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## Tectonics of Western Tibet, between the Tarim and the Indus

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### Abstract

A Tarim to Indus traverse provides insight into the tectonics of western Tibet. The Kunlun was the site of a Mid-Paleozoic collision. At least three phases of post-Paleozoic accretion have thickened the blanket of sediments that covers western Tibet. Sizeable parts of western Qiangtang have remained stable, however, since the Mid-Mesozoic. Since the Neogene, deformation and volcanism have been localized near the edges of the Plateau. Strike-slip motion along the Karakorum and Altyn Tagh faults has been coeval with overthrusting in the Himalayas and Kunlun. Such slip partitioning, and the volcanism, appear to result simply from northward subduction of India and southward subduction of the Tarim as Tibet is extruded eastwards by India's penetration into Asia.

*Keywords:* Kunlun Mountains; Xizang China; tectonics

### 1. Introduction

Since pioneering explorations earlier this century [1–6], western Tibet has been visited by few western geoscientists. We present here results of a Sino–French traverse between the southern Tarim basin and the upper Indus valley (Figs. 1 and 2). The observations made along the  $\approx 1100$  km long, Yecheng–Shiquanhe road complement prior work by

our Chinese colleagues [7–12] and by the 1988 Italian expedition to the Shaksgam valley [13]. Mapping on topographic maps (1:100,000 scale) and sampling within 40–80 km from the road were performed with help from Landsat and panchromatic SPOT satellite images. We pursued two principal goals. The first was to assess more clearly the nature, structure and limits of the various blocks and terranes that compose the Tibetan collage in that area [8,10,14–16], in order to compare them to those identified farther west [13–15], and east, along the Lhasa–Golmud traverse [17–27]. The second was to

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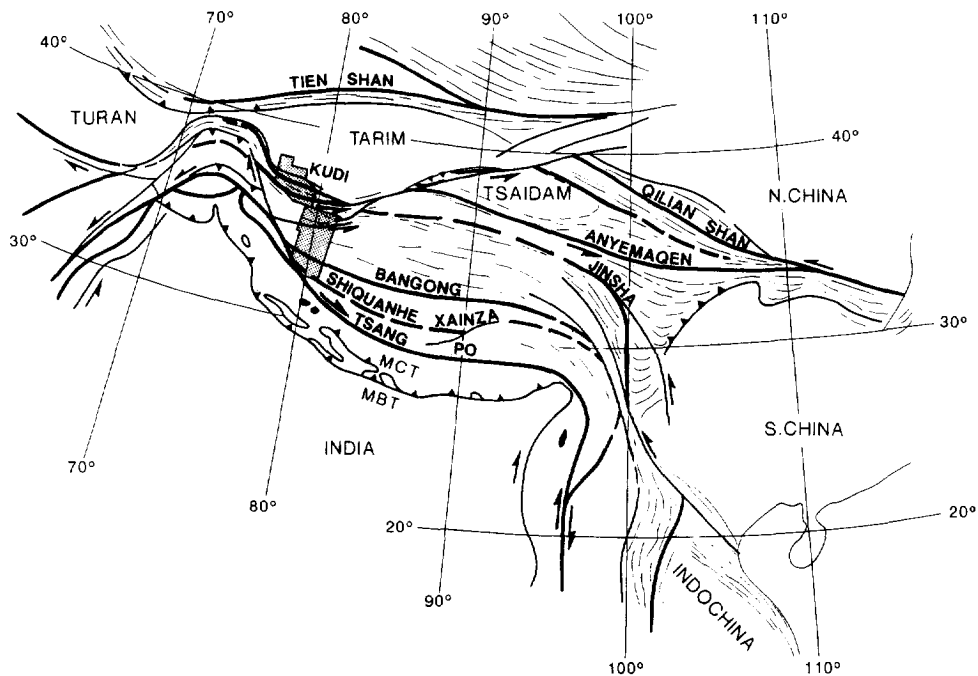


Fig. 1. Sketch map of large-scale paleogeography showing principal blocks, terranes, sutures and faults in Tibet and adjacent regions. Box outlines maps of traverse region in Fig. 2.

decipher the history of accretion, collision, deformation, igneous activity and uplift along the section, in order to constrain more closely the geodynamic processes that have shaped the western part of the Tibet plateau. For that purpose most granitic rocks were dated with  $^{40}\text{Ar}/^{39}\text{Ar}$  mass spectrometry.

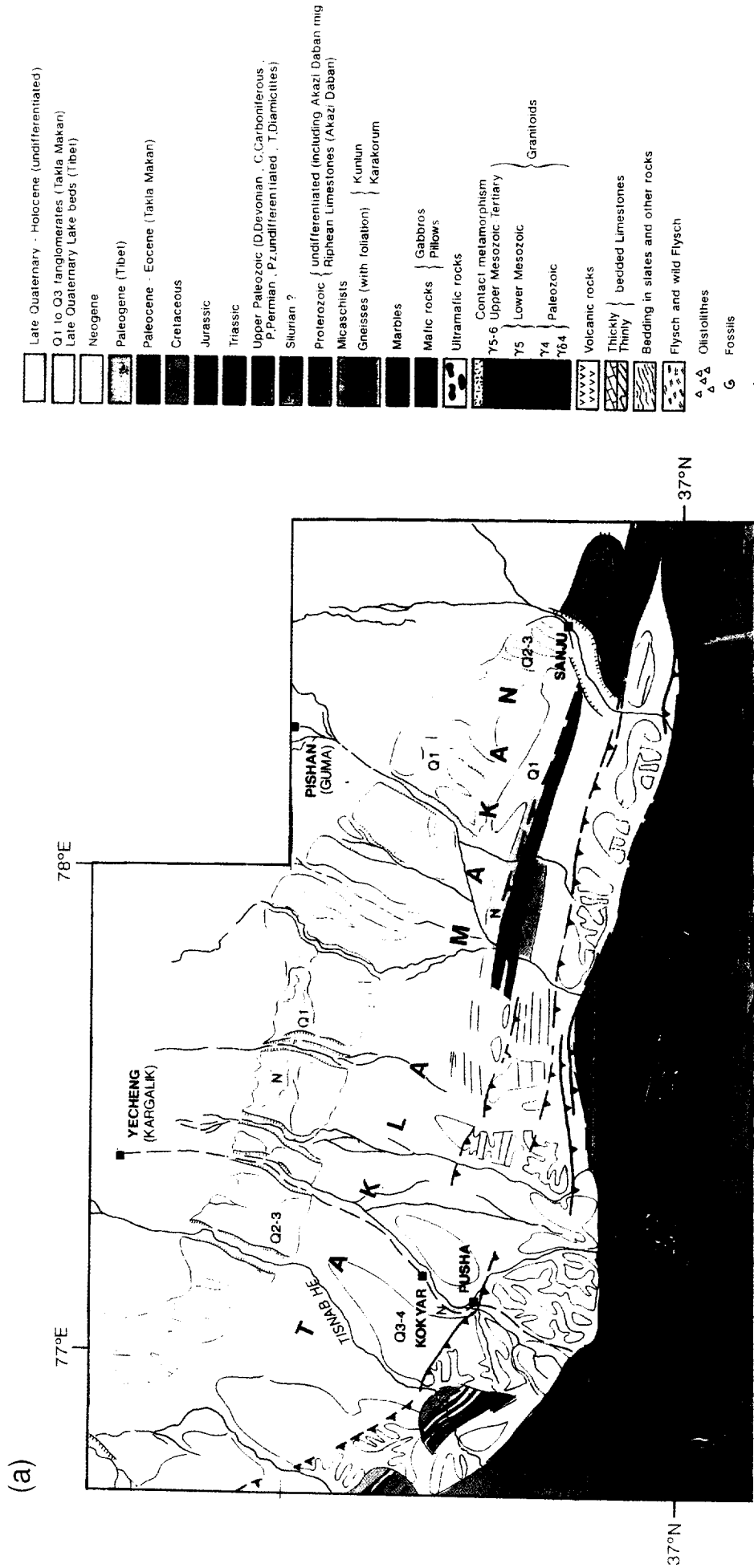
## 2. Main structural units of the traverse

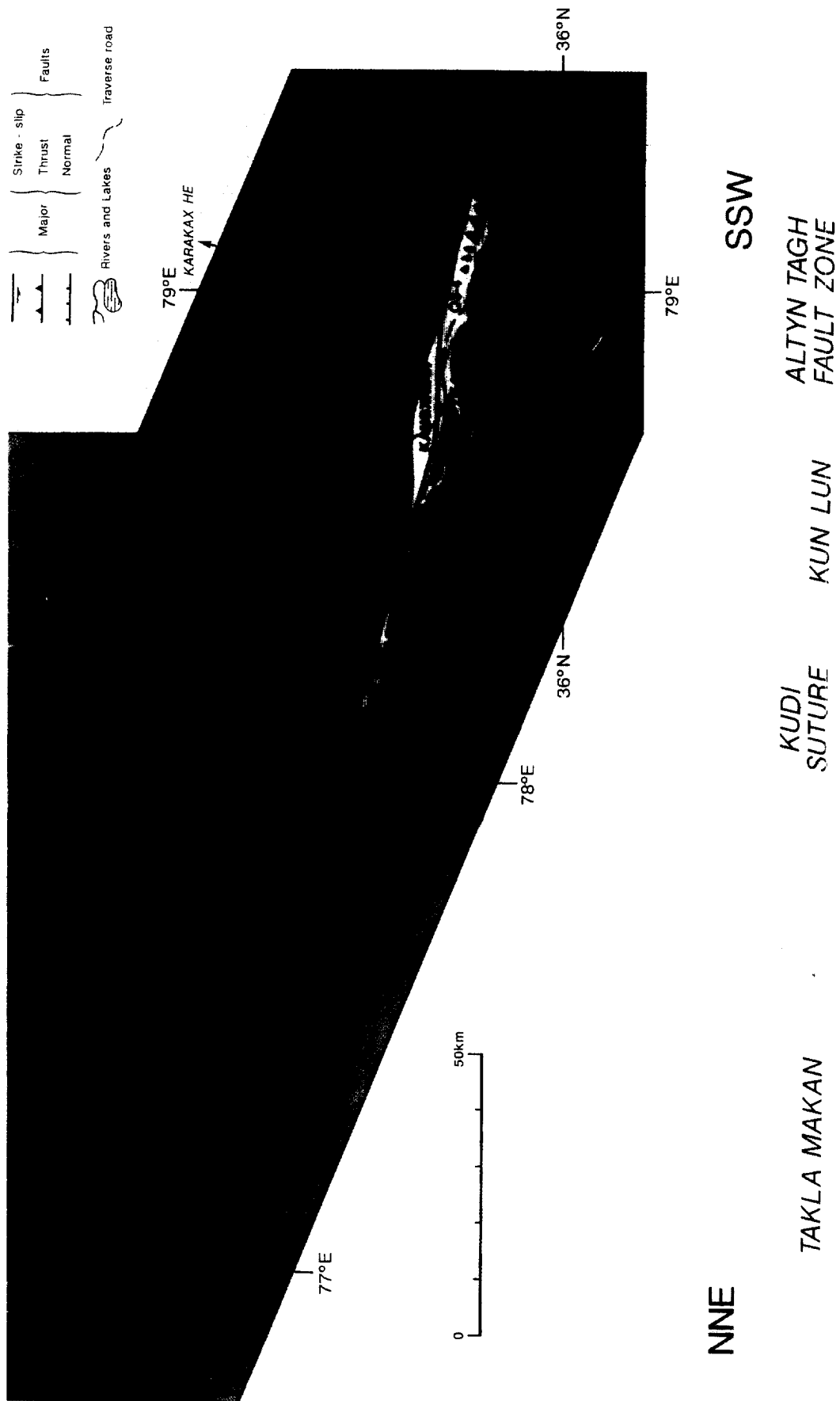
### 2.1. The Kunlun range, a rejuvenated Silurian collision belt

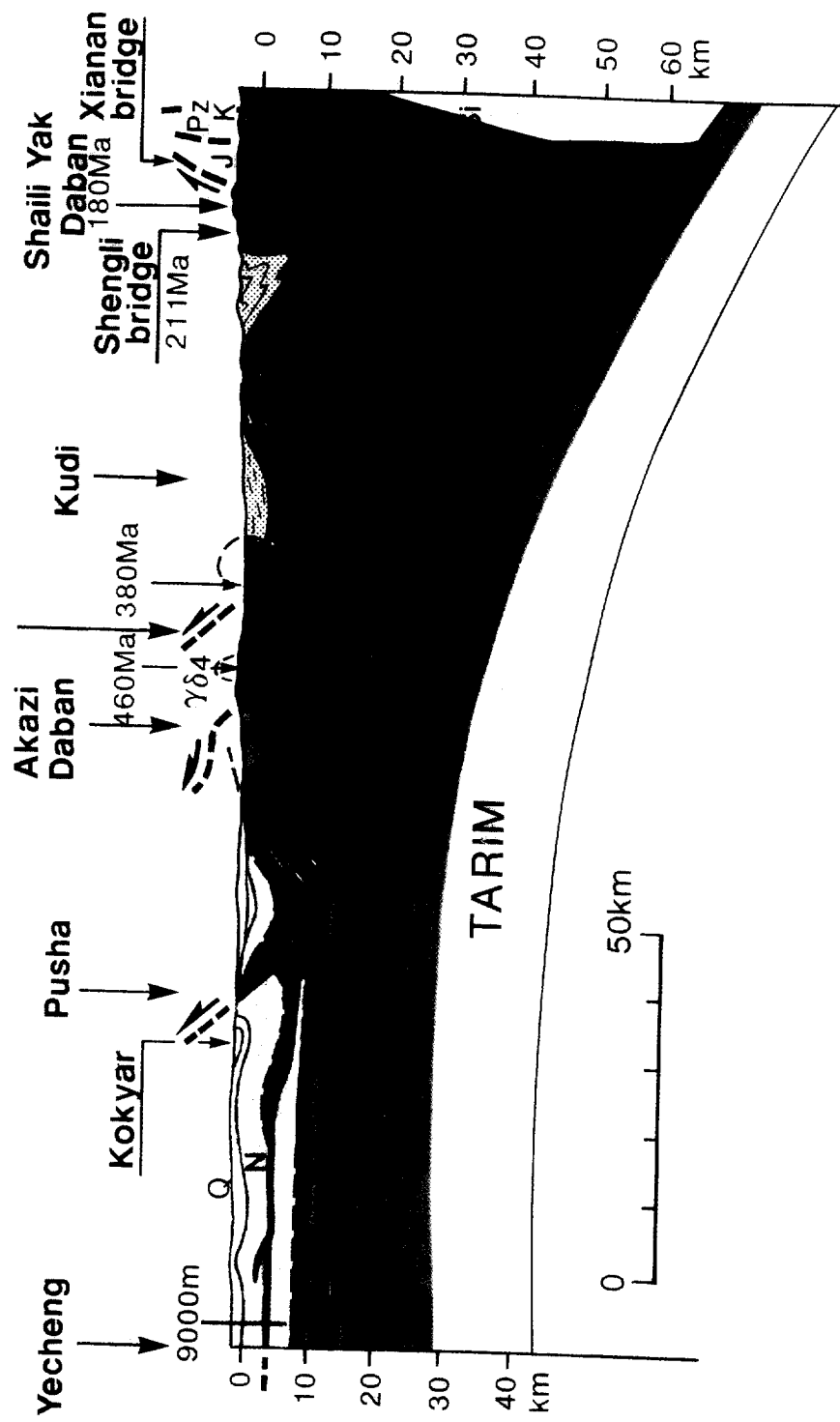
The western Kunlun range forms the northern edge of Tibet along the Tarim block. South of Yecheng it is  $\approx 100$  km wide (Fig. 2a) with elevations rising progressively southwards from  $\approx 1500$ – $2000$  m in the Tarim foreland to  $\approx 5500$ – $6400$  m along the Altyn Tagh–Karakash fault. A particularly

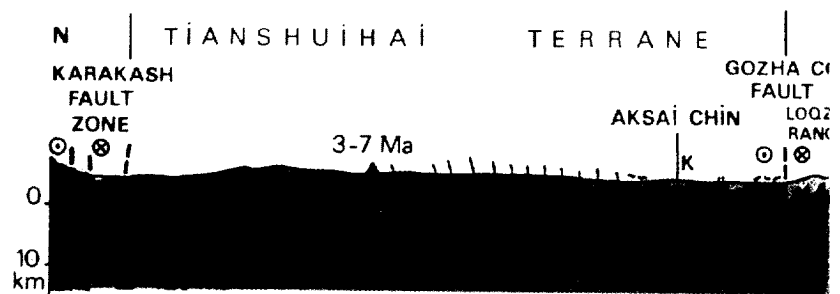
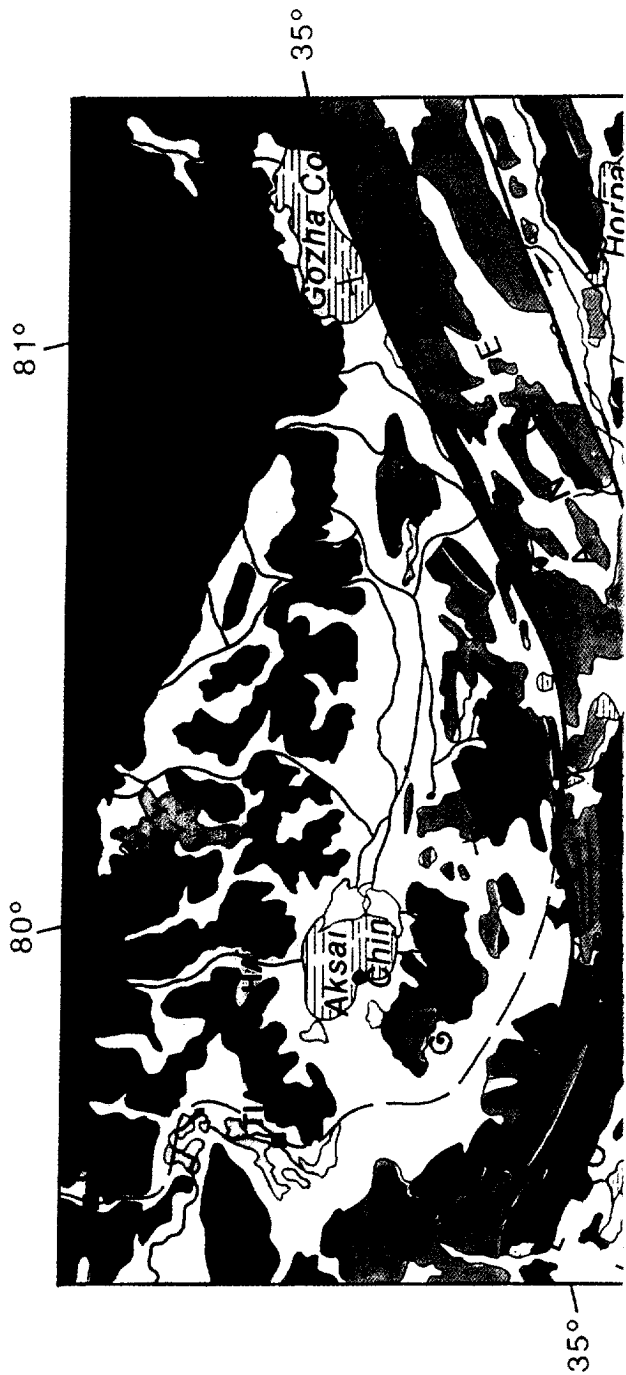
thick (up to  $\approx 9000$  m) accumulation of Neogene–Quaternary clastics covers the Tarim basement in the Hotien–Yecheng basin north of the range [28]. Near Yecheng, Oil Company reflection seismics and drilling place the base of the Pliocene sediments at a depth of 6025 m, and that of the  $\approx 3000$  m thick Miocene sequence at  $\approx 9000$  m above a relatively thin (1000 m) Paleogene [29] (Fig. 3). Westwards, near Sanju and Duwa, outcrops of the Paleogene formation, which is only a few hundred meters thick, very much thinner than the Miocene–Pliocene, include shallow marine, oyster-bearing limestones of Paleocene–Lower Eocene age [6]. Over a distance of  $\approx 100$  km, between Yecheng and Kudi, the Moho deepens from  $\approx 47$  to  $\approx 56$  km [28] (Fig. 2a). This, and the associated gravity anomalies [30], implies that the Tarim lithosphere is flexed down as the Kunlun range actively overthrusts its foreland. Structural evidence for the latter process is clear in the

Fig. 2. Simplified geological maps and sections (a) along the road of the western Kunlun range, and (b) western Tibet. Main faults, structural trends and contours are from fieldwork, Landsat and SPOT images interpretation and [6,8].









(b)

field. Two broad,  $\approx$  N120°E trending anticlines,  $\approx$  20 km south of Yecheng and  $\approx$  15 km north of Kokyar (Fig. 2a), fold the flexural basin infill, as well as Late Pleistocene–Holocene fluvial terraces at the surface. Active thrust ramps under these anticlines remain blind. South of a prominent syncline of Lower Quaternary conglomerates (Xiyu Fm. [11]) at Kokyar, the next  $\approx$  10 km of section cross a monocline of N dipping, southwards steepening, pink Miocene–Pliocene sandstones and mudstones, capped by a Late Quaternary terrace sloping gently north. A steep thrust ramp reaches the surface at Pusha, and truncates that monocline (Fig. 2a). On seismic sections this thrust can be seen to involve Paleozoic and Mesozoic sediments on top of the basement [29].

About 18 km south of Pusha, NE dipping Paleozoic limestones rise from beneath a loess-mantled, proximal Quaternary apron that contains big boulders and is affected by small-scale, gentle folds. The 1000 m thick crystalline limestones contain fusulinids of Upper Carboniferous age [5]. They cover  $\approx$  500 m of red, polymict conglomerates and arkoses of Devonian age (Tisnab beds; [7,10,31]). The Paleozoic rocks wrap the eastern pericline of one of several E–W trending basement antiforms that make the first prominent relief of the Kunlun (Fig. 2a). High-grade gneisses in the core of that antiform are exposed at Akazi Daban (3310 m). They contain K-feldspars, biotite, garnet and sillimanite, bear imprint of retrograde greenschist metamorphism, and are cut by large, steep, dolerite dykes that strike N120°E. These gneisses, which have yielded a zircon U/Pb age of 2261 Ma [32,33] and a Sm/Nd model age of 2800 Ma [34], probably represent the Tarim basement (Fig. 3).

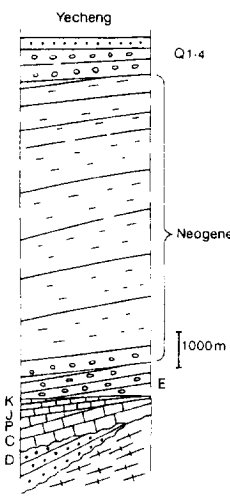
Deformed, south dipping limestones of possible Riphean age, which unconformably overlie the gneisses on the southern limb of the antiform, are tectonically overlain by strongly schistose metabasalts with intercalations of grey slates, silicic tuffs and calcschists. West of Akmechik, these rocks have suffered intense ductile strain and greenschist metamorphism. Down-dip stretching lineations on schistosity planes dipping at 60°S, asymmetric boudinage of calcschists and metabasalts, and C/S shear criteria indicate top-to-the-NNE transport (Fig. 3). Along the right bank of the Tisnab river, a steep NW

striking fault truncates the Akmechik thrust slice (Fig. 2a). South of that fault, a schistose granodiorite intrudes a thick unit of deformed mafic rocks, including pillow lavas and red–violet cherts. Elsewhere along strike, this unit also contains peridotites [7,10]. The slightly flattened and vertically stretched pillows form beds striking 100–120°E and dipping 80°S with right way up polarity. We found no fossils in that unit, except for radiolaria phantoms in the cherts. The granodiorite has yielded ages of 474 and  $449 \pm 24$  Ma ( $^{40}\text{Ar}/^{39}\text{Ar}$  on hornblende and whole rock), and 458 Ma (U/Pb on zircon) [33]. The mafic rocks thus represent a fragment of Lower Paleozoic (or Proterozoic) ocean floor intruded by an Ordovician magmatic arc [10]. They mark an important tectonic divide in the western Kunlun, which we refer to as the Kudi suture (Figs. 2 and 3) that probably continues westwards along the Tam Karaul fault zone [6].

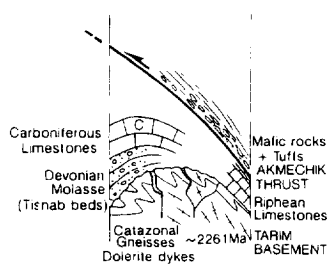
Further south along the Tisnab valley, north of Kudi, the section cuts an undeformed potassic granite batholith whose southern contact intrudes some marbles and a thick ( $\geq$  3000 m) sequence of dark biotite schists with quartz veins that tops tourmaline-bearing, migmatitic paragneisses with numerous melt dykes and sills. South of Kudi, the river follows the southwest limb of a broad gneiss dome, with foliations which alter in dip from 25°W to 30°SSW (Fig. 2a). The post-kinematic Kudi granite has yielded a U/Pb zircon age of 377 Ma, Rb/Sr ages of  $392 \pm 35$  Ma on whole rock, and of  $381 \pm 4$  Ma on biotite [32,33]. The biotite age derives from a complex spectra, with a maximum age (Fig. 4a) correlated with a K/Ca spectra minimum (Fig. 4b), suggesting coexistent chlorite or  $^{39}\text{Ar}$  recoil. Therefore, only an approximate age of  $380 \pm 10$  Ma may be inferred, in keeping with that given by other radiogenic systems. The migmatites south of Kudi have yielded a Sm/Nd model age of 1800 Ma, probably that of the protolith, while the complex  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra on K-feldspars (Fig. 4c) suggests a minimum age of 350–380 Ma for metamorphism, in rough agreement with post-kinematic emplacement of the Kudi granite (Fig. 3). Such ages imply that the main phase of deformation and metamorphism of the Kudi gneisses reflects Silurian collision between the Tarim and a continental block south of it (Fig. 5).

Under the high peaks of the Kunlun, at the apex

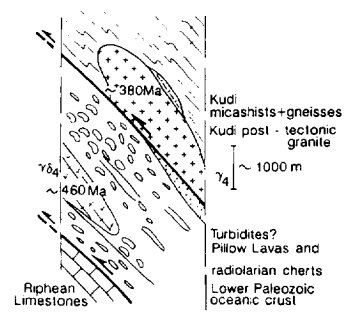
**TARIM FOREDEEP**



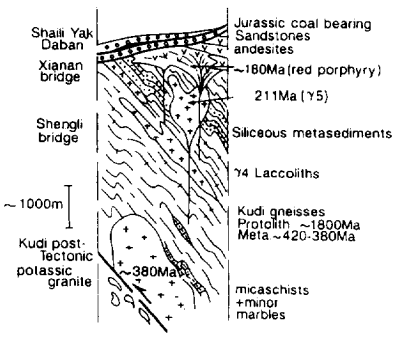
**NORTH KUN LUN  
(AKAZI DABAN PASS)**



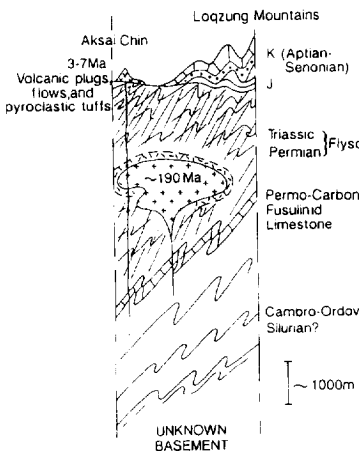
**KUDI SUTURE**



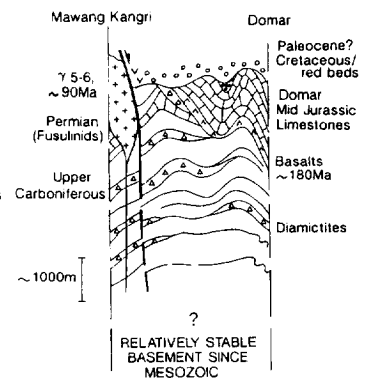
**SOUTH KUNLUN**



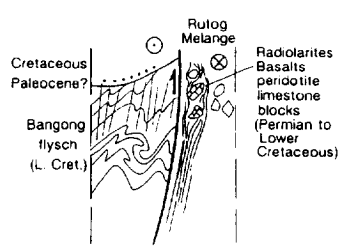
**TIANSHUIHAI TERRANE**



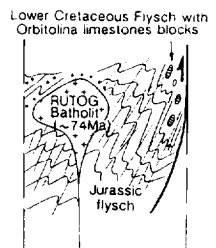
**W. QIANGTANG BLOCK**



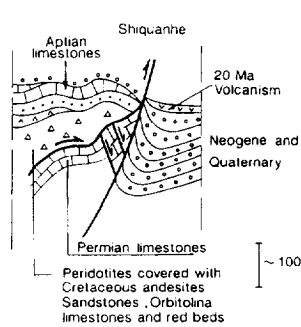
**BANGONG SUTURE**



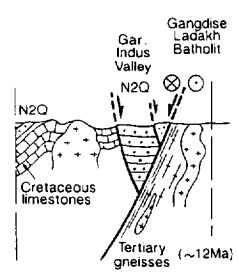
**RISUM ANTICLINORIUM**



**JAGGANG SHIQUANHE SUTURE**



**KARAKORUM FAULT ZONE**



of the Kudi gneiss dome, the flattish foliation is intruded by concordant laccoliths of two-mica anatectic granites. The roughly E–W striking, steeply south dipping hornfels that cap the southern limb of the dome are intruded by granites with mafic enclaves that have yielded a whole-rock  $^{40}\text{Ar}/^{39}\text{Ar}$  age of  $211 \pm 8$  Ma [33] and a  $^{40}\text{Ar}/^{39}\text{Ar}$  minimum age of  $180 \pm 10$  Ma on K-feldspars [34] at Shengli bridge (Figs. 3 and 4d). To the south, near Xianan bridge, red porphyries, dated at  $180 \pm 10$  Ma with Rb/Sr on whole rock [34], and andesitic agglomerates are thrust southwards on a tight synform of Jurassic continental sediments (Yarkand Group [7]), which include grey–beige, cross-bedded, gravelly sandstones, black, coal-bearing shales with plant fragments and conglomerates with chiefly red sandstone, andesite, rhyolite and limestone, but few gneiss pebbles (Figs. 2 and 3). The thrust fault that bounds the south Kunlun is a prominent feature of the landscape, extending westwards north of the road for at least 15 km, past Shaili Yak Daban (4962 m), and a comparable distance towards the east (Fig. 2a). Thrusting was concurrent with tight folding of the Jurassic synform, squeezed between the igneous rocks and the nearby Altyn Tagh fault zone, and probably coeval with Tertiary transcurrent motion along that zone.

### 2.2. The Altyn Tagh–Karakash strike-slip fault zone

Past Shaili Yak Daban, for about 200 km between Mazar and Dahongliutang, the road follows the western, N100–110°E striking segment of the Altyn Tagh fault zone [35–37], in part along the Yarkand and Karakash rivers (Fig. 2a). This remarkably linear strike-slip fault zone defines the southern limit of the western Kunlun range. The trace of the left-lateral active fault [37] generally follows the south wall of a near vertical,  $\approx 2$ –5 km wide, shear zone involving various parallel slices of steeply dipping rocks. Strain in that shear zone is part brittle, part ductile, with greenschist metamorphism. South of Shaili Yak Daban, lenses of brecciated Paleozoic limestones, black shales, yellow sandstones, boudinaged schists and Cretaceous red beds are juxtaposed for over 1 km of

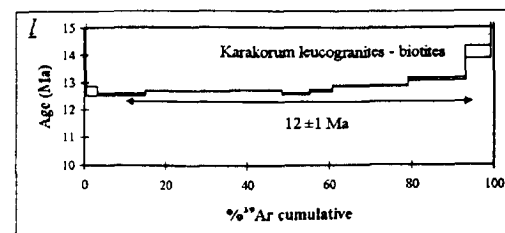
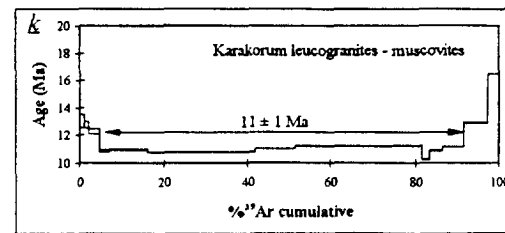
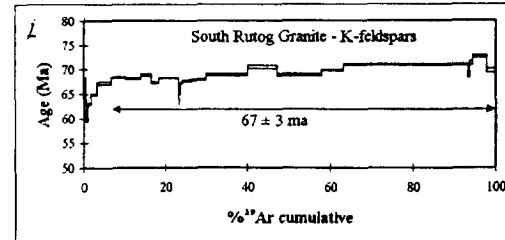
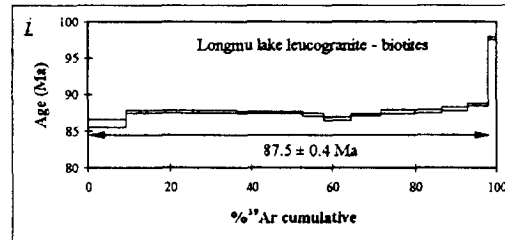
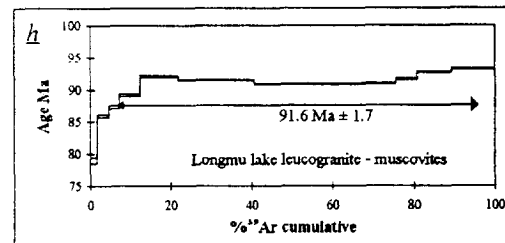
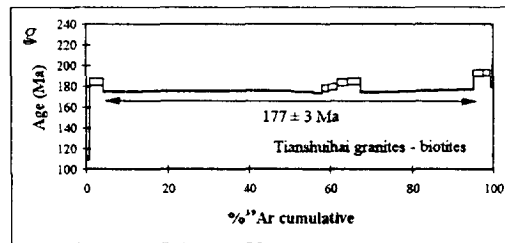
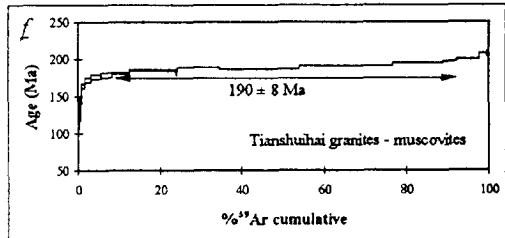
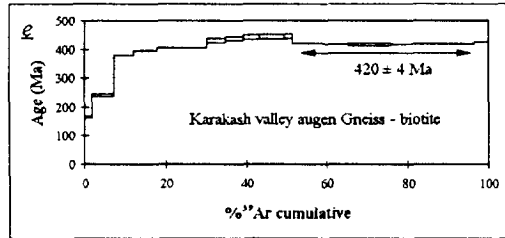
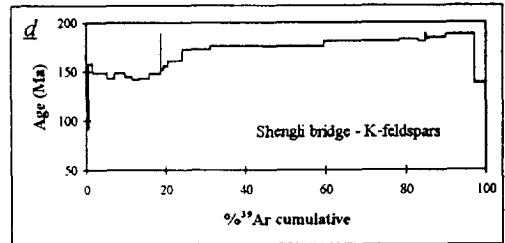
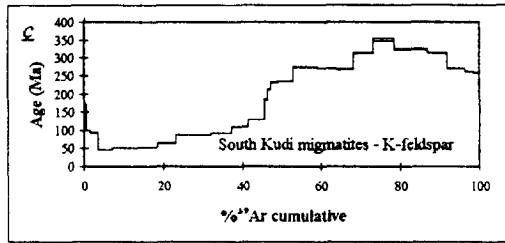
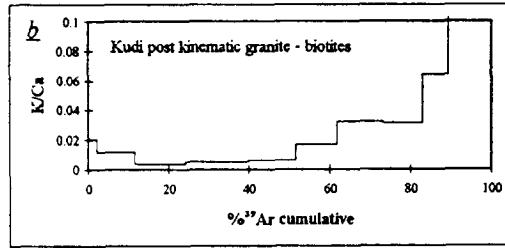
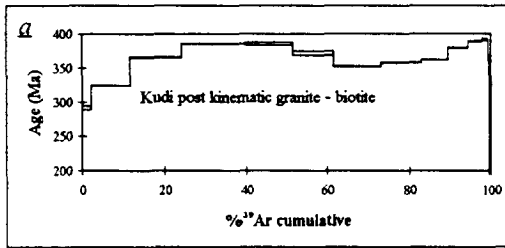
the section. East of the Yarkand–Karakash catchment divide at Kek Ate Daban (4918 m), slices of garnet–biotite mica-schists, of marbles with tremolite veins, and of gabbro–diorites and augen gneisses derived from the southern Kunlun igneous core extend for tens of kilometres along the fault. The gneisses, which have yielded biotite  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $420 \pm 4$  Ma (Fig. 4e), are cut by narrow shear zones bearing horizontal lineations and sinistral indicators on steep, N100–120°E striking planes.

Rocks south of the fault are completely different from those north of it. Most of them are fine-grained siliceous clastics affected by only low-grade metamorphism. Bedding and cleavage generally strike 10–30° more southerly than the fault, consistent with left-lateral movement on it. The strong contrast, for 200 km along strike, in the nature and grade of rocks on either side of the Altyn Tagh–Karakash zone confirms that it is a major crustal strike-slip fault with subordinate throw, uplifting the Kunlun relative to Tibet (Figs. 2 and 5).

### 2.3. The Tianshuihai terrane

From the Karakash shear zone to the Karakorum fault, a distance from north to south of  $\approx 450$  km, no metamorphic basement rocks are exposed along section (Fig. 2b). A uniform sequence of generally unfossiliferous, reportedly Lower Paleozoic [7], grey–greenish slates and sandstones (Bazar Dara Fm. [13]), crops out along the Yarkand valley, between Mazar and Kek Ate Daban. A first cleavage, nearly parallel to bedding and generally dipping N, is folded by folds a few hundred metres long trending  $\approx$  N120–130°E. Near Kek Ate Daban, darker slates, which include brownish sandstone beds with flute-casts, contain quartz veins, chloritoid and garnet, probably related to contact metamorphism. Those dark slates can be followed eastwards past Dahongliutang and Quanshuigou to Tianshuihai (Fig. 2), where they make a thick ( $\geq 6000$  m?), uniform sequence that reportedly reaches into the Triassic [7,10]. They have a flyschoid aspect and are tightly folded with undecided or south vergence and locally steep axial

Fig. 3. Tectono-thermal, magmatic and stratigraphic history of structural units crossed along the traverse.



plunges. The bedding and the usually steeper cleavage strike in the SE quadrant. South of Aksai, on the east side of the road, two prominent marble layers with a lineation stretching down-dip, outline the N120–130°E bedding cleavage strike for over 40 km. Along the Karakash valley, the Tianshuihai slates are intruded by muscovite and tourmaline-bearing pegmatite dykes and by granites with feldspar phenocrysts, surrounded by post-cleavage metamorphic aureoles with static, randomly oriented minerals such as andalusite (Fig. 3). These granites have yielded ages of 187, 196 and 215 Ma ( $^{40}\text{Ar}/^{39}\text{Ar}$  on biotite) [34] and 192 Ma (U/Pb, zircon, lower intercept) [33]. New  $^{40}\text{Ar}/^{39}\text{Ar}$  measurements on muscovites and biotites (Fig. 4f,g) give plateau ages at  $190 \pm 8$  Ma and  $177 \pm 3$  Ma, respectively, confirming an Upper Triassic to Lower Jurassic emplacement.

The ages of the igneous rocks south of Kudi and the structural relationship between the slates and granites south of the Karakash thus imply that the southern edge of the Kunlun block was an active margin, with a magmatic–volcanic arc as well as late-kinematic plutons intruding the shortened Tianshuihai flysch wedge in the Late Triassic–Early Jurassic [10] (Fig. 5). This flysch probably represents a western equivalent of the Bayan Har Group found south of the Kunlun range on the Lhasa–Golmud traverse [10,24,25].

Near the Aksai Chin Lake, strongly deformed schists and brachiopod-bearing marbles are exposed under the generally N dipping Tianshuihai slates. South of the lake, reportedly Carboniferous [7,10], isoclinally folded greenschists and greywackes with apparent southwestward vergence are unconformably capped by flat-lying conglomerates, red sandstones and limestones (Fig. 3) containing rudists of Albian–Aptian age (*Eoradiolites Gilgitensis*, determined by J. Philip). The age of this unconformity [4,6,7], and the facies of the Cretaceous sediments above it, make it similar to that found west of Nam Co in eastern Tibet [18,21]. Towards the south and west, the Cretaceous limestones become thicker, reaching into the Senonian [4,6] and cap, with less

pronounced angular unconformity, marine Jurassic black shales, sandstones and limestones [4,6,7,10]. While only gently warped and cut by N–S trending normal faults near Aksai Chin, the Cretaceous beds are strongly folded to the south and east, with locally steep cleavage, forming the jagged crests of the curved, fan-shaped Loqzung range [4,6]. The fold trends swing counterclockwise by 60° from west to east, due to sinistral Cenozoic movement on the ENE striking Longmu and Gozha Co faults (Fig. 2b) [35–37].

Thus, between the Karakash valley and Longmu Co, in western Tibet, there is evidence for at least three periods of approximately NNE shortening prior to emplacement of the  $\approx 200$  Ma post-kinematic granites, before 110 Ma (unconformity of the Lower Cretaceous), and after  $\approx 110$  Ma (folding of the Cretaceous).

Late Miocene–Pliocene volcanism exists north of Quanshuigou [6] and north of Aksai Chin [7]. About 18 km south of Dahongliutang, a small ignimbrite flow dated at 3.3 Ma (K/Ar [38]), floors the river valley's left bank, under Quaternary fanglomerates. To the north-northeast of Aksai Chin, we reached a large, tabular, basalt flow [7], and two small volcanic plugs, one of them rhyolitic (Fig. 2b and Fig. 3), that yielded ages of 4–6.6 Ma (K/Ar [38]). The volcanic rocks appear to be comparable in composition and age to those found farther east along the northern edge of the Tibet plateau [6,11,39,40].

#### 2.4. The western Qiangtang block

The active Gozha–Longmu Co strike-slip fault system (Figs. 1 and 2) separates the Tianshuihai terrane from the Qiantang block, slicing the folded Jurassic and Cretaceous beds of the eastern Loqzung range (Fig. 2b). The Gozha Co fault, also referred to as the Hongshanshu–Qiaoertianshan [10] or Lake Lighten fault [6,16] fault/suture, is lined with Permian, fusulinid-rich limestones and fragments of hydrothermally altered mafic rocks. It marks the southern limit of greenschist metamorphism in the Tianshuihai schists. With the Longmu Co fault, it also

Fig. 4.  $^{39}\text{Ar}/^{40}\text{Ar}$  Radiometric ages of the main magmatic and metamorphic rocks along the Yecheng–Shiquanhe traverse.

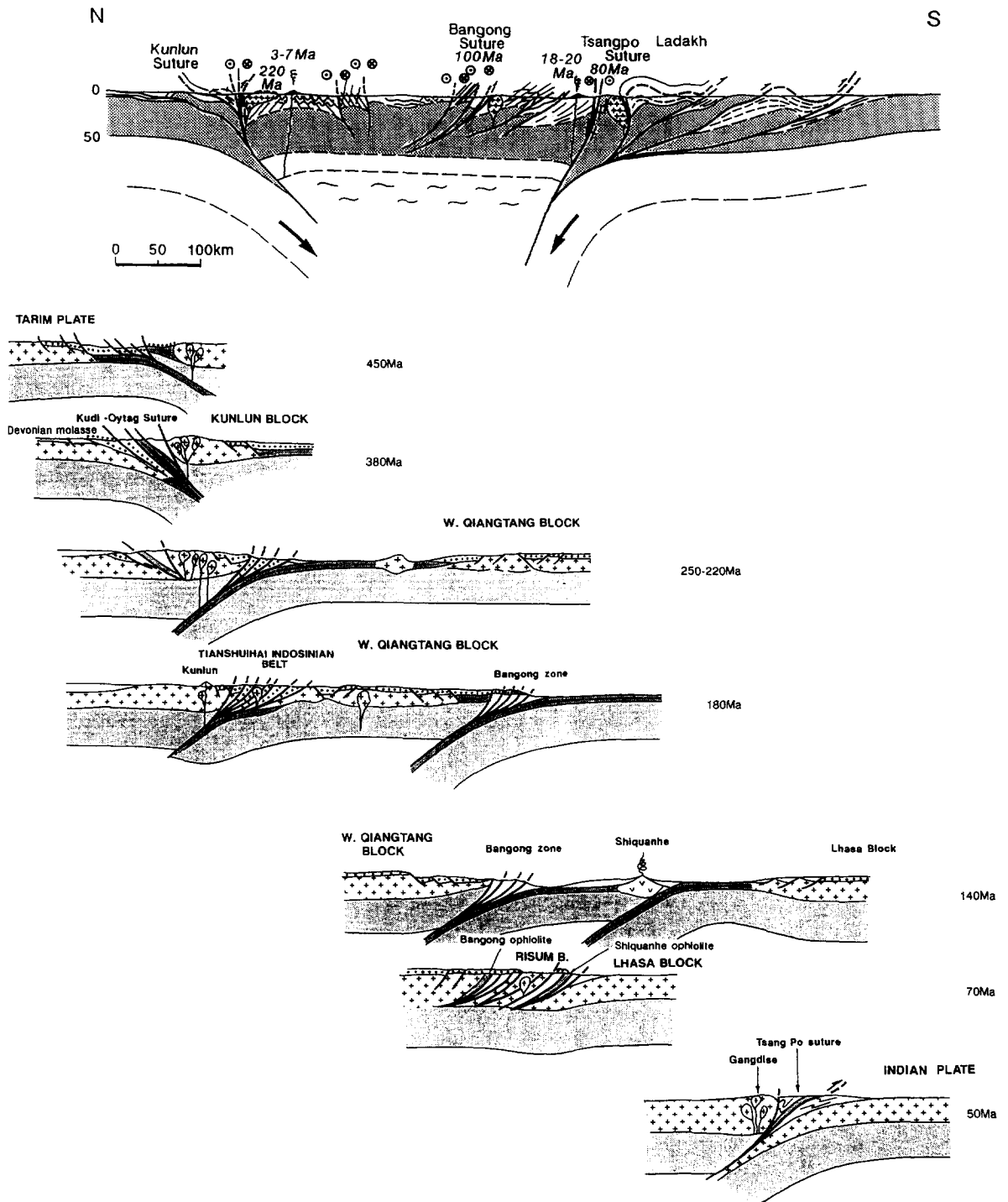


Fig. 5. Present-day section (upper cross-section), and sequential block and terrane accretion, from the lower Paleozoic to Tertiary, at lithospheric scale, of Western Tibet. Only the present-day section is drawn to scale.

marks the divide between that monotonous slate belt and a region with generally less deformed, unmetamorphosed, and richly fossiliferous Permo–Carboniferous rocks of Tethyan–Gondwanian affinity to the south [6,7,10,16].

The twin Longmu and Sumxi lakes (Tsaggar and Nopta Tso) lie in a Quaternary pull-apart basin, within a left step of the Longmu Co fault (Fig. 2b). To the south, in the Mawang Kangri mountains, which rise  $\approx 1700$  m above the plateau, granites and granodiorites intrude Permo–Carboniferous, fusulinid-bearing limestones and shales [5–7,10], (Fig. 2b). East of Mangtsa Co, other small granitic plutons intrude Cretaceous limestones [6]. One leucogranite southeast of Longmu Lake has yielded  $^{40}\text{Ar}/^{39}\text{Ar}$  ages around  $91 \pm 2$  Ma on muscovite and  $87 \pm 1$  Ma on biotite (Fig. 4h,i), each with average quality plateaus confirmed by inverse isochron probability. A prominent fault along the south edge of Mawang Kangri bounds the ENE-striking Changer Char graben, filled with dark red, Cretaceous–Tertiary conglomerates and sandstones, in which Norin reports Tertiary porphyries [6] (Fig. 2b and Fig. 3). High triangular facets imply active normal throw on that fault, which probably splays from the Longmu fault across the Mangtsa graben (Fig. 2b).

Between the Mawang Kangri and Gyipug, for  $\approx 70$  km, the section crosses thick ( $\geq 3000$  m), Permo–Carboniferous [7,10], black shales with quartzite horizons. These sediments, which are warped by broad,  $\approx$  ENE trending anticlines [6], form the cover of the western Qiangtang platform. They are the least deformed pre-Cretaceous sequence in western Tibet (Fig. 3), implying that northwestern Qiangtang remained rather stable in the Mesozoic and Tertiary. We found outstanding diamictites  $\approx 30$  km north of Gyipug and  $\approx 20$  km northwest of Domar (Fig. 2b). The latter, with striated quartzite dropstones a few centimetres in size, embedded in dark, finely laminated mudrock, clearly belong to the Late Carboniferous glacio-marine sequence described near Horpa Co [6], confirming, as for the Lhasa block [17,24], the Gondwanian origin of the west Qiangtang block [6]. Locally, this sequence is overlain by Permian shales and limestones that contain Tethyan fusulinids [41], and by Triassic conglomerates, but northwest of Domar it is capped by  $\approx 100$  m of volcanic flows, including basalts dated

at  $180 \pm 5$  Ma by K/Ar on whole rock [34], beneath thinly bedded, fossiliferous, Mid-Jurassic marine limestones [7,10] (Fig. 3). Near Domar, these limestones are tightly folded, with locally steep axial plunge, and cut by steeply NW dipping thrusts, such as the prominent Domar–Wujiang thrust (Fig. 2b). Isolated, fault-bounded troughs of red conglomerates and sandstones (Cretaceous–Paleocene?), disconformably overlying upon steeper Jurassic beds, make pinched synclines within the Domar fold belt (Fig. 3). On the north shore of Bangong Co, near Wujiang, gently folded Tertiary red beds unconformably overlie EW trending, sheared, tightly folded, Carboniferous slates with stretched, boudinaged marbles, and flysch. The generally S dipping red beds are faulted and warped in a broad flexure, attesting to Cenozoic throw on the Domar–Wujiang thrust. About 100 km east of Domar, on Landsat images, the Jurassic limestones [7] broaden into a  $60 \times 20$  km wide, little deformed mesa incised by canyons, attesting to heterogeneous shortening since the middle Mesozoic. This notwithstanding, there is clear evidence for three phases of localized SSE vergent shortening and folding along the southern edge of the west Qiangtang platform. The first, weak phase predates the Jurassic basalts (180 Ma) that disconformably cap the Carboniferous–Triassic series (Fig. 2b and Fig. 3). The second predates the Cretaceous to Paleocene red beds, and the third is of Tertiary age.

### 2.5. The Bangong Lake suture zone

About 30 km south-southwest of Domar the road crosses the 30 km wide Bangong Co flysch melange belt, north of Rutog (Fig. 2b and Fig. 3). This belt, traced eastwards about 1200 km to Ando, north of Lhasa [7], marks the Bangong–Nujiang suture [7–10,15,18,21–23,43,44] between the Qiangtang and Lhasa blocks. The outstanding wildflysch west of Bangong Lake (locally Nyak Co) displays most of the elements that typify ophiolitic melanges, with a close resemblance to that seen north of Lhasa. It contains blocks of harzburgites varying from a few metres to hill size, serpentized peridotites with chromite, microgabbros, basalts, including pillow lavas, red radiolarian cherts, blocks of platform limestones ranging in age from Permo–Carboniferous to

Aptian (determined by J. Philip), and sandstones containing mafic debris. Particularly characteristic are blocks of breccias with serpentinite clasts embedded in a limy matrix, identical to those of Yila Shan, north of Nachu [21]. The melange is in tectonic contact with a thick sequence of thinly bedded flysch, reportedly of Upper Jurassic–Lower Cretaceous age [7,10], best exposed east and north of Nyak Co. This fine-grained flysch has suffered polyphase shortening coeval with greenschist metamorphism. Early isoclinal folds with N–S trending limbs and steep axial plunges are cut by a steep,  $\approx$  EW striking slaty cleavage that is coeval with the regionally better developed EW trending folds (Fig. 3).

To the south, near Rutog, the melange belt is bounded by a prominent,  $\approx$  EW striking, steeply north dipping, sinistral shear zone with a component of south-directed thrusting. Serpentine blocks form asymmetric boudins with clear C/S indicators. Shear was probably coeval with south vergent folding in the adjacent Cretaceous limestones.

#### 2.6. The Risum anticlinorium

Between Rutog and Jaggang (Fig. 2b), the section cuts a 40 km wide anticlinorium of black, reportedly Jurassic, flyschoid shales intruded by a large pluton of granodiorite and alkaline granite (Fig. 3), whose summits reach  $\approx$  6000 m. These rocks, whose contact aureole is marked by prominent, up to 200 m thick, hornfels, have been dated at  $74 \pm 1$  Ma by Rb/Sr on biotite [34]. They appear to have intruded shallow levels of the crust, with rapid cooling between 70 and 60 Ma, revealed by  $^{40}\text{Ar}/^{39}\text{Ar}$  (Fig. 4j) and apatite fission track thermochronology [34,45].

Near Jaggang, the anticlinorium displays a large inverted limb, attested by bedding cleavage relationships and upside-down sole marks. The Jurassic shales stand above a younger flysch with blocks of limestones varying in size from a few metres to a few hundred metres and containing orbitolinids of Albian age (determined by M. Moullade) (Fig. 3). Layers of calcarenites in the flysch contain similar, reworked orbitolinids. South-facing, overturned folds with axes plunging 10–30°E show N100°E striking, 50°N dipping axial plane slaty cleavage. This cleavage flattens southwards close to a major tectonic contact, the Jaggang thrust.

The timing of granite emplacement relative to regional shortening is complex. Near Rutog, N trending, isoclinal folds in hornfels next to the locally little deformed granite formed prior to contact metamorphism. However, the thermochronology suggests intrusion before south-directed transport on the Jaggang thrust, further south.

#### 2.7. The Jaggang–Shiquanhe suture zone

North of Shiquanhe, Lower Cretaceous, shallow marine and terrestrial deposits (orbitolinid and rudist bearing limestones of Aptian age, plant-bearing sandstones and conglomerates and andesitic volcanics) unconformably overlie kilometre wide massifs of serpentinitized peridotites (Fig. 2b) with rare gabbros and, locally, Permo–Carboniferous limestones, dipping 40°W, containing cool-water faunas [10] and cut by large, S dipping normal faults. In turn, the Aptian limestones are unconformably overlain by Tertiary red conglomerates. Although the relationship between the peridotites and the Permo–Carboniferous limestones, the oldest rocks of the area, is poorly exposed along the section, it is likely that the peridotites and gabbros were thrust southwards onto the Permian prior to the Tertiary (Figs. 3 and 5), forming remnants of a late Mesozoic suture.

The Permian–Tertiary sequence is folded, with south-facing, E–W trending, pinched synclines outlined by perched Aptian limestones. Along the northern boundary of the Shiquanhe basin, the limestones are thrust southwards onto N95°E trending, vertical beds of Pliocene–Quaternary conglomerates, sandstones and marls (Fig. 2b and Fig. 3). East of Shiquanhe, flat trachytic lava flows of continental crust chemical affinity, dated at 18–20 Ma ( $^{40}\text{Ar}/^{39}\text{Ar}$  on whole rock [34]), unconformably overlie folded limestones and schistose basalts. South of the Shiquanhe synclinal basin, similar limestones are intruded by rhyolitic plugs and leucogranites (Fig. 2b).

#### 2.8. The Karakorum fault and Ladakh range

The traverse ends beyond the Indus, just south of the NW striking, steeply NE dipping Karakorum fault, which marks the base of the Ladakh range front, along the floodplains of the Indus and Gar

ivers. This active, normal-dextral fault is the greatest geomorphic boundary of the southern half of the section. Cumulative scarps tens of meters high across Late Pleistocene moraines, 2 km high triangular facets, and perched glacial valleys attest to rapid vertical throw on the fault [46]. Dextral offsets of 300–400 m of post-glacial fans and channels imply a Holocene slip rate of the order of 3 cm/yr [46]. Such motion has produced the conspicuous  $\approx 120$  km offset of the Indus river course [46,47] (Fig. 2b). Recent uplift along the fault has exhumed strongly sheared gneisses, with horizontal lineation on  $\approx N140^\circ E$  striking,  $\approx 60^\circ NE$  dipping foliation planes parallel to the active fault trace (Fig. 3). For over 2 km along the section, such mylonitic gneisses derive from granodiorites with numerous pegmatite and aplite dykes. Most dykes are reoriented parallel to the foliation, implying large finite strain, and C/S indicators show unequivocal dextral motion. The timing of ductile strain is constrained by  $^{40}Ar/^{39}Ar$  plateau ages of  $11 \pm 1$  Ma and  $12 \pm 1$  Ma (Fig. 4k,l) [33] on micas recrystallized in the S/C planes of a sheared leucogranite.

### 3. Tectonic history of Western Tibet

Our observations along the Yecheng–Shiquanhe traverse support earlier inferences [1–6,10] and bring new insight to the deformation and tectonic history of Western Tibet.

The most prominent structures, which stand out in the landscape and expose deep metamorphic rocks, are of Cenozoic age. The main features lie along the northern and southern boundaries of the plateau. Together, the active, sinistral Altyn Tagh–Karakash and dextral Karakorum strike-slip faults keep accommodating northeastward extrusion of the Tibetan lithosphere [36,37,48–51]. They also form the inner boundaries of the Kunlun and Karakorum–Himalaya ranges, along which strong cooling, attested by K-feldspar and biotite Ar/Ar thermochronology or by fission tracks, whether on exhumed basement or foreland detrital sediments [33,56,57], has taken place in the last 20 Ma as a consequence of vigorous erosion and uplift (Fig. 5). Such uplift has been primarily driven by concurrent throw on the thrusts that carry the ranges northwards and southwards,

onto the Taklamakan and Pundjab foredeeps. We interpret those paired thrust and strike-slip fault systems as resulting from oblique subduction of the Tarim and Indian lithospheric mantle, to the south and north, respectively, beneath the escaping Tibet plateau [52–54] (Fig. 5). The two discrete  $\approx E$ – $W$  trending belts of ultra-potassic volcanism located just north of the Karakorum fault ( $\approx 18$ – $20$  Ma) and south of the Altyn Tagh–Karakash fault ( $\approx 3$ – $7$  Ma) [38], are most simply accounted for as products of such diachronic subductions (Fig. 5). Subduction would have started later in the north, consistent with the growth of the plateau away from the Indian collision front [38,53].

Inside the plateau, during the Cenozoic, a few narrow thrust belts and fault zones (Loqzung–Longmu Co, Domar–Wujiang, Rutog and Shiquanhe) have accommodated heterogeneous,  $\approx N$ – $S$  shortening between the less deformed Tianshuihai, Qiangtang and Lhasa blocks. The disconformable Aptian–Senonian beds are tightly folded, mostly along such zones, which coincide roughly with the Mesozoic sutures between the blocks. Only the Longmu Co fault, the southern splay of the Altyn Tagh [37], and the Shiquanhe thrust, near the Karakorum fault, show clear evidence of Holocene strike-slip and Pliocene–Quaternary thrusting, respectively. This is consistent with the outward migration of strain, concurrent with the surface increase of Tibet since the onset of the collision between India and Asia.

Except at the western edge of Mawang Kangri [49], and as a secondary component along active transcurrent faults, Quaternary normal faulting is less prominent along the Yecheng–Shiquanhe traverse than elsewhere on the plateau [36,49].

The deformation and accretion history prior to the India–Asia collision is characterized by southward jumps of the active margin with time, attested to by the systematic younging of granitic plutons from north to south. Exhumed magmatic intrusives and ductile strain in the northern Kunlun range pre-date the Late Devonian. The intrusion of granodiorites ( $\approx 460$  Ma) into oceanic crust implies the existence of Ordovician subduction followed by the Silurian collision that led to deformation, metamorphism and anatexis of the Kudi gneisses before intrusion of the post-kinematic Kudi granite ( $\approx 380$  Ma) (Fig. 5).

Chiefly north-directed thrusting, with low-grade metamorphism, in the range is partly of Cenozoic age. However, a similar northward vergence during the middle Paleozoic collision may be inferred from the presence of red Devonian molasse, the probable infill of a foredeep basin, on the Tarim basement.

The well developed Triassic to Lower Jurassic magmatism ( $\approx 180$ – $215$  Ma), on either side of the Altyn Tagh–Karakash fault, implies north-dipping subduction under the Kunlun at that time. Strong folding of the Tianshuihai flysch was in large part due to shortening of the related accretion prism (Fig. 5).

Along the Bangong zone, an ophiolitic wildflysch identical in composition to that found over 1000 km eastwards, north of Nachu [9,10,15,21,22,43] formed as a subduction melange prior to  $\approx 110$  Ma (Fig. 5). Following isoclinal folding and flattening due to south vergent suturing, that zone was smeared by left-lateral shear in the Tertiary.

South-directed folding and thrusting of the olistolithic Cretaceous flysch near Jaggang and of the ultramafics and Cretaceous volcanics north of Shiquanhe probably took place in the late Cretaceous–Paleocene (80–60 Ma), concurrent with cooling and uplift of the Risum–Rutog batholith (Fig. 5). We interpret the Shiquanhe ultramafics as marking the trace of a distinct suture, separated from the Bangong suture by the small, intervening Risum block (Fig. 5). A Cretaceous volcanic arc on the southern edge of that block was welded to the southern Lhasa block prior to closure of the Indus–Zangbo suture (Figs. 1 and 5).

#### 4. Conclusions

The Yecheng–Shiquanhe traverse provides key evidence for assessing longitudinal differences and similarities within the  $\approx 3000$  km long Pamir–Tibet collage.

The roughly N–S trending section of the plateau near  $\approx 79^\circ\text{E}$  is about three times shorter than that near the Lhasa–Golmud road ( $\approx 92^\circ\text{E}$ ), where Tibet is broadest. Correspondingly, it shows drastic reduction of most structural units. The average elevations, the amounts of Tertiary shortening per unit length due to folding and thrusting, and the degrees of

exhumation and denudation on either section, however, appear to be similar. Hence, short of comparably drastic, Late Mesozoic paleolatitudinal differences between  $79^\circ$  and  $92^\circ\text{E}$ , which paleomagnetic studies do not indicate [60,61], a large fraction of the structural reduction that characterizes western Tibet ought to be due to Cenozoic transcurrent slicing and extrusion of various blocks within the collage [48,51].

That the fairly short  $79^\circ\text{E}$  section crosses one prominent dextral, and as many as three large sinistral strike-slip faults and/or shear zones (Figs. 1 and 5), supports this inference. The two outermost fault zones in fact coincide with the geomorphic boundaries of the plateau and form particularly sharp geological divides. Moreover, the Karakorum fault truncates and/or bends clockwise most of the sinistral faults and structural units of western Tibet (Fig. 1). That it was already a dextral shear zone  $\approx 12$  My ago implies that its finite Cenozoic offset at  $79^\circ\text{E}$  is several times that of the Indus River ( $\approx 120$  km), which could have accrued in only  $\approx 4$  Ma at the present slip rate ( $\approx 3$  cm/yr), [46].

In spite of structural reduction, several of the blocks, terranes and sutures seen along the Yecheng–Shiquanhe section can be unambiguously correlated with those identified eastwards along the Lhasa–Golmud traverse and farther north (Figs. 1 and 5), or westwards in Afghanistan and Pakistan, corroborating or improving long-held views (e.g., [9,10,14,15,22,43,62–67]). Subduction of the various oceanic basins, including those belonging to the Paleotethys, was not always towards the north, however.

Silurian collision between the Western Kunlun and Tarim blocks along the Kudi suture ( $\approx 380$  Ma) probably followed south dipping subduction of oceanic lithosphere attached to the Tarim plate (Fig. 5). Similar pre–Late Devonian ('Caledonian') orogenic belts and sutures exist 1500–1800 km to the east, along the northern and southern edges of the Qaidam basin [22,58,59], and in the Qilian Shan [7,9], south of the Altyn Tagh fault (Fig. 1). Which of them might correspond to that near Kudi remains to be established, but all are truncated, hence sinistral offset hundreds of kilometres by this fault [14,51].

The Early Jurassic collage of the Tianshuihai terrane and Gondwanian Qiangtang block with the

Kunlun ( $\approx 180$  Ma) was the ultimate result of the north dipping, Triassic subduction of Paleotethysian lithosphere under Laurasia (Fig. 5). Such 'Indosinian' accretion, magmatism and deformation is closely comparable to that observed 1500–3500 km eastwards, along and south of the eastern Kunlun [10,15,16,22,23,25,26], or within the Songpan–Garze region and Qinling–Dabie Shan, where large mid-crustal decollements are inferred [55]. However, markers of the suture(s) corresponding to the Tianshuihai subduction–accretion complex, like the mafic–ultramafic rocks described farther east (Ulug Muztagh, Anyemaqen and Jinsha) [39,58,59] (Fig. 1), are lacking on the 79°E traverse, probably because of sinistral smearing by the Altyn Tagh fault and its splays since the Jurassic. The south-dipping Gozha and Longmu Co faults now obscure the original nature and attitude of the boundary between the Tianshuihai terrane and the Qiangtang block (Fig. 5), which may have dipped south [10].

Early Cretaceous suturing between the Qiangtang and northern Lhasa (Risum) blocks, along the conspicuous Bangong suture, terminated north dipping subduction of the Neo-Cimmerian ocean (Fig. 5). Such final welding may have occurred somewhat later at 79°E than in the Nujiang region,  $\approx 1200$  km to the east, even though the ophiolitic wildflyschs found in either locality are remarkably similar [9,10,15,21,22,43].

The tectonic setting and rock assemblages, particularly the Albian Orbitolina flysch and Cretaceous volcanics of the Jaggang–Shiquanhe melange zone, resemble those found over 1000 km eastwards, near Nam Co and Xainza [21,42,43], and westwards, north of the Kohistan arc in Pakistan, and north of the Kabul block in Afghanistan [14,62–64]. Because field evidence near Shiquanhe implies continuity of that zone over at least  $\approx 2000$  km, from the Altinur range to the Nyainqentanglha, it is best interpreted as a distinct suture [64], rather than as a repetition of the Bangong suture [42,65]. This supports the idea that two Late Cretaceous–Early Tertiary sutures divide southern Tibet (one within the so-called Lhasa 'block') and that two subduction zones led to the demise of the Neotethys north of India, as long argued from fieldwork in eastern Afghanistan and Pakistan [14,62]. Correlating the Shiquanhe ultramafics with those in the Saltoro range would imply

at least  $\approx 300$  km of Cenozoic smear and offset by the Karakorum fault at 78°E. A better estimate of finite motion on that fault at this longitude requires more convincing identification of the Bangong–Panjao suture across the Pamir prong than has been made to date [65–67].

The Neogene volcanics dated and analyzed on the Yecheng–Shiquanhe section belong to two discrete belts that follow the northern and southern edges of the plateau up to  $\approx 1200$  km eastwards [11,20,39], about 150 and 250 km south and north of the corresponding foreland thrusts, respectively. Such a location is identical to that of volcanism landwards of subduction zones, suggesting that the lithospheric mantles of both India and the Tarim plunge under Tibet (Fig. 5). The peculiar chemistry of the lavas might be due to thicker crust. Their age, younger in the north, would then imply migration of Tertiary shortening in a direction opposite to that of Mesozoic accretion, compatible with post-collision growth of the plateau by triggering of south-dipping, continental subduction zones farther and farther into Asia's interior [52,53].

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## Appendix A. $^{40}\text{Ar}/^{39}\text{Ar}$ Analytical techniques

High purity separates were obtained using heavy liquid and a magnetic separator, and by hand picking. K-feldspars were irradiated for 60 h in the H5 position in the Ford nuclear reactor at University of Michigan. Micas were irradiated for 24 h in site 69 of the Siloé reactor, CEA, Grenoble. Samples irradiated in France were shielded by cadmium foil to reduce neutron interactions on  $^{40}\text{K}$ . All samples in each group were irradiated at the same time, with  $\text{CaF}_2$  and  $\text{K}_2\text{SO}_4$  to account for interfering nuclear reactions, and flux monitors in the upper and lower positions in each vessel. For irradiations in the USA, Fish Canyon tuff sanidine (27.8 Ma) was used for the flux monitor. For irradiations in France, we used both the Caplongue hornblende (344.5 Ma) and LP6 biotite (128.5 Ma). Step heating analyses were performed on the VG1200S and VG3600 mass spectrometers of the  $^{40}\text{Ar}/^{39}\text{Ar}$  laboratories of UCLA and Clermont-Ferrand, respectively. Identical samples run on both instruments yielded results agreeing to within 2%. Details of the analytical procedures are given in [34]. Age spectrum calculations do not include error on the J factor, while plateau and isochron ages do.

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