconformably on the deformed graded mudstones, but are folded into a large open syncline which may be of similar age to the F3 deformation phase in the underlying rocks.

To the south, most of the structure is obscured by Neogene deposits or by Palaeocene red beds, and the nature of the Jinsha Suture is unknown. Outcrops of supposedly ophiolitic rocks are reported from 60 km west of the main road, and other ophiolites associated with radiolarites have been recognized far to the west and eastsoutheast (Chang & Pan 1981). How much deformation was related to this suture and what structures are associated with obduction of the ophiolite are completely unknown.

(*f*) *Summary and interpretation of the structure of the Kunlun Terrane*

The structures can be considered in terms of the accretion of deep water sediments on to a magmatic arc, which punched through a terrane with a cover of Palaeozoic rocks. There is no structural evidence from the present traverse of any basement older than the Palaeozoic rocks, though isotope studies on the Kunlun granites suggest reworking of an older Mid-Proterozoic crust (Harris, Xu, Lewis, Hawkesworth & Zhang, this volume). The Palaeozoic sediments consist of Ordovician volcanic rocks, shales and limestones, which are often conglomeratic and underlie Upper Palaeozoic basic volcanics. Apart from possible minor unconformities, there is no evidence of any deformation affecting these rocks before the deposition of the Permo–Carboniferous sequence. There must have been some pre-Triassic uplift, however, as the Triassic boulder conglomerates were derived from Ordovician rocks and hence the Upper Palaeozoic rocks must have been removed.

The turbidites, coarse conglomerates and boulder beds, east of Naij Tal, presumably represent the proximal phase of Triassic turbiditic sediments deposited on the older Palaeozoic sediments, though all the observed steep contacts are tectonic. The Ordovician sediments are themselves intensely sheared in the region between Naij Tal and the Xidatan, where they are inferred to have been originally thrust over the phyllonites. These phyllonites probably mark the southern edge of the Kunlun Terrane proper and form the zone of most intense deformation. Their lithologic origin is unknown; they may be intensely deformed Palaeozoic sediments or, more likely, Triassic sediments derived from the magmatic arc. The phyllonites were originally thrust over deep water, more distal turbiditic sediments of the Kunlun Pass to Budongquan section. No basement rocks occur in the thrust wedges south of the Kunlun Pass and hence the thrusts probably decoupled above the basement. The original basement under these deep water sediments must have been subducted, presumably to the north beneath the Kunlun. The total section covered by these intensely-deformed sediments is over 100 km across strike. If they originally lay on a continental basement, then, assuming a minimum of 50% shortening, 100 km of that basement would have been subducted beneath the Kunlun. We favour the interpretation that these sediments were deposited on continental margin or ocean floor rocks which were then subducted below the Kunlun, generating the later part of the Kunlun granitic magmatism.

Thus the deep water sediments themselves may be considered as part of the suture zone. There may be several individual sutures within the zone, especially if the accretion involved thicker parts of oceanic crust (seamounts), or arcs. The degree of outcrop south of the Kunlun is insufficient clearly to identify any major thrusts or sutures, and the mapped Jinsha Suture is simply the line of scattered ophiolitic outcrops at the southern edge of this zone. That the structure may be more complex than the normal thrust accretion in a foredeep wedge is indicated by the long fold history near Wudaoliang.

Thus much of the repetition in the deep water sediments may be considered as pre-collisional, during the accretion of ocean floor material. The final arrival of the Qiangtang Terrane must have tightened the structures, steepened the thrusts and possibly produced the south-dipping cleavage at Wudaoliang. The upright folds and southward-directed thrusts in the Kunlun may be pre-collisional or may have developed during terrane collision. Certainly back-steepening of thrusts and tightening of folds affected the Kunlun ranges, with the production of north-verging thrusts at Wanbaogou, carrying Permian limestones back over the intensely deformed Palaeozoic rocks. It also produced the north-verging folds and thrusts, north of Shuinichang. The deformation intensity decreases in the north of the Kunlun range, where, near the main Kunlun batholith, the Palaeozoic sediments and volcanics are not cleaved only, openly folded or faulted. The batholith and associated dyke swarm show no evidence of regional tectonic strain.

Molassic sediments were formed in the Kunlun, particularly along the southern margin, near the present Xidatan fault. These must have developed in some form of inter-montane (piggy-back or pull-apart) basin, to be subsequently incorporated into the late phase of thrust tectonics, which itself might have been in a largely strike-slip setting. Locally this late phase of deformation was as intense as in the Xidatan phyllonites. The Triassic turbidites and conglomerates of the eastern section may also have developed in a syn-tectonic basin, above already intensely deformed rocks. From the deformation state of the granites between Naij Tal and the Xidatan, the deformation must have been diachronous, or there must have been superposed co-axial episodes. Thus though the general accretion can be considered in terms of footwall-propagating thrust tectonics, back-steepening the earliest thrusts, there is clear evidence for later hanging-wall deformation, in the form of the northward-directed thrusts and the deformation of the molassic basins.

The dominant overthrust directions were towards the southsoutheast and northnorthwest, suggesting that this was the main plate convergence vector, as well as the accretion direction of ocean floor material. There is a slight swing of the lineations near the Xidatan zone, suggesting a sinistral shear component here. As this shear deformation does not affect the late granites which punch through the Kunlun, nor are the contact metamorphic minerals deformed by any regional tectonics, we attribute the shearing to Triassic collision.

3. STRUCTURE OF THE QIANGTANG TERRANE

(a) *General*

The Qiangtang Terrane occupies much of the northern part of the Tibet Plateau and extends for over 300 km from the Jinsha Suture south to the Banggong Suture. The stratigraphy is summarized by Chang *et al.* (1986) and by Yin *et al.* (this volume). The oldest exposed rocks are Permian to Triassic in age and include clastic sediments with coals and some limestones, with basaltic and silicic volcanics. However, the sedimentary sequence in the Qiangtang Terrane is dominated by thick (> 2 km) Jurassic molassic deposits, which were presumably derived from the Kunlun Terrane to the north (see Chang *et al.* 1986). No older basement rocks were seen. All show post-Jurassic, pre-Palaeogene deformation, which we interpret as related to the Banggong Suture.

The exposure of the Mesozoic rocks is poor. Most of the Palaeozoic and Mesozoic rocks are covered by Neogene deposits or recent scree and alluvium. In the north, near Erdaogou, there are Palaeogene red beds, which show considerable folding and thrust repetition. This deformation must locally affect the older rocks. Thus the structure of the Qiangtang Terrane will be described in two parts: deformation which affected the Tertiary rocks and that which affected only the older sediments.

(b) *The Tertiary deformation of Erdaogou and the Fenghuo Shan*

Cross sections through the Fenghuo Shan and ranges to the south are shown in figures 5*a* and 5*b*. The eastern section (figure 5*a*) displays open folds in the Palaeogene red beds to the north, but tight to isoclinal structures and southward-directed thrusts in the south. The thrusts and folds are upright, having been back-steepened by the development of lower thrusts in a piggy-back propagation sequence. To the west, (figure 5*b*) the red beds have been further thrust over Neogene sediments south of Erdaogou. There are folds in the Palaeogene red beds on the hanging-wall of a thrust in the hills close to the Tuotuo River (figure 5*b*). Figure 6 shows a composite section through these ranges, where all the thrusts and folds are considered to have developed above a sole fault inclined to the north at the base of the red beds at Erdaogou and on a lower fault within the Mesozoic basement near the Tuotuo River.

The thrusts and folds strike ENE and from slickensides the dominant overthrust direction was towards the SSE, though on some faults there are subhorizontal slickensides indicating a component of strike-slip displacement. The shortening can be estimated at about 40%, possibly up to 50 km across the whole zone. This shortening must have occurred since the Palaeogene.

(c) *Deformation in the Palaeozoic and Mesozoic sediments*

Between Erdaogou and Wenquan Station the Permian and Jurassic sediments show upright folds which are locally tight and have steep northwest-trending axial surfaces. The folds are slightly asymmetric, generally verging towards the north east. There is a weak cleavage in the steeper-dipping beds and the structures are dismembered by numerous steep faults, generally parallel to the fold axial surfaces. Near Yanshiping the Jurassic red beds are folded and

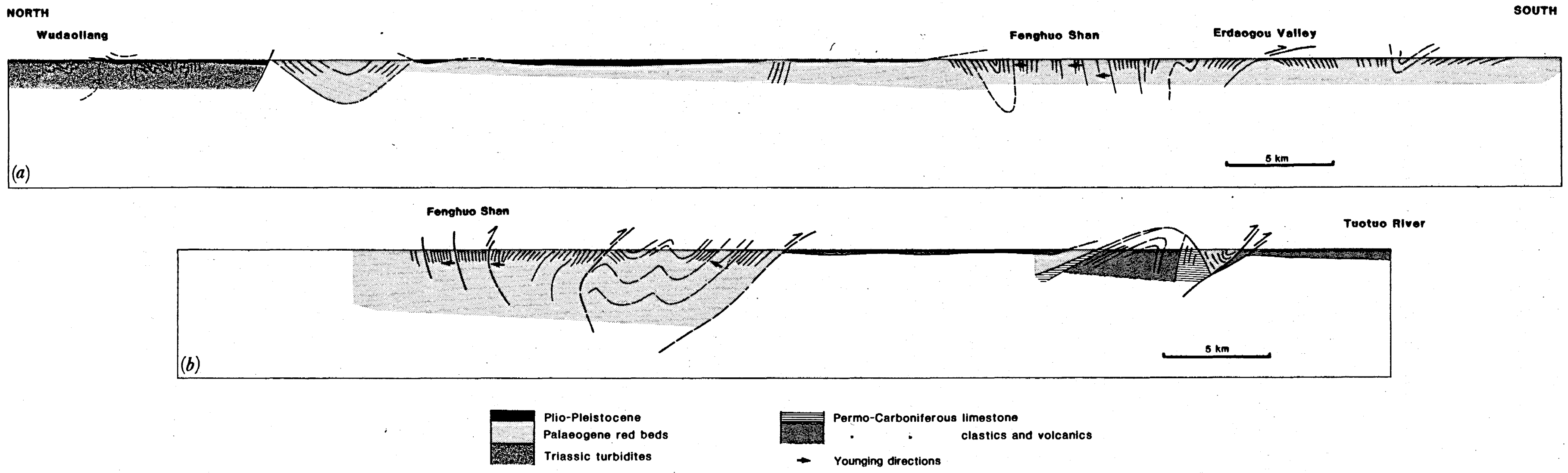

FIGURE 5. Cross sections through the Qiangtang Terrane, section lines shown on figure 1.

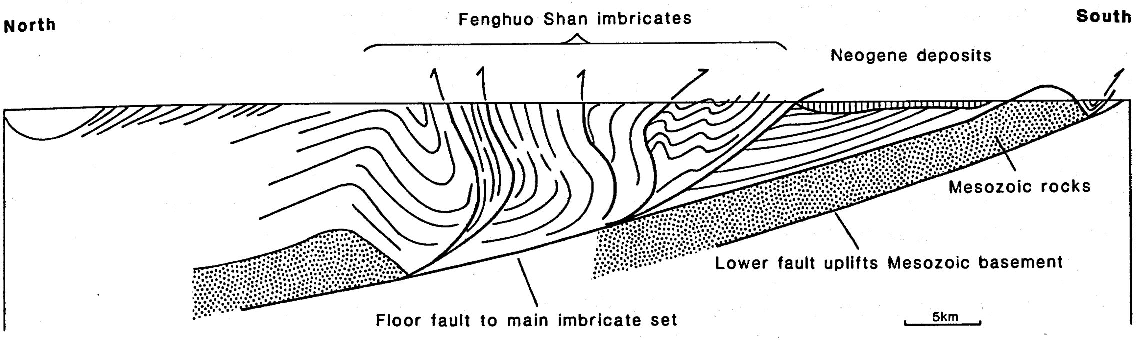

Figure 6. Simplified but composite cross sections through the Fenghuo Shan, to show the form of the Tertiary thrust imbrication.

imbricated by low-angle thrusts and cut by later normal faults. The structures probably decoupled on evaporites at depth; a gypsum diapir has risen into the core of an anticline about 10 km south of Yanshiping. The Jurassic red beds show only weak deformation, with steep fractures inclined to the south and generally no cleavage. Where cleavage does occur, it dips steeply either northwards or southwards.

At Wenquan Station there is a WNW-trending zone 5 km wide of strike-slip movement which locally disrupts the red beds. Kinematic indicators, such as slickensides and oblique vein and fracture sets in the zone, give a left-lateral shear sense. Secondary normal and thrust faults are common within this densely faulted zone, and vertically-plunging folds are locally prominent. Indications of left-lateral strike-slip faulting were also seen in the Jurassic strata outside this zone, near Yanshiping. The age of this zone of strike-slip faulting is unconstrained. South of Wenquan Station there are several low-angle thrusts with hanging-wall folds of similar style to those seen farther north. The thrusts and the folds verge towards the north or northeast. Between the Tanggula Pass and the Banggong Suture near Amdo there are open folds which are tighter to the south, where they are unconformably overlain by the Amdo red beds, considered to be Cretaceous or possibly Tertiary in age.

Thus the Qiangtang Terrane is relatively weakly deformed. Southward-directed thrusts of Tertiary age affect the region north of the Tuotuo River, but to the south there is no evidence for Tertiary deformation and Palaeogene red beds within 10 km of Amdo are flat and unconformably overlie northwest-trending open to close folds in the Jurassic sediments. The Mesozoic deformation was of variable intensity; the folds are upright to northeast-verging and often decouple on the lower Mesozoic evaporites. This northwest-trend to the folds is in marked contrast to the eastnortheast-trend of the later Tertiary structures.

4. THE BANGGONG SUTURE AND THE LHASA TERRANE

(a) General

The stratigraphy of the Lhasa Terrane is markedly different from that of the Qiangtang Terrane to the north. The oldest rocks consist of Precambrian to Cambrian basement gneisses which outcrop south of Amdo and give a U–Pb zircon age of about 530 Ma (Xu *et al.* 1985). They show an intense tectonic fabric which was isoclinally folded by structures with north-trending axial planes, under amphibolite facies conditions. Sillimanite-bearing assemblages suggest crustal anatexis at > 680 °C (Harris, Xu & Jin, this volume). The isoclines were refolded by later east-trending folds and were then carried south on major biotite-grade shear zones and later brittle thrusts. We consider that only these late shear and thrust zones developed in the Mesozoic or Tertiary and that the earlier intense deformation, with associated high-grade metamorphism, developed during late Precambrian tectonic events. All the observed lithological contacts between younger rocks and the gneisses were either tectonic or intrusive.

The oldest Phanerozoic sediments in this Terrane observed on the Geotraverse were Carboniferous in age and consist of sandstones with some glaciomarine deposits, overlain by Permian shelf carbonates and Triassic and Jurassic reef limestones and clastics. North of the Nyainqentanglha Shan, the Mesozoic succession is dominated by a thick sequence of Jurassic (?) flysch (Yin *et al.* this volume).

A change in sedimentation occurred during the Cretaceous, with the deposition of a thick sequence of red sandstones and intermediate volcanic rocks. These were followed by Albian–Aptian Orbitolina limestones and then more red beds and volcanics. A phase of deformation affected these rocks before the deposition of the youngest red beds and volcanics during the early Tertiary. Where interbedded with the Orbitolina limestones, or overlying the end-Cretaceous unconformity, as observed northwest of Lhasa, the red beds are easy to date. Elsewhere however, as near Amdo, the age of the red beds, and hence of their deformation, is uncertain.

The northern boundary of the Lhasa Terrane is taken to lie north of the northernmost outcrops of ophiolite, which extend from Amdo to Dongqiao within the Geotraverse area, but can also be traced approximately eastwards and westwards across most of the central Tibetan Plateau. Scattered outcrops of ophiolite occur south of this line. All of the ophiolites show evidence of having been thrust approximately southwards during the Mesozoic or Tertiary and we consider the scattered outcrops to be parts of a single nappe which was subsequently disrupted by later faulting.

The deformation of the Lhasa Terrane occurred in several phases, as summarized below.

(i) Southward obduction of the ophiolites from the approximate line of the Banggong Suture, for a present distance of 150 km over the Lhasa Terrane. Some deformation of the underlying Mesozoic rocks probably occurred at this time.

(ii) Deformation of the Palaeozoic and Mesozoic rocks, before the intrusion of Lower Cretaceous granites and granodiorites and before the deposition of Lower to Middle Cretaceous red beds and volcanics. This deformation is most prominent in the central part of the Lhasa Terrane.

(iii) Deformation of the Cretaceous red beds together with the older Mesozoic sediments in the Lhasa area, before the deposition of lower Tertiary volcanics and red beds and before the intrusion of the Gangdise granitic batholith.

(iv) Deformation of the Tertiary red beds, particularly in the region south of the Nyainqentanglha Shan. Cretaceous red beds are deformed across much of the Lhasa Terrane, but it is not known how much of this deformation is Cretaceous and how much is Tertiary.

The evidence for these different episodes and the regional structure will be described in a series of cross sections from the Amdo region, from the Dongqiao–Gyanco–Namco region, from Nyainqentangla and from Lhasa.

(*b*) *The Amdo region*

Much of the earlier structure of the Amdo region is unfortunately obscured by late Tertiary faulting. Ophiolites occur south of Amdo and are overlain by red beds of unknown age, which mask the possible site of the suture. The red beds are folded gently and are bounded to the north by a normal fault which drops the red beds down to the south. North of this fault, Jurassic sediments of the Qiangtang Terrane are thrust over the red beds as shown in figure 7*a*. (For a map of the Amdo area, see Kidd *et al.*, this volume, figure 4).

South of the Amdo ophiolite, there is a 6 km wide east–west-trending late Tertiary graben. On the southern side of the graben, Cretaceous (?) granites intrude the Amdo basement gneisses, which are thrust over Carboniferous clastics and Mesozoic limestones to the south (figure 7*b*).

This structural pattern changes slightly west of Amdo, across a northnorthwest-trending tear fault, which presumably acted as a transfer zone during the compressional deformation and the later extension. West of this tear fault, the red beds overlie ophiolitic material, but all show evidence of imbrication on thrusts directed to the south. Some thrusting is possibly young, carrying red beds over (?) Pliocene–Pleistocene deposits.

The red beds in the western part of the range are in a large asymmetric syncline with a steeply north-dipping axial surface, which is offset by two prominent northwest-trending tear faults. The red beds are uncleaved except very locally near the southern margin of the range. Nearer Amdo, the ophiolitic ultramafic and gabbroic rocks are imbricated with the red beds, thrust over them both southward, and, locally northward. In one section near Amdo, altered ultramafics overlie a gently north-dipping inverted section of probable Cretaceous andesites with minor red bed intercalations. Folded and faulted red beds obscure the relation between Jurassic sediments of Qiangtang Terrane affinity, and the ophiolitic rocks. Several steep ENE-trending faults cut this section and limited evidence of a component of left-lateral strike-slip was seen in outcrop, besides the components of vertical displacement. The overall structure seen in this range, west of Amdo, is reminiscent of the 'flower structure' seen in compressional segments of large strike-slip fault zones where outward-directed thrusts mingle with steep faults having oblique displacements.

Thus this region shows evidence of ophiolite uplift, though the base of the ophiolite was not seen, followed by post-Cretaceous, and possibly Tertiary, thrusting. Compressional tectonics continued until Recent times. The thrusts were directed both northwards and and southwards. Restoration of the thrusts north of Amdo indicates that ophiolites with their cover of red beds must have been thrust north, along with the Jurassic limestones; presumably the northward- and southward-directed thrusts interdigitate at depth. However, no accurate cross sections can be constructed until more regional studies are done, as the region has certainly suffered some strike-slip tectonics. At the present level of erosion, there is no indication of any major deformation related to the collision of the Qiangtang and Lhasa Terranes; if the terranes were locally intensely deformed, this deformation zone must be buried by post-Cretaceous over-thrusting, or removed in this transect by strike-slip displacements.

The original obduction direction is difficult to identify from the Amdo structures, but ophiolites occur as thrust slices about 75 km southsoutheast of Amdo, northwest of Nagqu. From the scattered outcrops in this region, the ophiolite stratigraphy can be seen to be repeated by thrusting and the underlying Jurassic and older sediments show moderate to tight south-verging folds and thrusts.

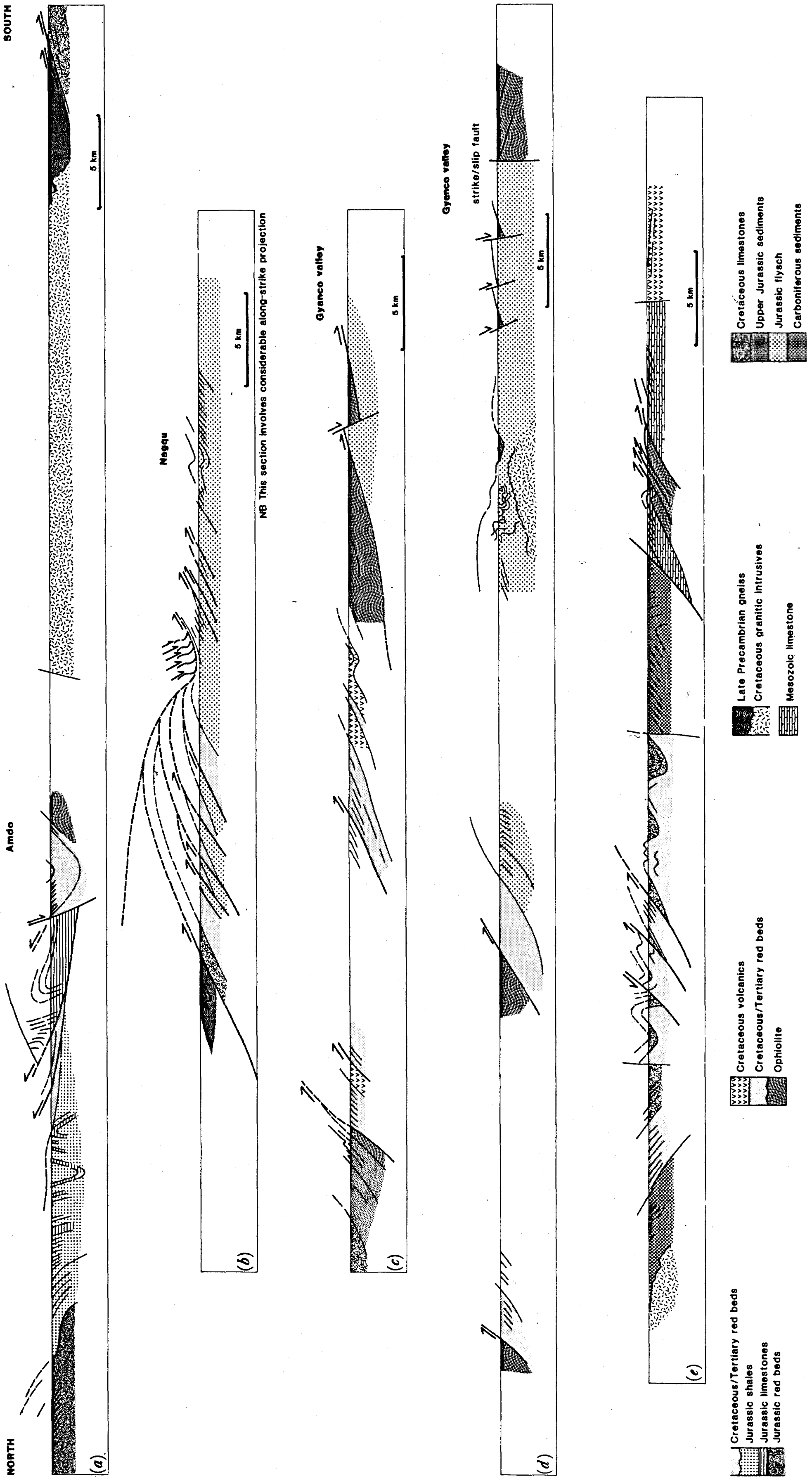

FIGURE 7. Cross sections through the northern part of the Lhasa Terrane, section lines are shown on figure 1.

(*c*) *The Dongqiao–Gyanco region*

Northwest of Dongqiao, ultramafic rocks of the ophiolite suite are unconformably overlain by soil horizons and fluvial sandstones and limestones of Upper Jurassic age, indicating that the ophiolites had been obducted before this time. The ophiolites dip steeply and face to the north. The suture is considered to lie somewhere to the north of these outcrops under Neogene sediments.

South of Dongqiao there are outliers of an originally more extensive thrust sheet of ophiolite. Observations of ductile shear zones at the base of the ophiolitic remnants suggest that the sheet was emplaced towards the southsoutheast. It was thrust over Jurassic flysch, which is deformed into moderately-tight inclined folds with axes trending eastnortheast and axial planes with an associated axial–planar cleavage dipping steeply to the northnorthwest. We consider that much of this folding and the shearing at the base of the ophiolite occurred during obduction. There is no evidence for any higher level thrust sheet of Carboniferous–Permian sediments above the ophiolite, as suggested by Girardeau *et al.* (1984).

In fact, these Carboniferous–Permian clastics and limestones, possibly including some Jurassic limestones as well, underlie the ophiolite thrust sheet, forming slivers at its base. Confusion has arisen because late Tertiary–Recent normal faulting has modified the elevation of the base of the ophiolite sheet; if these faults are not detected, it can appear as if the Carboniferous–Permian rocks locally overlie the ophiolite (see Kidd *et al.*, this volume). Post-mid-Cretaceous thrust imbrication may also locally contribute to reversal of the original tectonic sequence.

Between Dongqiao and Gyanco the ophiolite was probably largely unconformably covered by later Cretaceous volcanics and red beds. There are large Cretaceous granitic bodies which cut the ophiolite and the folded flysch and have generally undeformed zones of contact metamorphism (Harris, Xu, Lewis & Jin, this volume).

As shown in figure 7*c* and *d*, the ophiolite sheet has been dismembered by later faulting. Jurassic flysch sediments have been thrust on to the ophiolite and ophiolite is locally thrust over the Cretaceous succession. This deformation is part of the widespread regional post-Cretaceous deformation which also affects the red beds and the ophiolite at Amdo. All the thrusts are cut by steep normal faults related to Neogene graben formation. Figure 8 shows a map of part of this faulted region, north of Gyanco. For details of the Neogene tectonics in this region, see Armijo *et al.* (1986).

(*d*) *The Gyanco–Dejing section*

At Gyanco there are steep WNW-trending Neogene faults, with dextral strike-slip movement; to the south the rocks are predominantly Carboniferous sandstones and mixtites, cut by Cretaceous granites. Cleavage is only weakly developed in the sediments and the sandstones show little to no cleavage, though there are numerous tension gash arrays indicating a north–south maximum compression direction. In the north these sediments are deformed into large open folds. On the southern margin of the Cretaceous batholith, however, the deformation is more intense and the rocks have an upright to south-dipping cleavage. The Cretaceous granites are undeformed and appear to have been intruded after the deformation of the Carboniferous sediments. About 10 km N of Nam Co, the deformed sediments are unconformably overlain by conglomeratic red beds, which have only a gentle dip to the south, though the pebbles are slightly cracked and stretched with a maximum elongation direction

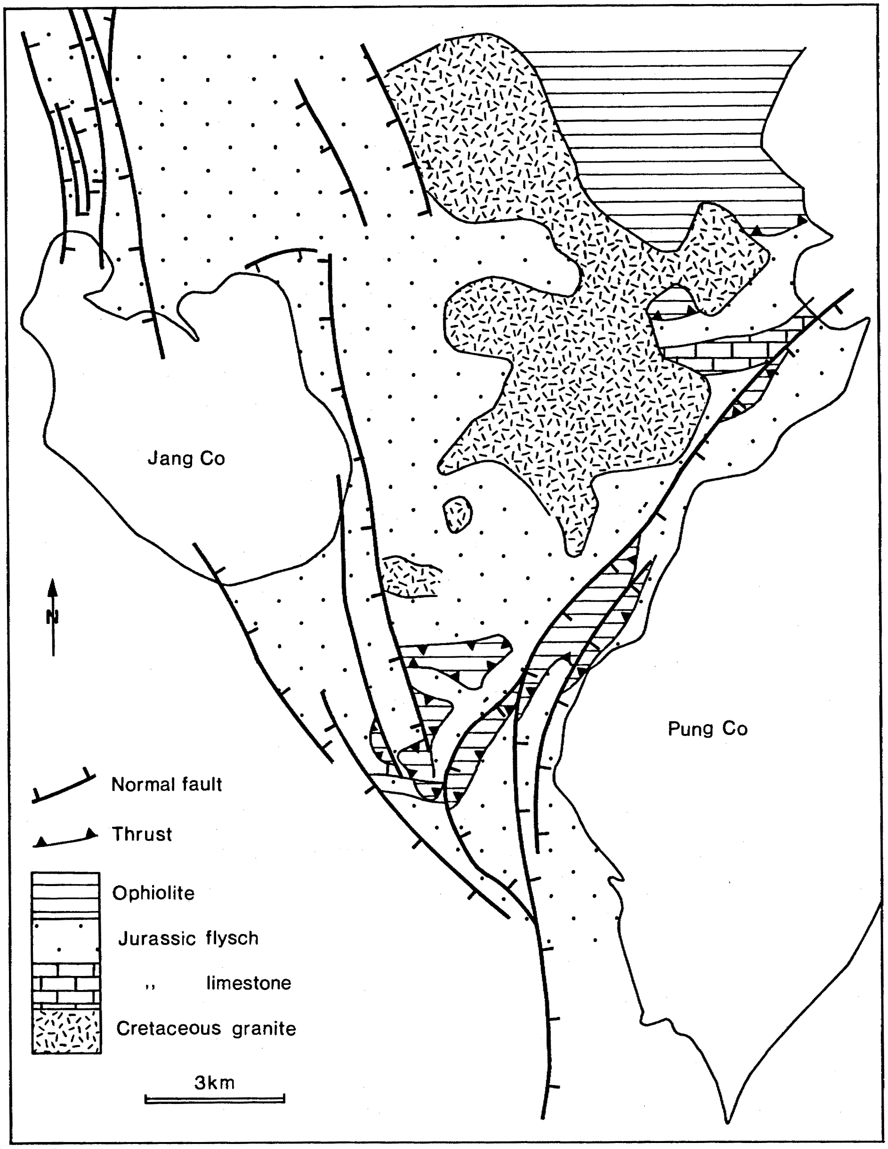

Figure 8. Detailed map showing the break up, by thrusts and normal faults, of the once widespread Jurassic ophiolite suite, north of Gyanco (locality shown by box '8' on figure 1).

plunging steeply to the SSE. To the south are Orbitolina limestones, which are deformed by post-Cretaceous folds and thrusts as shown on figure 7*e*. Near the northwest corner of Nam Co, outcrops of Cretaceous rocks end at another zone of probably steep strike-slip Neogene faults. South of this are faulted and folded quartzites, shales and limestones, supposedly Upper Palaeozoic in age (1:1.5 M Geol. Map of Tibet). Limestones extend south to a complex imbricate zone in which slices of limestone and ophiolite alternate. The structurally-lowest ophiolite seen outcrops in a flat dome, where it is overthrust by limestones of Jurassic age (Smith & Xu, this volume), whose steep bedding is cut off against the thrust. A possible interpretation of this zone, involving several breaching thrusts, is shown in Figure 7*e*. This ophiolite zone is known to extend more than 120 km to the WNW (1:1.5 M Geol. Map of Tibet).

How these ophiolites were obducted into their present position is unknown. The original base of the obducted sheet was not seen. Presumably they were thrust over Jurassic and older rocks and the sequence then thoroughly imbricated during subsequent deformation. All the kinematic indicators suggest thrusting to the southsoutheast and we believe that these Namco–Dejing ophiolites were originally part of the same sheet as that north of Gyanco. To the south, this 20 km wide block, comprising Upper Palaeozoic and Jurassic sediments and ophiolite slices, is faulted against gently-dipping Cretaceous limestones and red beds; south of these to a fault zone near Dejing is a sequence apparently several kilometres thick, of Upper Cretaceous volcanics (Coulon *et al.*, 1986) which, away from the Dejing faults, dip gently northwards.

(*e*) *The Nyainqentanglha range*

The Nyainqentanglha Range is an uplifted block trending about N 060°, separated by faults from the Yangbajian Graben to the southeast and the Nam Co depression to the northwest. It widens from about 10 km in the northeast to about 35 km in the southwest.

The eastern part of the range consists mainly of pelitic sediments with some orthoquartzites and calcareous slates with a general east–west strike. The pelitic rocks are weakly to moderately strong cleaved and are mapped as Jurassic (1:1.5 M Geol. Map of Tibet). Farther to the west, pelitic sediments are associated with calc-phyllites, phyllitic-matrix conglomerates and an olistostrome with limestone blocks. These rocks, which are more deformed and metamorphosed in the greenschist facies, have been mapped as Carboniferous (1:1.5 M Geol. Map of Tibet), but we consider them, at least in part, to be the same as the supposed Jurassic rocks farther east, since both contain a very distinctive marly rock with calcareous concretions. These sediments, where seen near the Damxung to Nam Co track, vary in strike, both of bedding and cleavage, from northeast-trending in the north, through north-trending to east-trending in the southern half of the section. The lineation shown by the metamorphic minerals and strongly elongate conglomerate clasts plunges to the eastsoutheast, suggesting locally an oblique shear component. The cleavage is crenulated by later structures, whose crenulation cleavages and axial planes dip to the northwest. The rocks show syn- to post-tectonic garnet and staurolite growth, which indicate metamorphic conditions of *ca.* 700 °C and 5 ± 2.5 kbar (Harris, Holland & Tindle, this volume).

Still farther west, there are gneissose rocks, mainly orthogneiss but with some metasediments. The foliation in the orthogneiss dips gently. In places the rocks are cataclastic and their strike is approximately northeast, parallel to the range, but between these cataclastic zones, the strike is nearly north–south, transverse to the range. The northeast-trending cataclastic fabric appears to be superimposed on earlier structures.

Isotopic studies indicate that the Nyainqentanglha granitic orthogneiss is about 50 Ma old, not Precambrian as suggested on the 1:1.5 M Geological Map, although Precambrian crustal material (1200–2000 Ma) was involved in its generation (Xu *et al.* 1985). Late to post-tectonic metamorphic minerals such as andalusite may be associated with granite intrusion, but much of the intense deformation in the slates and phyllites must be earlier, as the cleaved rocks are clearly unconformably overlain by Cretaceous sediments on the northern side of the range (figure 9*a*). Pebbles in the basal conglomerates, which have been transported northwards off the range, are mostly of quartzite, limestone and quartz, without any boulders of Nyainqentanglha granite. The Cretaceous red beds have been subsequently deformed into north-verging northeast trending folds. They locally show a weak north-verging cleavage.

Thus the tectonic history of the Nyainqentanglha Range includes:

(i) folding and locally intense cleavage development in the slates and phyllites, with some metamorphism;

(ii) uplift and erosion followed by the deposition of Cretaceous red beds;

(iii) intrusion of the Nyainqentanglha granite at about 50 Ma;

(iv) folding of the Cretaceous red beds, uplift and deformation of the granite and probably refolding of the cleavage in the slates and phyllites.

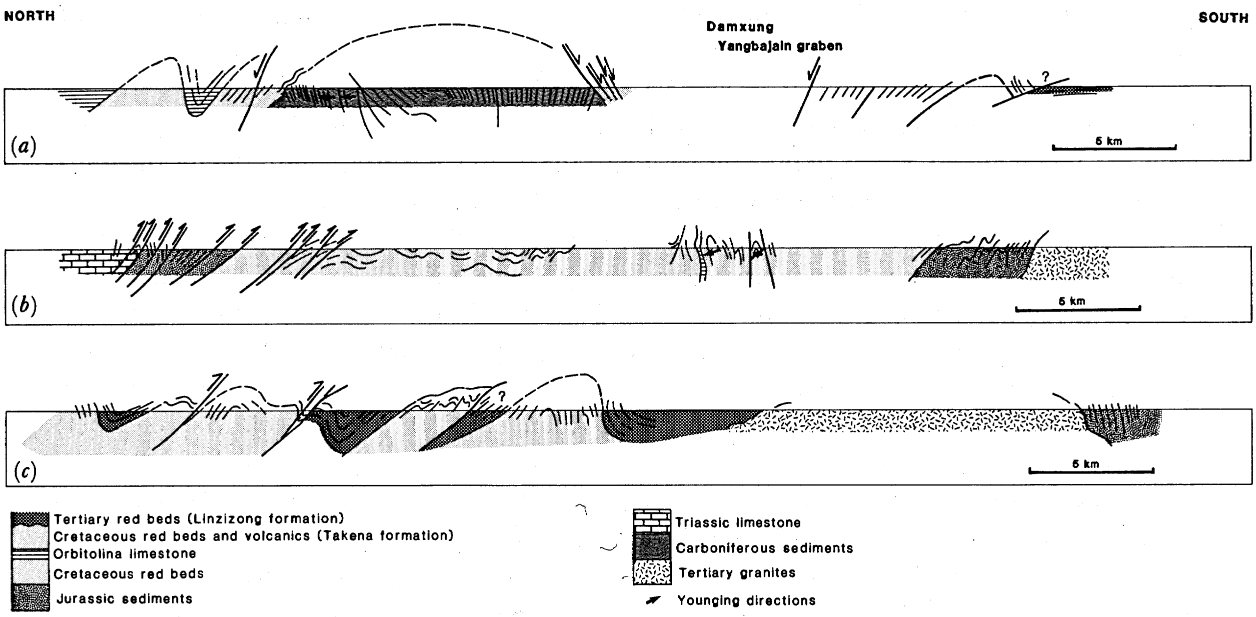

FIGURE 9. Cross sections through the southern part of the Lhasa Terrane, from the Nam Co to north of Lhasa; lines are shown on figure 1. The '?' indicate a degree of uncertainty in the age and/or structure of the red beds.

The Nyainqentanglha granite is itself strongly sheared along its southeastern margin and shows an intense and locally mylonitic fabric with shear bands indicating that the shear direction was analogous to that of a low angle normal fault, with its top side moving down to the southeast. Elongate quartz ribbons define a pronounced southeast-plunging lineation. The origin of this fabric may be due to:

(i) shearing associated with granite emplacement, unrelated to regional tectonics;

(ii) low-angle extensional faulting, producing a detachment along the northwest side of the Yangbajain graben, similar to the ductile detachment zones in the Basin and Range (Davis & Lister, in press); or

(iii) low angle thrust faulting, reoriented by underlying thrust structures.

The ductile thrust model is considered possible, though the thrust would have to be folded along the Nyainqentanglha range, to root on the northwest side. No evidence for this thrust was found on the northwest side of the range, though it could have been disrupted by later normal faults.

There is some support for the low-angle extensional model in that unpublished ^{39}Ar/^{40}Ar dates on micas and feldspars from the Nyainqentanglha granite and the high strain zone indicate rapid uplift within the last 10 Ma (W. Kidd, pers. comm. 1987). This zone shows high ductility related to these possible extensional tectonics. Elsewhere in this region the normal faulting forms only high-level brittle structures, though normal faults, with red beds on the hanging-walls, do detach on the Nyainqentanglha shear zone.

The model of shear related to intrusion is possible, if one believes that granites can be intruded by such a mechanism, involving intense simple shear along the upper margin. The preference of one of the authors (R.M.S.) is that the intrusion of the granites itself produced all the shear deformation. It is possible that the granites were intruded into an active, relatively deep level, shear zone. Similar ductile mylonite-bearing shear zones were observed in the Gangdise batholith south-east of Lhasa, where the shear sense is analogous to low angle normal faulting where the hanging-wall has dropped to the north. If these interpretations, that the granites intruded into a deforming regime, are correct, then the Gangdise batholith can be considered to have been intruded into a region undergoing NNW–SSE extension.

(*f*) *The region between Yangbajain and Lhasa*

The Yangbajain graben is a Pleistocene to Recent structure (Armijo *et al.* 1986) with well-preserved fault scarps in the valley sides and present-day hydrothermal activity. It is part of a system of north–south-trending grabens, linked by westnorthwest dextral tear faults (see Armijo *et al.* 1986).

Southeast of the Yangbajain graben, Carboniferous rocks are folded into large upright to south-verging structures. The age of this deformation is uncertain. To the southeast there are large thrusts which carry Mesozoic rocks to the southeast over Palaeogene sediments and volcanics (figures 9*b* and *c*). These folds and thrusts trend northeast and are associated with NNW-trending tear faults, suggesting a NNW to SSE transport direction.

Where no unconformity is present, it is difficult to separate the deformation affecting the Tertiary rocks, which in the area north-west of Lhasa are essentially volcanics known as the Linzizong Formation, from earlier deformation affecting the Cretaceous Takena Formation. Deformed unconformities between the Linzizong and Takena Formations were studied in the two regions shown by the sections in figure 9*b* and *c*. In these areas the post-Linzizong deformation produced open to close folds verging to the southeast, while the pre-Linzizong deformation produced upright to north-verging folds.

The intensity of deformation in the Takena Formation increases southwards, towards Lhasa, where the structures are obscured by intrusions related to the Gangdise batholith. South of Lhasa, Mesozoic sediments show locally intense deformation, with a steep cleavage cut by a later gently northward-dipping crenulation cleavage. The main-phase folds are upright to northward-verging and the cleavage carries a mineral lineation which plunges steeply down dip. Small shear zones, with a sense of overthrusting from the south, cut the bedding and cleavage. Burg *et al.* (1983) described three phases of deformation from these sediments south of Lhasa, including an early pre-cleavage phase, but no evidence for their earliest deformation phase was found during our work.

(*g*) *Summary of the structure in the Lhasa Terrane*

The Lhasa Terrane appears to have had the structure of a passive margin until mid Jurassic times. During the mid Jurassic, ophiolitic material was obducted at least 150 km southwards onto the Lhasa Terrane. This is the present distance across strike covered sporadically by the dismembered ophiolite sheet. As the zone has been shortened by post-Cretaceous deformation, the distance covered by the ophiolite obduction may have been much greater, possibly of the order of 200 km.

The obducted sheet was probably originally relatively thin, only a few kilometres thick, as there is no evidence for any thrust cover during obduction. It is difficult to envisage what driving mechanism could thrust such a thin wedge so large a distance, without the sheet being thoroughly broken. It is possible that the ophiolite was not part of one single sheet, but represents several individual obducted slices, but this would imply several sutures. We observed no structural evidence for sutures within the Lhasa Terrane nor did we observe any zones of anomalous deformation or metamorphism which could indicate the presence of a suture: we consider the Mesozoic stratigraphy to be continuous across the Terrane. Rather these ophiolites appear as thrust slices or klippen, probably as an imbricated overthrust sheet.

There was probably some deformation of the footwall of the obducted ophiolite, producing folds in the Jurassic flysch. Some of the ophiolite obduction may have occurred by transport on thrusts within the Mesozoic succession.

Between Gyanco and Yangbajain the Carboniferous to Jurassic sediments were deformed by pre-Cretaceous, upright to approximately northward verging structures. To the northwest of Gyanco the pre-Cretaceous structures have a different vergence; Jurassic flysch shows southeast-verging structures probably associated with ophiolite obduction. The north-verging deformation was obviously localized. It may somehow be related to early collisional events on the Banggong Suture, but probably it is related to localized intracratonic deformation.

There seems to have been little deformation associated with the collision between the Qiangtang and Lhasa Terranes. No zone of locally intense deformation comparable to that of the western Alps or western Himalayas was observed along the line of the suture; indeed, as described above, the most intense Mesozoic deformation and metamorphism occurs to the south, in the Nyainqentanglha range. Any zone of deformation along the Banggong Suture has subsequently been buried by later thrusting or by Tertiary sedimentation. There is little evidence for major crustal thickening of the Qiangtang Terrane during this collision; the Mesozoic sediments are only weakly deformed by northward-verging structures. Similarly across the Lhasa Terrane there is no evidence for a late Mesozoic mountain belt, in that thick molassic deposits are absent and Albian–Aptian limestones extended across the terrane, suggesting shallow water marine conditions.

The Gangdise batholith was generated by northward subduction from the Tethyan ocean to the south. Granite intrusion dates from over 90 Ma, but the main phase occurred from about 60 to 40 Ma (Harris, Xu, Lewis & Jin and Harris, Xu, Lewis, Hawkesworth & Zhang, this volume). Deformation of the Mesozoic sediments around Lhasa occurred after deposition of the Middle to Upper Cretaceous sediments (*ca.* 100 Ma) and before the Linzizong volcanics, dated at 56 Ma (Xu *et al.* 1985). Estimates of the timing of collision between India and the northern collage of micro-continents range from 55 to 40 Ma, based on the movement of India as determined from magnetic anomalies in the Indian Ocean and by the disappearance of the last remnants of the Tethyan ocean. The deformation of the Mesozoic sediments on the Lhasa Terrane may pre-date this closure and relate to the intrusion of parts of the Gangdise batholith (England & Searle 1986). Alternatively it may be related to the first stages of closure along this suture zone, or to the accretion of minor island arc or sea-mount material, similar to the origin of the post Albian–Aptian deformation which affects the Karakoram region to the west, in northern Pakistan (Coward *et al.* 1986). However the deformation appears to be synchronous with the strong deformation of the Xigatse flysch along the Zangbo Suture to the southwest and may be subduction-related.

The post-Albian–Aptian, but pre-Linzizong deformation in the Lhasa region forms upright to northward-verging structures, which decrease in intensity northwards. Thus the SSE-verging structures which affect the red bed successions throughout the central and northern parts of the Lhasa Terrane, as in the Amdo region and northwest of the Nyainqentanglha Shan, are considered to be part of the Tertiary deformation, similar to the SSE-verging folds and thrusts which affect Palaeogene red beds between Lhasa and Yangbajain (figure 9*b* and *c*). We consider this supposedly Tertiary deformation to be related to the closure of the main Indus–Zangbo Suture. However, on the 1:1.5 M Geological Map of Tibet, Eocene rocks are shown unconformable on Cretaceous, west of Nam Co and west of Baingoin; in the Lunpola Basin, Eocene (?) conglomerates of the Niubao Formation rest unconformably on the Cretaceous (Song & Liu 1981). Without more detailed study of these areas, it is not possible to determine how much of the deformation is late Cretaceous and how much is post-Eocene.

5. TERTIARY SHORTENING AND CRUSTAL THICKENING ACROSS TIBET

Figure 10 shows the regions which have suffered possible Eocene deformation on the SSE-directed thrusts, which are thought to be related to Tertiary collision. There is clear evidence for Tertiary deformation in the Erdaogou region, possibly accounting for about 50 km displacement. There may have been some Tertiary shortening of the Kunlun ranges; indeed some shortening and thickening of northern Tibet is indicated from the growth history of the Tertiary flexural basins of the Tarim and Tsaidam along the northern margin of Tibet. However the nature of this deformation is obscure, as any Tertiary thrusts are covered by Neogene deposits or indistinguishable from earlier Mesozoic structures in the Kunlun. South of the Tuotuo River, however, there was little to no Tertiary shortening; in fact there was relatively little total shortening across this part of the Qiangtang Terrane. Along the traverse line the obvious Tertiary deformation appears to be concentrated near the older (Jinsha) suture and may have involved reworking of earlier Triassic thrusts.

South of the Banggong Suture, some Eocene deformation affects the rocks of the Lhasa Terrane as far south as Lhasa. The amount of shortening is relatively small. Apart from the basement gneisses south of Amdo and the Nyainqentanglha metamorphic rocks, there is no evidence for any intense crustal shortening which brought up metamorphic rocks. The generally low metamorphic grade suggests that the shortening was taken up by small movements on several thrusts. It is impossible to make any accurate estimates of the amount of shortening because of the later strike-slip faulting which offsets structural domains. Estimates of the shortening, based on simple reconstructions of the sections as they stand, ignoring the strike-slip components, gives values between 30 and 40%, that is, there may have been between 75 and 100 km shortening across the Lhasa Terrane.

Thus the total post-Eocene shortening across Tibet can only be estimated in terms of a few hundred kilometres. This contrasts with the estimates of 2000 ± 500 km shortening across the Asian Plate made using the movement pattern of the Indian Plate, as shown by magnetic anomaly stripes in the Indian Ocean (Molnar & Tapponnier 1975; Patriat & Achache 1984). However considerable crustal shortening could be attained by movement on the network of strike-slip faults which cut through Tibet, or by major strike-slip displacements along the

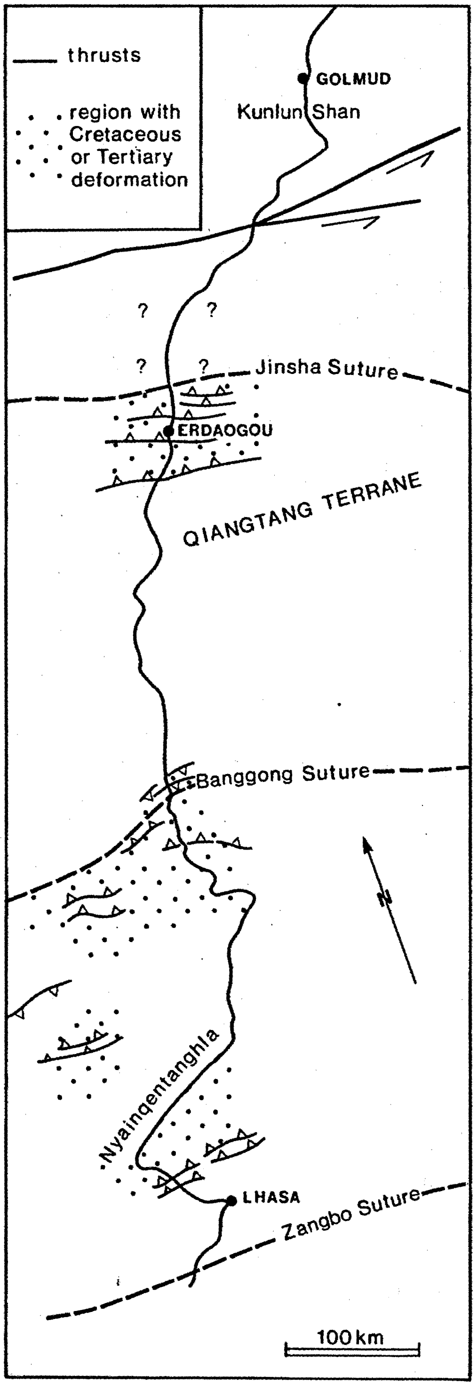

FIGURE 10. Simplified map to show the distribution of Tertiary deformation across Tibet.

Kunlun and Zangbo fault zones as is discussed by Tapponnier *et al.* 1982) and Kidd & Molnar (this volume). Our data do not support the hypothesis put forward by Dewey & Burke (1973) and England & Houseman (1986) that plane strain shortening during the Tertiary collision doubled the crustal thickness, allowing for up to 2000 km displacement across Tibet (England & Houseman 1986). Similarly our data do not support the models of Allègre *et al.* (1984)

involving shortening on several large scale thrusts. We recognize only a small amount of shortening on distributed thrust zones. Some mechanism, other than one involving solely regional pure shear or alternatively crustal-scale thrust-stacking, is needed to explain the thickening of the Tibetan crust. Such mechanisms will be discussed in a later chapter (Dewey *et al.* this volume).

References

Allègre, C. J. and 34 others 1984 Structure and evolution of the Himalayan-Tibet orogenic belt. *Nature, Lond.* **307**, 17–22.

Armijo, R., Tapponnier, P., Mercier, J.-L. & Han Tonglin 1986 Quaternary extension in southern Tibet: Field observations and tectonic implications. *J. geophys. Res.* **91**, 13803–13872.

Bally, A. W., Allen, C. R., Geyer, R. B., Hamilton, W. B., Hopson, C. A., Molnar, P. H., Oliver, J. E., Opdyke, N. D., Plafker, G. & Wu, F. T. 1980 Notes on the geology of Tibet and adjacent areas – report of the American plate tectonics delegation to the Peoples' Republic of China. *Geol. Surv. Amer. Open File Rept* **80–501**.

Burg, J.-P., Proust, F., Tapponnier, P. & Chen, G. M. 1983 Deformation phases and tectonic evolution of the Lhasa block (southern Tibet, China). *Eclog. geol. helv.* **76**, 643–665.

Chang Chengfa & Pan Yusheng 1981 A brief discussion on the tectonic evolution of the Qinghai-Xizang plateau. In *Geological and Ecological Studies of the Qinghai-Xizang* (*Tibet*) *Plateau* **1**, 1–18. Beijing, Science Press.

Chang Chengfa and 26 others 1986 Preliminary conclusions of the Royal Society and Academia Sinica 1985 geotraverse of Tibet. *Nature, Lond.* **323**, 501–507.

Coulon, C., Maluski, H., Bollinger, C. & Wang, S. 1986 Mesozoic and Cenozoic volcanic rocks from central and Southern Tibet: ^{40}Ar/^{39}Ar dating, petrological characteristics and geodynamical significance. *Earth planet. Sci. Lett.* **79**, 281–302.

Coward, M. P., Windley, B. F., Broughton, R., Luff, I. W., Petterson, M. G., Pudsey, C., Rex, D. & Khan, M. A. 1986 Collision tectonics in the N. W. Himalayas. In *Collision tectonics* (ed. M. P. Coward & A. C. Ries). *Spec. Publ. geol. Soc. Lond.* **19**, 203–219.

Dahlstrom, C. D. A. 1969 Balanced cross-sections. *Can. J. Earth Sci.* **6**, 743–757.

Davis, G. A. & Lister, G. S. (in press) Detachment faulting in continental extension: perspectives from the southwestern U.S. Cordillera. *Mem. geol. Soc. Am.*

Dewey, J. F. & Burke, K. C. A. 1973 Tibetan, Variscan and Precambrian basement reactivation: Product of continental collision. *J. Geol.* **81**, 683–692.

England, P. C. & Houseman, G. A. 1986 Finite strain calculations of continental deformation. 2. Comparison with the India-Asia collision. *J. geophys. Res.* **91**, 3664–3676.

England, P. C. & Searle, M. 1986 The Cretaceous–Tertiary deformation of the Lhasa block and its implications for crustal thickening in Tibet. *Tectonics* **5**, 1–14.

Girardeau, J., Marcoux, J., Allègre, C. J., Bassoullet, J. P., Tang Youking, Xiao Xuchang, Zao Yougong & Wang Xibin. 1984 Tectonic environment and geodynamic significance of the Neo-Cimmerian Dongqiuo ophiolite, Banggong-Nujiang Suture zone, Tibet. *Nature, Lond.* **307**, 27–31.

Hossack, J. R. 1979 The use of balanced cross-sections in the calculation of orogenic contraction, a review. *J. geol. Soc. Lond.* **136**, 705–711.

Li Chunyu, Liu Xueya, Wang Quan & Zhang Zhimeng. 1979 A tentative contribution to plate tectonics of China. *Institute of Geology, Chinese Acad. Geol. Sci.* Mimeographed handout.

Molnar, P. & Tapponnier, P. 1975 Cenozoic tectonics of Asia: effects of a continental collision. *Science, Wash.* **189**, 419–426.

Patriat, P. & Achache, J. 1984 India–Eurasia collision chronology and its implications for crustal shortening and driving mechanisms of plates. *Nature, Lond.* **311**, 615–621.

Sengör, A. M. C. 1984 The Cimmeride orogenic system and the tectonics of Eurasia. *Geol. Soc. Am. Spec. Paper* **195**, 82.

Song Zichen & Liu Gengwu 1981 Palynological assemblages from Xizang with reference to their palaeogeographical significance. In *Geological and Ecological Studies of the Qinghai-Xizang* (*Tibet*) *Plateau* **1**, 207–214. Beijing, Science Press.

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

Watson, M. P., Hayward, A. B., Parkinson, D. N. & Zhang, Z. M. (in press). Plate tectonic history, basin development and petroleum source rock deposition onshore China. *J. marine Petrol. Geol.*

Xu Ronghua, Scharer, U. & Allègre, C. J. 1985 Magmatism and metamorphism in the Lhasa block (Tibet): a geochronological study. *J. Geol.* **93**, 41–57.

Zhang, Z. M. 1984 An outline of the plate tectonics of China. *Bull. Geol. Soc. Am.* **95**, 295–312.