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Arc-ophiolite obduction in the Western Kunlun Range (China): implications for the Palaeozoic evolution of central Asia

WENJIAO XIAO[1], BRIAN F. WINDLEY[2,3], JIE HAO[1] & JILIANG LI[1]
[1]*Key Laboratory of Lithosphere Tectonic Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, PO Box 9825, Beijing 100029, P.R. China (e-mail: wj_xiao@263.net)*
[2]*Department of Geology, University of Leicester, Leicester LE1 7RH, UK*
[3]*Present address: Department of Earth and Planetary Sciences, Tokyo Institute of Technology, O-okayama 2-12-1, Meguro, Tokyo 152-8511, Japan*

Abstract: The nature of the 'Kudi ophiolite' in the Western Kunlun Range is hotly debated. Our new structural–geochemical data reveal that it is actually an arc ophiolite comprising: (1) arc- or ophiolite-derived turbidites of two generations containing Late Ordovician–Silurian and Late Devonian–Early Carboniferous radiolarians; (2) a central intra-oceanic (Yixieke) arc with basalt–andesite–tuff–agglomerate; (3) lower (Buziwan) oceanic crust containing dunite–harzburgite–gabbro. We propose the following tectonic evolution. South-dipping subduction in Late Cambrian to earliest Ordovician time generated the Yixieke arc on top of the Buziwan oceanic crust–mantle. This subduction led to emplacement of the arc northwards onto the North Kunlun terrane (Tarim block), creating an active continental margin with northward subduction below it. The Kudi ophiolite was thrust southeastward over the incoming Kudi continental (gneiss) terrane in mid-Ordovician–mid-Devonian time. During a tectonic hiatus in the Kudi region Late Devonian–Carboniferous subduction further west led to development of the Oytag arc, formerly regarded as an equivalent of the Kudi ophiolite. Lower Permian arc lavas and Upper Triassic granites in the Xiananqiao arc south of Kudi mark the resumption of north-dipping subduction before final collision with the incoming Qiangtang block. Comparison with the Lapeiquan ophiolite in the Eastern Kunlun assists regional correlation along this Palaeozoic orogen and constrains Cenozoic displacement of the Altyn Tagh fault.

Keywords: Kudi, Western Kunlun Range, island arcs, ophiolites, obduction.

The Western Kunlun Range, located along the northern periphery of the Tibetan plateau, is a 1000 km long NW–SE mountain belt extending from the Pamir syntaxis in the west to the Altyn Tagh and the East Kunlun Range in the east (Fig. 1). It is generally accepted that the Western Kunlun Range resulted from the collision between the Tarim and Qiangtang blocks in Early Mesozoic time (Dewey *et al*. 1988; Searle 1991; Şengör & Okurogullari 1991; Sun *et al*. 1991; Jiang *et al*. 1992; Matte *et al*. 1996; Li & Xiao 1999; Yuan 1999; Mattern & Schneider 2000) and was subjected to Cenozoic deformation by the far-field effect of the India–Asia collision on the southern side of the Tibetan plateau (Molnar & Tapponnier 1975; Brunel *et al*. 1994; Matte *et al*. 1996; Kao *et al*. 2001; Li *et al*. 2002). Nevertheless, the Palaeozoic tectonic evolution of the Western Kunlun Range is still poorly understood, in particular the role of ophiolites and arcs north of the Mazar–Kangxiwar fault (Fig. 1) where average elevation is over 5000 m with several peaks higher than 7000 m. The Palaeozoic geology is well exposed in deep river sections that traverse key tectonostratigraphic units. Among those, the Kudi ophiolite marks the western segment (Matte *et al*. 1996; Pan 1996; Mattern & Schneider 2000) of a possible Mid-Palaeozoic suture extending along the northern Tibetan plateau eastward to Lapeiquan in the Altyn–East Kunlun orogen, which is on the south side of the Ruoqiang–Xinxinxia fault and the north side of the Altyn Tagh fault (Fig. 1). This suture is a remnant of the Palaeo-Tethyan ocean in central Asia (Pan 1996; Sobel & Dumitru 1997; Sobel & Arnaud 1999). Thus investigation of the nature, tectonic setting and structure of the Kudi ophiolite and related rocks is of considerable importance, not only because it improves understanding of the tectonic evolution of Palaeo-Tethys, but also because it provides additional constraints on the still controversial geodynamics of the Altyn Tagh fault system in central Asia (Molnar & Tapponnier 1975; Zhou & Graham 1996; Wang 1997; Sobel & Arnaud 1999; Yue & Liou 1999).

Several models have been proposed to explain the evolution of the Palaeozoic Western Kunlun Range based on or including investigations of the Kudi ophiolite. For example, Şengör & Okurogullari (1991) proposed a Late Proterozoic–Carboniferous, north-dipping, subduction-related accretionary origin for the whole Western Kunlun Range; Yao & Hsü (1994), Hsü *et al*. (1995) and Yin & Harrison (2000) favoured back-arc collapse to explain the presence of the Kudi ophiolite; Mattern *et al*. (1996), Pan (1996) and Mattern & Schneider (2000) proposed an Early Palaeozoic terrane accretion model; and Matte *et al*. (1996) envisaged a rejuvenated Silurian collisional orogen. Collectively, several important questions remain open as to when and in what direction did the ocean (represented by the Kudi ophiolite) subduct. There are two contrasting opinions: Matte *et al*. (1996) and Pan (1996) suggested that Late Proterozoic or Early Palaeozoic oceanic crust in a back-arc basin was subducted to the south, whereas Yao & Hsü (1994), Hsü *et al*. (1995) and Yin & Harrison (2000) proposed north-dipping subduction of a Permian back-arc oceanic basin. The former is negated by the recent discovery of Late Devonian–Early Carboniferous radiolarians in cherts of the upper sequence of the Kudi ophiolite and by the lack of Proterozoic arc plutons or volcanic rocks, whereas the latter is contradicted by radiometric ages of granites that

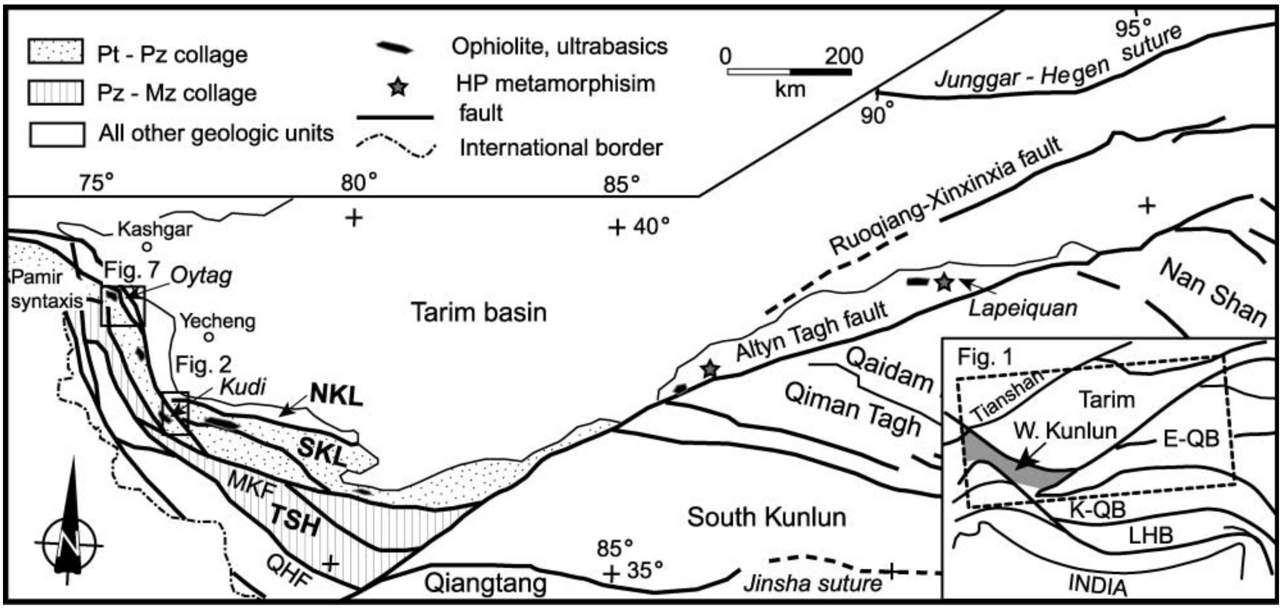


Fig. 1. Schematic tectonic map of the Western Kunlun Range and adjacent region (modified after Yin & Bian 1995; Pan 1996; Xiao *et al*. 1998; Sobel & Arnaud 1999; Mattern & Schneider 2000); areas shown in Figs. 2 and 7 are marked by boxes. Inset is a schematic tectonic map of central Asia with a box showing the position of the Western Kunlun Range. NKL, North Kunlun terrane; SKL, South Kunlun terrane; TSH, Tianshuihai terrane; MKF, Mazar–Kangxiwar fault; QHF, Qiertianshan–Hongshanhu fault; E-QB, Eastern Kunlun and Qaidam blocks; K-QB, Karakoram–Qiangtang block; LHB, Lhasa block.

were thought to intrude the Kudi ophiolite. Our recent field, structural and geochemical data reveal that the ‘Kudi ophiolite’ is actually an arc ophiolite that was thrust southward over a 404 Ma granite and juxtaposed against a 490 Ma granodiorite to the north (Fig. 2). This paper reports our recent work on the arc-ophiolite complex in the framework of a Sino-British joint tectonic study in the last 5 years. We integrate these results with our new data from the Oytag arc. Accordingly, we propose a scenario of Late Palaeozoic arc-ophiolite obduction, forming an Andean-type margin in the northern Western Kunlun Range in the Late Permian. We emphasize for the first time the role of a major continental margin arc and collisional tectonics in Late Palaeozoic time on the northern side of the Tibetan Plateau. We also compare the Western Kunlun Range with mid-Palaeozoic geology near the Lapeiquan ophiolite in the Altyn–East Kunlun orogen (Sobel & Arnaud 1999), and discuss the implications for the reconstruction of the Palaeozoic structure of northern Tibet and the geodynamic nature of the Altyn Tagh and associated faults.

Regional geology

Pan (1990, 1996) subdivided the Western Kunlun Range into the North Kunlun, South Kunlun and Tianshuihai terranes separated by the Kudi and Mazar–Kangxiwar sutures, respectively (Fig. 1). For detailed geology and stratigraphy, readers are referred to Matte *et al*. (1996), Pan (1996) and Mattern & Schneider (2000). Here we concentrate on the tectonic architecture of the northern Western Kunlun Range (Fig. 1).

The northernmost belt near Akaz Daban (Fig. 2) mainly comprises basement of the Tarim block (Unit I in Fig. 2), which is composed of Proterozoic gneiss, schist, migmatite, stromatolite-bearing limestone, clastic rocks and chert, overlain by Sinian conglomerates, tillites, clastic rocks and carbonates (Fig. 3). The Akaz fault (Fig. 2) is an important tectonic boundary against which the Tarim passive margin (North Kunlun terrane) in the north was juxtaposed to the Kunlun active arc in the south during Late Proterozoic to Early Palaeozoic time; we term this the Akaz suture.

Greenschists and marbles cropping out on the southern side of Akaz Daban are complexly imbricated in tectonic slices (Unit II, Fig. 2). The protolith of the greenschist is basalt (Pan & Wang 1994; Pan 1996), which has a within-plate trace element signature (Yuan 1999); in contrast, the marbles represent a shallow-water oceanic environment (Deng 1989; Pan 1996). This sequence is very similar to that of the volcanic seamount tectonic facies of Robertson (1994). Pan (1996) considered this complex to be of late Precambrian age. However, crinoids in the marbles and radiolarians in chert in the basaltic rocks suggest that the age extends to Cambrian–Ordovician time (Zhang *et al*. 1997; Fig. 2). The complex is overlain unconformably by Devonian and Permo-Carboniferous marine sediments and Permo-Triassic terrestrial sediments (Fig. 3a). In summary, we interpret Unit II (Fig. 2) as a fragment of a volcanic seamount incorporated into an Early Palaeozoic accretionary prism.

To the south, a 128 km (road signpost) granodiorite (Fig. 2), which has U/Pb ages of 490.9 ± 2.8 Ma (Yuan 1999) and U/Pb ages of $460 + 2.4/-2.5$ Ma age (Xu *et al*. 1996; Sobel & Arnaud 1999), represents the main component of an Early Palaeozoic arc (Matte *et al*. 1996; Pan 1996; Sobel & Arnaud 1999; Yuan 1999).

Unit III (Figs. 1–3) is a gneiss–schist complex, the Kudi terrane, that extends as the main ridge of the Western Kunlun Range. It is composed of gneiss and migmatite that contain minor lenses of schist, marble, phyllite and quartzite. The gneisses contain either biotite or hornblende. Where hornblende bearing, they include many lenses of amphibolite and several generations of amphibolite (metamorphosed diabase) dykes. The

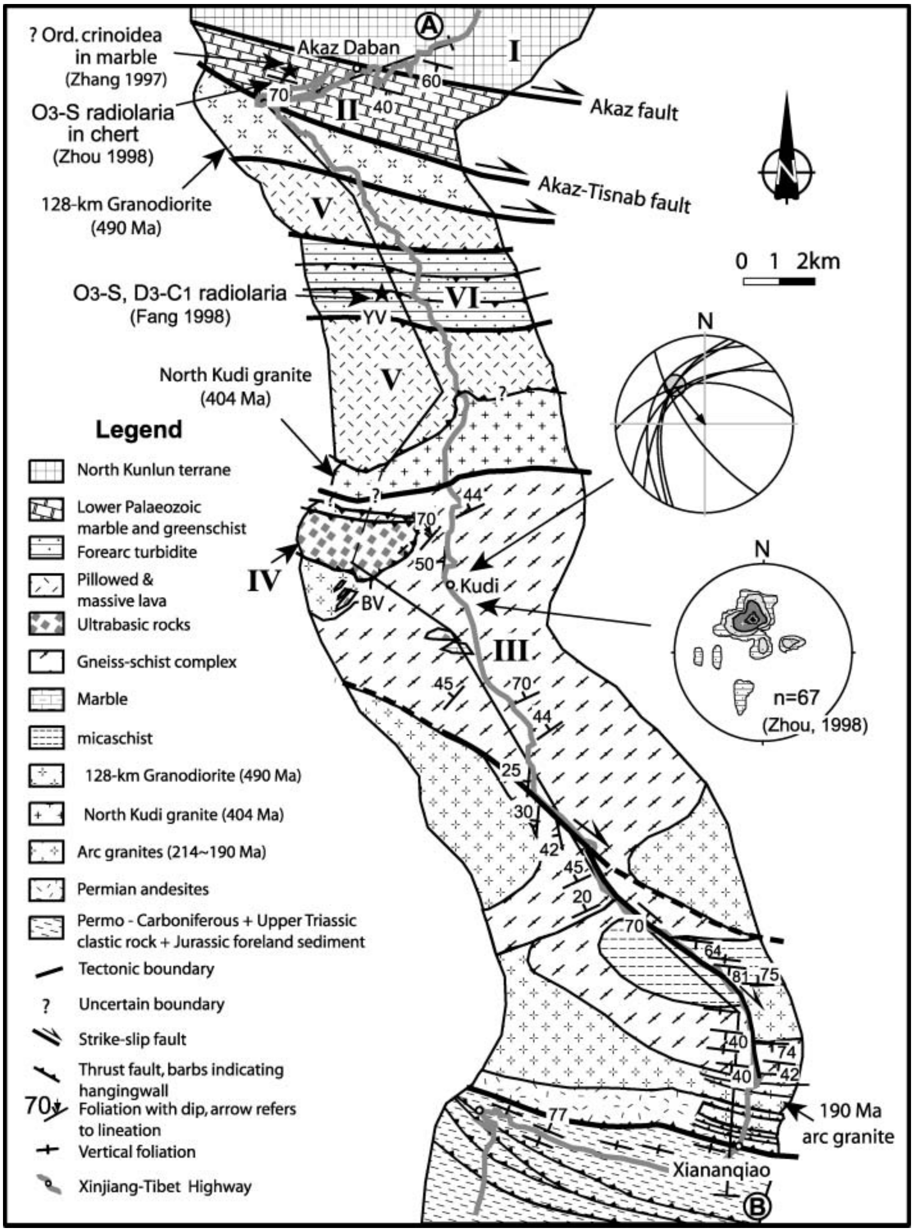
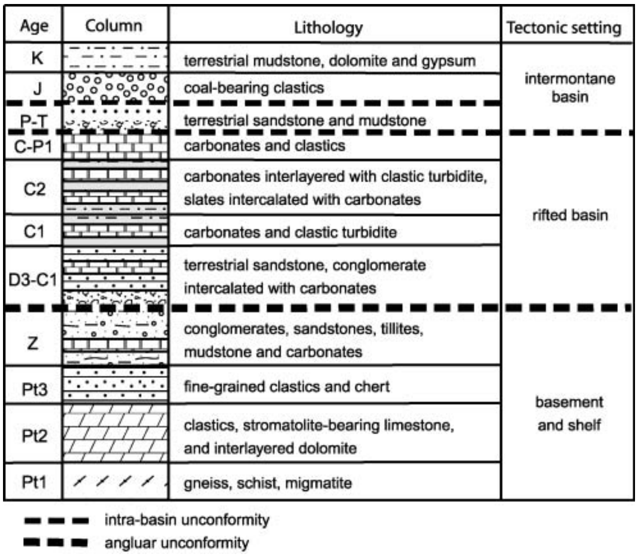


Fig. 2. Tectonic facies map of the Akaz–Kudi area, based on our field data incorporated with those of Li *et al*. (1995), Matte *et al*. (1996) and Mattern & Schneider (2000). The isotopic data are mainly from Yuan (1999). Also shown is the A–B section line. BV, Buziwan Valley; YV, Yixieke Valley. I–VI are numbers of the tectonic units mentioned in the text.

last generation consists of subhorizontal dykes highly discordant to the steep gneisses, this highly angular relationship demonstrating that there has been no shearing after emplacement of the dykes. Some biotite paragneisses contain rare lenses of marble and quartzite (with or without garnet). The rocks are deformed into kilometre-scale monoclinal folds, the axes of which plunge moderately to steeply NNW; they generally strike NE and dip to the NW (Fig. 2). This gneiss–schist complex was thought to be Proterozoic in age (Pan 1990, 1996; XBGMR 1993; Ding *et al*. 1996; Hu *et al*. 2001). However, ^{40}Ar/^{39}Ar dates on lineated hornblende (452 ± 5 Ma) and biotite (428 ± 2 Ma) in the gneiss–schist complex suggest that Late Ordovician–Early Silurian ductile deformation affected the gneisses (Matte *et al*. 1996; Zhou 1998; Zhou *et al*. 1999). The North Kudi granite (Matte *et al*. 1996; Mattern & Schneider 2000), which has a U/Pb zircon age of 380.0 + 1.9/ − 0.7 Ma (Xu *et al*. 1996) and a U/Pb zircon age of 404.0 ± 3.1 Ma (Yuan 1999), intrudes the Kudi gneiss–schist complex (Zhou 1998). On their southern side the gneisses are overlain unconformably by well-bedded metapelites (Fig. 4). Neither ductile deformation nor high-grade metamorphism have been reported in the bedded metasediments so far, therefore we suggest that the unconformity between the bedded metasediments and the gneisses could be of Palaeozoic age. However, the precise age requires further geochronological study. In summary, the Kudi gneiss–schist complex is a Precambrian continental fragment overlain by Palaeozoic cover sediments (Fig. 3b). This is in good agreement with the fact that granites intruding the Kudi gneisses yield Nd model ages of 1.1–1.5 Ga (Yuan 1999). On the other hand, the Kudi gneisses are imbricated with an ophiolitic slice south to Kudi, and overthrust by the Buziwan ultrabasic rocks. These rocks, structural relations and isotopic ages are not present in the North Kunlun or Akaz units, nor in



Age	Column	Lithology	Tectonic setting
K		terrestrial mudstone, dolomite and gypsum	intermontane basin
J		coal-bearing clastics	
P-T		terrestrial sandstone and mudstone	
C-P1		carbonates and clastics	rifted basin
C2		carbonates interlayered with clastic turbidite, slates intercalated with carbonates	
C1		carbonates and clastic turbidite	
D3-C1		terrestrial sandstone, conglomerate intercalated with carbonates	
Z		conglomerates, sandstones, tillites, mudstone and carbonates	basement and shelf
Pt3		fine-grained clastics and chert	
Pt2		clastics, stromatolite-bearing limestone, and interlayered dolomite	
Pt1		gneiss, schist, migmatite	

Fig. 3. Schematic stratigraphic column of the North Kunlun terrane (XBGMR 1993; Yin & Bian 1995).

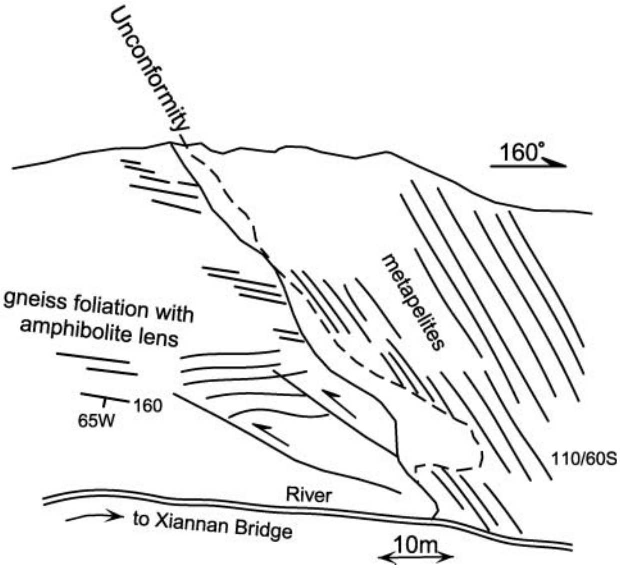


Fig. 4. Line drawing showing the unconformity that dips steeply south reflecting the undulating landscape of the gneisses at the time. The unconformity is not dated but is inferred to be of Late Palaeozoic age as it unconformably overlies the 380 Ma Kudi gneisses. Location is 184.6 km along the Xinjiang–Tibet Highway. Looking east.

the Kudi arc ophiolite. Therefore, we regard the Kudi gneiss–schist complex as a separate terrane tectonically distinct from the geological units to the north.

Kudi arc ophiolite

The previously proposed 'Kudi Ophiolite Suite' (Matte *et al*. 1996; Pan 1996; Mattern & Schneider 2000) is mainly composed of the Yishak Group in the Yixieke Valley and of ultrabasic rocks in both the Buziwan and unnamed valleys south of Kudi (Figs. 1 and 2).

Buziwan ultrabasic rocks (Unit IV, Figs. 2 and 5)

A major ultrabasic slab, about 3 km thick, is located NW of Kudi, and in the Buziwan Valley and its surrounding area (Li *et al*. 1995). Stratigraphically from bottom to top it is composed of sheared serpentinite on the basal thrust, layered harzburgite–dunite, layered dunite with chromitite, and harzburgite with fine-grained gabbro (Fig. 5a). No plagiogranite dykes are known. No isotopic data are available to date precisely these rocks. Although shown on the geological map as a 15 km long, continuous, SE-trending lens, it has been highly intruded and dismembered by an Early Mesozoic granite, which has yielded consistent zircon ages of 212 ± 1.9 Ma for granodiorite and 214 ± 1.0 Ma for monzogranite (Yuan 1999). Within the granite are two main lenses of fine-grained gabbro 30 m and 100 m across, plus a 100 m wide body of dunite, which contains a 20–30 m wide lens of chromitite. A similar slab of dunite (*c*. 1.5 km wide and 3 km long) occurs on the eastern side of the granite. The dunite has coarse- and fine-grained layers plus layers of clinopyroxenite, and is traversed by discordant veins of clinopyroxenite, olivine–orthopyroxene and asbestos. On its eastern side the dunite overlies the gneisses on a thrust, which dips moderately to steeply NW and on which there are 50 m of mylonite (25 m of sheared serpentinite and 25 m of augengneiss) (Fig. 5b); the ultrabasic rocks were clearly thrust southeastwards over the Kudi gneiss–schist complex. The Kudi gneisses below the eastern side of the dunite dip consistently to the NW. Following Matte *et al*. (1996), Pan (1996), Mattern & Schneider (2000) and Wang *et al*. (2001), we interpret these ultrabasic rocks as the lowermost unit of the Kudi ophiolite. A strong down-dip lineation (with a plunge of 70° NW) on the foliation of the mylonitic gneiss at the contact suggests that the ophiolite was obducted to the SE (Fig. 2).

Minor metaperidotites and metaharzburgites, located in unnamed valleys south of Kudi, occur as lenses up to several hundred metres long and 10–20 m wide within the marbles and metasediments of the gneiss–schist complex (Pan 1996; Shen *et al*. 1996). Their southward imbrication within the Kudi gneisses, the similar lithology and occurrence close to the Buziwan ultrabasic rocks near Kudi village may indicate they could have been part of Buziwan ophiolite. Therefore their southward imbrication may indicate an early obduction phase. Of course, this notion needs further geochemical and geochronological confirmation.

Yixieke arc (Unit V, Fig. 2)

As shown in Fig. 5a, the Yixieke arc consists of basaltic and andesitic lavas. The lithology includes fine- and coarse-grained basaltic pillow lava with interbedded red chert, amygdaloidal andesite, andesitic basalt and tuff, and welded andesitic breccia and agglomerate in the Yixieke Valley and along the Xinjiang–Tibet Highway road section (Wang 1995; Pan 1996). Andesites mostly overlie basalts (see Fig. 5a).

Evidence for the age of the Yixieke arc is provided by the following. A maximum age is indicated by the Cambrian Akaz seamount in an accretionary prism, the presence of which implies the existence of a trench adjacent to the arc. The 490–460 Ma Andean-type, 128 km granodiorite (Fig. 2) provides a maximum, earliest Ordovician age for the island arc, and a precise age of the formation of the active continental margin arc. Late Ordovician (*c*. 450 Ma) radiolarians in forearc turbidites (see later) immediately overlying the arc lavas indicate that volcanism had ceased by this time.

In the section north of Unit VI turbidites (see Fig. 2), Fig. 6

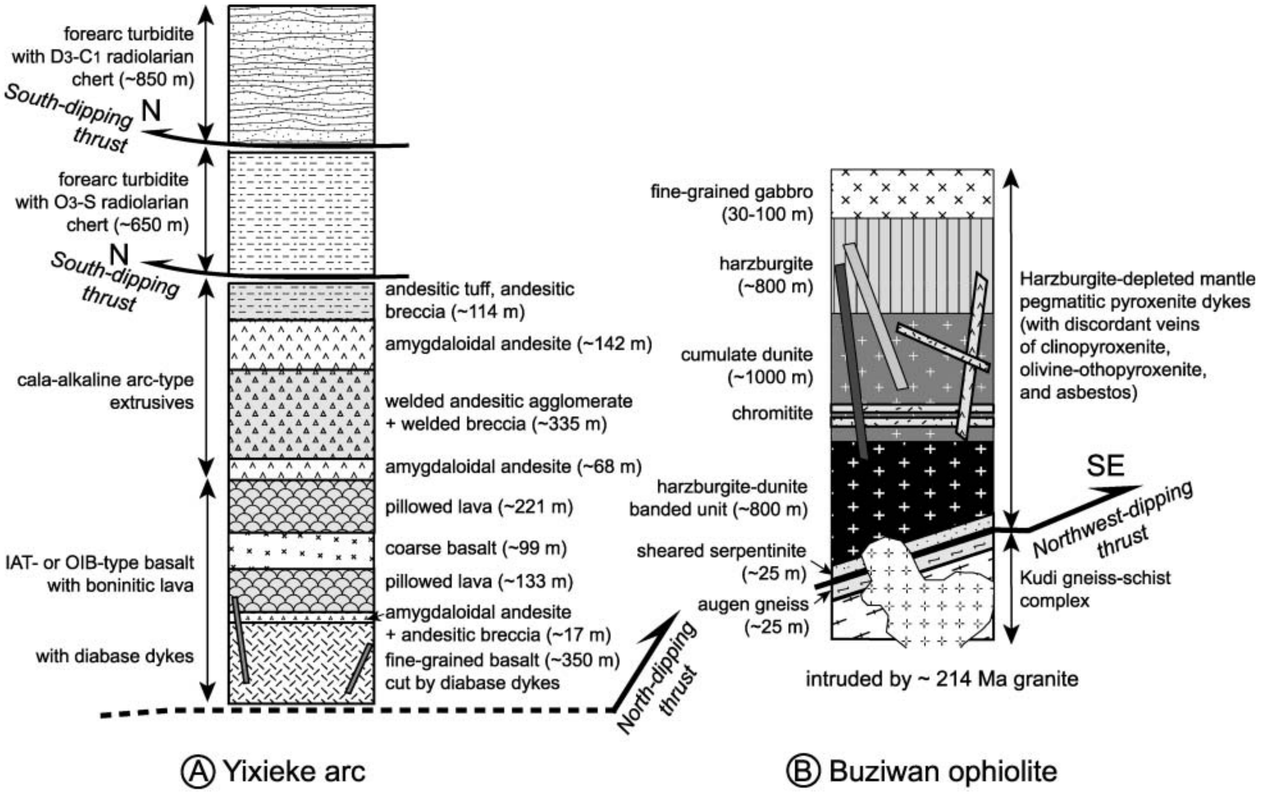


Fig. 5. (**a**) Stratigraphic column of the Yixieke arc and forearc basin turbidites (based on our field work modified by of that of Wang (1995), Yuan (1999) and Mattern & Schneider (2000)). Not to scale. (**b**) Stratigraphic column of the Akaz–Kudi area showing mainly Buziwan ophiolite that is thrust over the Kudi gneiss complex and intruded by a 214 Ma arc granite. Not to scale.

shows that the rocks dip shallowly to the south, and that basalts in the north are overlain southwards by andesites and turbidites. In contrast, in the section south of the turbidites the lavas dip steeply northwards, and basalts are overlain by andesites. From these relations Li *et al*. (1995) envisaged the limbs of a major syncline. However, the contacts between many volcanic and turbidite units are commonly thrusts (Fig. 6), thus we conclude that thrusting has imbricated the lava–turbidite stratigraphy.

Trace element data and isotopic analysis including ϵ_{Nd} values of $+5.8$ to $+8.0$ demonstrate that the arc is composed of islandarc tholeiite (IAT) and ocean-island basalts (OIB) and calc-alkaline arc-type extrusive rocks (Yuan 1999). On the basis of major and trace element data, Yuan inferred that the lavas show a strong arc signature as a result of possible mixing of the different proportions of three components, i.e. fertile OIB, depleted sub-arc mantle, and fluids from a subducting slab resulting in formation of the volcanic rocks in a juvenile oceanic arc. The recognition of an OIB component (Yuan 1999) does not support the idea of Deng (1995) that the basalts represent oceanic crust. Moreover, in the middle of the volcanic arc basaltic andesites have major and trace element data that indicate a boninitic affinity (Yuan 1999). From their high Al_3O_3/TiO_2 values of >20, low TiO_2 and Al_2O_3, high SiO_2 and Na_2O values, and ϵ_{Nd} values lower than $+3.0$, Yuan (1999) suggested they are akin to evolved boninites of the Mariana forearc. This idea is in agreement with geochemical–petrogenetic studies of Fang (1998), who suggested a forearc setting, and of Wang (1983) and Yang *et al*. (1996), who proposed an island-arc origin.

Yixieke forearc (Unit VI, Fig. 2)

Ophiolite-derived debris flows form a 1500 m thick turbidite succession, most of which lies tectonically above the arc volcanic rocks (Figs. 2, 5a and 6). The sequence includes tuffaceous sandstone, andesitic sandstone and radiolarian chert (Wang 1983; Pan 1996). Fang (1998) described sandy contourites and well-preserved radiolarians in siltstone and mudstone. Late Ordovician–Silurian radiolarians occur in lowermost beds of turbidite immediately above the volcanic rocks (Fang 1998; Zhou 1998); these provide a minimum age for the arc volcanism.

In the Yixieke Valley the volcanic and sedimentary rocks mostly dip to the south and have been thrust northwards towards the accretionary prism of Unit II; in the absence of any evidence of subsequent overturning, we infer that the subduction polarity was to the south. The fact that the basalts are mostly in the north, andesites further south, and felsic lavas in the far south confirms this polarity. Geochemistry and petrology of the turbidites suggest deposition in a forearc basin (Fang 1998).

The youngest turbidites, which lie on a thrust above the Upper Ordovician–Silurian turbidites (Fig. 5a), contain radiolarians of Late Devonian–Early Carboniferous age (Fang 1998; Zhou 1998). Accordingly, we place them in a D_3–C_1 forearc basin (Unit V, Figs. 2 and 6). Recently, Carboniferous–Permian

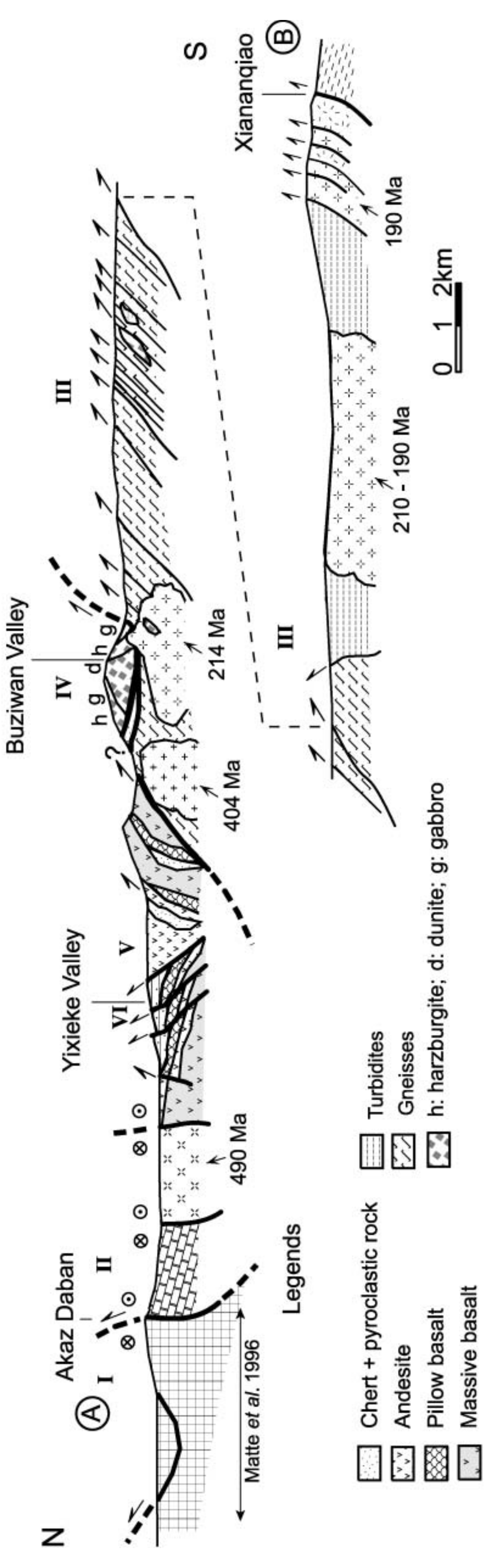


Fig. 6. Cross-section A–B along the section line shown in Fig. 2. Legends as in Fig. 2 except as indicated. The roman numbers are the same as in Fig. 1, referring to the tectonic units in the text. (See text for discussion.)

radiolarian cherts have been reported (Mattern & Schneider 2000); this implies that forearc deposition may have continued to Permian time. Considering the age range of the turbidites, the arc was covered not only by a forearc basin but also probably by post-collisional clastic debris.

Tectonic setting of the Kudi arc ophiolite

The Kudi arc ophiolite is mainly characterized by harzburgite-depleted mantle overlain by IAT- or OIB-type rocks with boninitic and calc-alkaline lavas, which are in return covered by arc- or ophiolite-derived debris. This sequence is similar to the suprasubduction zone ophiolite tectonic facies of Robertson (1994), although no sheeted dykes are present. We suggest that the stratigraphy can be best interpreted as a substrate of Buziwan ocean floor (ophiolitic ultrabasic–basic rocks) overlain by an Ordovician–Silurian intra-oceanic, suprasubduction arc, in turn overlain by a Late Devonian–Early Carboniferous turbiditic forearc basin.

Oytag arc

In the western part of the Western Kunlun Range near Oytag (Figs. 1 and 7), there are outcrops of mostly mafic rocks, which have been regarded as the westerly equivalent of the Kudi ophiolite (Deng 1989, 1996; Pan 1996; Sobel & Arnaud 1999).

Our studies indicate that on the Sino-Pakistan Highway on the south side of Neogene deposits there is an island arc, which has a Carboniferous age on the geological map of XBGMR (1993). Northerly dipping basalts are succeeded northwards by red

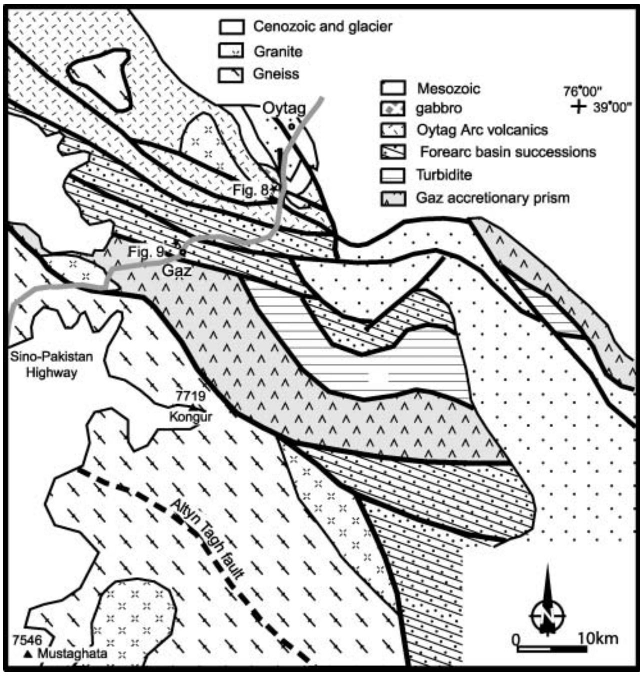


Fig. 7. Geological map of the Oytag area (modified after XBGMR 1993; Brunel *et al.* 1994; Yin & Bian 1995; Sobel & Arnaud 1999), the position of which is marked in Fig. 1. Also shown are the positions of Figs. 8 and 9. ▲, Kongur and Mustaghata Peaks with elevations. The extension of the Altyn Tagh fault is mainly modified after Brunel *et al.* (1994).

andesites and andesitic breccias. Pillow basalts interbedded with red cherts (Deng 1989, 1995; Pan 1996), suggesting a deep-water ocean-floor setting, may form a substrate to the Oytag arc.

A gabbro–diabase south of the volcanic rocks has been regarded as one of the important components of the 'Oytag ophiolite' (Deng 1989, 1995; Pan 1996). We observed no ultrabasic rocks, but Deng (1995) and Pan (1996) described a boulder of serpentinite. Between road marks 1578 km and 1579 km metabasalts are intruded by multiple, steep basic dykes, which appear superficially like sheeted dykes. However, there are no chilled contacts between the dykes. Elsewhere, many different types of dykes mutually crosscut, and there are no steep or vertical dykes. To the south of the lavas a hornblende tonalite pluton is intruded by many (up to 5–10% of the body) dykes, which trend 070° and consist of basalt, andesite and rhyolite; early dykes are sheared. They vary considerably in trend, forming an interconnecting swarm or reticulate network. On the north side of the tonalite a homogeneous hornblende gabbro contains very many dykes. There is as much gabbro as dykes, but locally the dykes increase in density until they become 100% sheeted dykes for a width of more than 150 m, measured normal to the dyke trends. It is important to note that this swarm contains as many rhyolite dykes as basaltic dykes. At one end of the 150 m wide section there are more rhyolitic than andesitic and basaltic dykes, but at the other end the reverse is the case.

Rhyolite dykes, which are commonly porphyritic with phenocrysts of either plagioclase or quartz, are intruded by dykes of homblende tonalite, and the gabbro is likewise intruded by tonalite dykes. These tonalite dykes occupy the same structural position as plagiogranite dykes in an ophiolite, but the term 'tonalite dykes' is more appropriate for an arc setting. Associated with these acid–basic dykes are net-veined dykes up to 20 cm wide of commingling diorite and tonalite.

The Oytag 'complex' cannot be an oceanic-ridge ophiolite because of the presence of rhyolite, andesite, tonalite and net-veined acid–basic dykes; however, basic, intermediate and acidic dykes are common in subduction-generated arcs, and suprasubduction zone ophiolites (Shervais 2001). We have no evidence that the Oytag arc was developed on continental crust, and so cannot conclude that it is an Andean-type arc. The basalt–chert succession points more probably to an island arc developed on oceanic crust.

West of Oytag a 3000 m thick pile of massive and pillowed basalt, dacite and tuff is overlain by phyllite, arkose, lithic arenite, argillite, limestone and marble, containing Late Carboniferous and Early Permian fossils (Wen *et al*. 1996). We propose that these sediments were deposited in a forearc or back-arc basin of the Oytag arc.

Published Chinese geological maps show that Carboniferous rocks continue to the west as far as the Tajikistan border; if they include arc and ophiolitic rocks (Heubeck 2001), the belt would constitute an extensive Carboniferous arc on the northern margin of the Kunlun Range and on the southern margin of palaeo-Asia (Heubeck 2001).

Gaz forearc

South of and in fault contact with the Oytag arc (Fig. 7) is the Bulakebashi Group, which was considered to be of mid-Devonian age by Wen *et al*. (1996). The lithologies are mainly imbricated phyllite, schist, metasandstone, siliceous limestone, limestone and coarse-grained sandstone, which have a thickness of about 4000 m, and turbidites, which are about 1400 m thick (Wen *et al*. 1996). These sediments yield no fossils; the mid-Devonian age is mainly derived from regional correlation. In fault contact with this group is the fossiliferous Upper Devonian Qizilafu Formation of terrigenous turbidites, which are weakly metamorphosed and have an outcrop thickness of >5200 m (Wen *et al*. 1996). These thicknesses are apparent because of strong deformation. On its south side the Oytag arc is thrust over Carboniferous sandstones and limestones that are folded into spectacular nappes (Fig. 8). This area is close to the Pamir syntaxis and consequently was reactivated in Mesozoic–Cenozoic time (Arnaud *et al*. 1993; Brunel *et al*. 1994). We interpret these rocks that lie south of the Oytag arc as remnants of an early, imbricated forearc, because of their lithologies, and

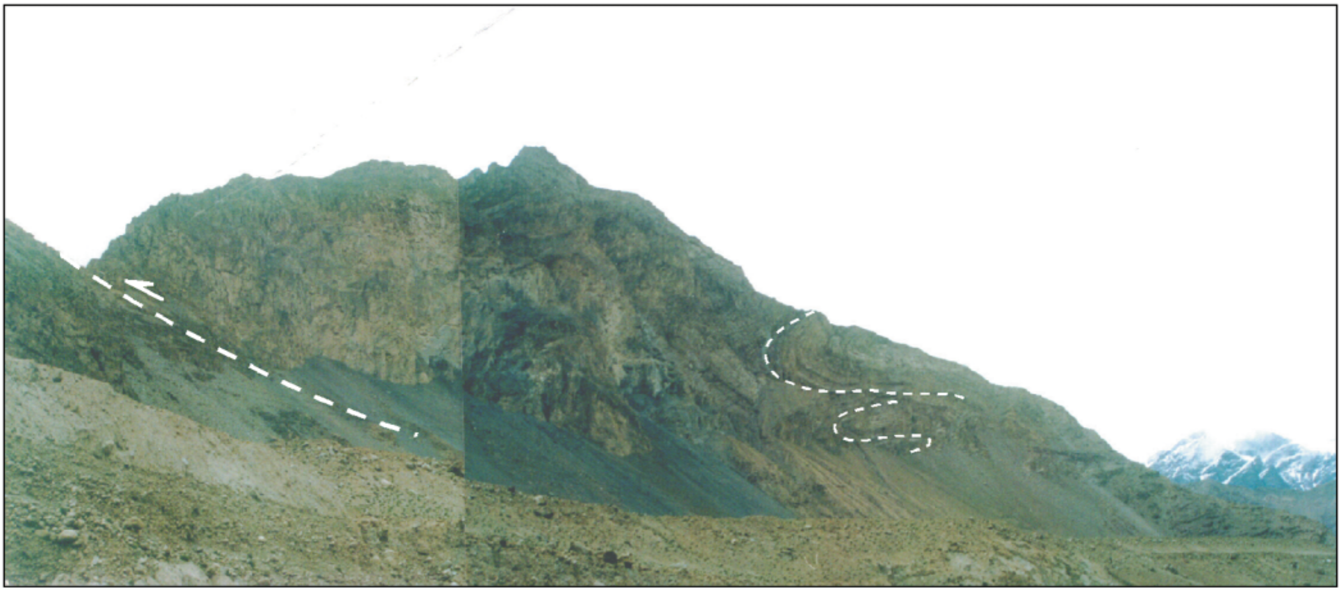


Fig. 8. Photograph near Gaz near the 1591 km road signpost on the Sino-Pakistan Highway showing large-scale fold nappe structures in Carboniferous limestones. Looking NW.

because they occupy a tectonic position in front of an arc and face another continent block (the Kongur gneiss complex) that has accreted to the arc. Unconformably overlying these rocks is an unmetamorphosed >2000 m thick, sedimentary sequence composed of quartzo-feldspathic sandstone, calcareous and argillaceous siltstone, limestone and bio-limestone. Late Devonian–Early Carboniferous corals and brachiopods (Wen *et al*. 1996) from the phyllite-free sequence provide a minimum age constraint on the Oytag arc. We suggest that these Late Palaeozoic sediments were deposited in a later forearc basin.

Kongur gneiss

Further to the south are the Kongur and Mustaghata gneisses, which range from homogeneous foliated biotite gneisses to augengneisses. The Altyn Tagh fault was inferred by Brunel *et al*. (1994) to pass along the structural boundary between the Kongur and Mustaghatra gneisses. However, on the geological map of XBGMR (1993) there is no fault between the two gneisses, and currently there are no structural or petrological reasons to separate these gneisses. Although they have suffered recent doming and syntectonic normal faulting (Brunel *et al*. 1994), the gneisses may occupy the same tectonic position in the Western Kunlun Range as the Kudi gneisses because they are both located on the south side of a (Late) Palaeozoic arc. It is unlikely that the Kongur (and Mustaghata gneisses) are equivalent to the Akaz Daban gneisses, because they contain no isotopic ages as old as 2261 Ma as do the latter (Sobel & Arnaud 1999).

It is currently unknown when the Kongur gneiss docked against the Oytag arc, because of lack of an appropriate geological record and because of the severe Cenozoic and Mesozoic deformation (Brunel *et al*. 1994; Li *et al*. 2002). The end of arc volcanism in Permian time may suggest that docking took place in the Permian period or soon after; this requires confirmation. Cenozoic thrusting has carried the gneisses southwards over Devonian sediments and post-Devonian granites; presumably this deformation took place during north–south shortening related to formation of the Pamir syntaxis.

Tectonic model

From north to south along the Kudi traverse the Western Kunlun Range is composed of the following tectonic units: (1) Tarim block (Unit I); (2) Akaz accretionary prism with seamounts (Unit II); (3) Yixieke arc (Unit V); (4) Yxieke forearc basin (Unit VI); (5) Buziwan ultrabasic rocks (Kudi ophiolite, Unit IV); (6) Kudi continental fragment (Kudi gneiss–schist complex, Unit III). The western Oytag traverse south of the Tarim block is composed of several tectonic units: (1) Oytag arc; (2) Gaz forearc basin; (3) Kongur gneiss complex. The Oytag arc may be equivalent to the Late Palaeozoic part of the Yixieke arc in the east, and the Kongur gneiss complex may correlate with the Kudi schist–gneiss complex–continental fragment (Unit III) in the east. Below we present a tectonic history of the Western Kunlun Range through Palaeozoic time illustrated with a new tectonic model.

Late Cambrian to Earliest Ordovician time

The southern margin of the Tarim block (North Kunlun terrane) was probably a passive continental margin since Late Proterozoic time, with an ocean (Proto-Tethys) to the south (Pan 1996). South-dipping subduction of this oceanic lithosphere generated the Buziwan ophiolite in Late Cambrian to earliest Ordovician time (Fig. 9a). An intra-oceanic arc (Yixieke arc) was constructed upon the Buziwan ultrabasic rocks in earliest Ordovician time as subduction continued (Fig. 9a). A seamount capped by limestone (Akaz seamount) was incorporated into the accretion-

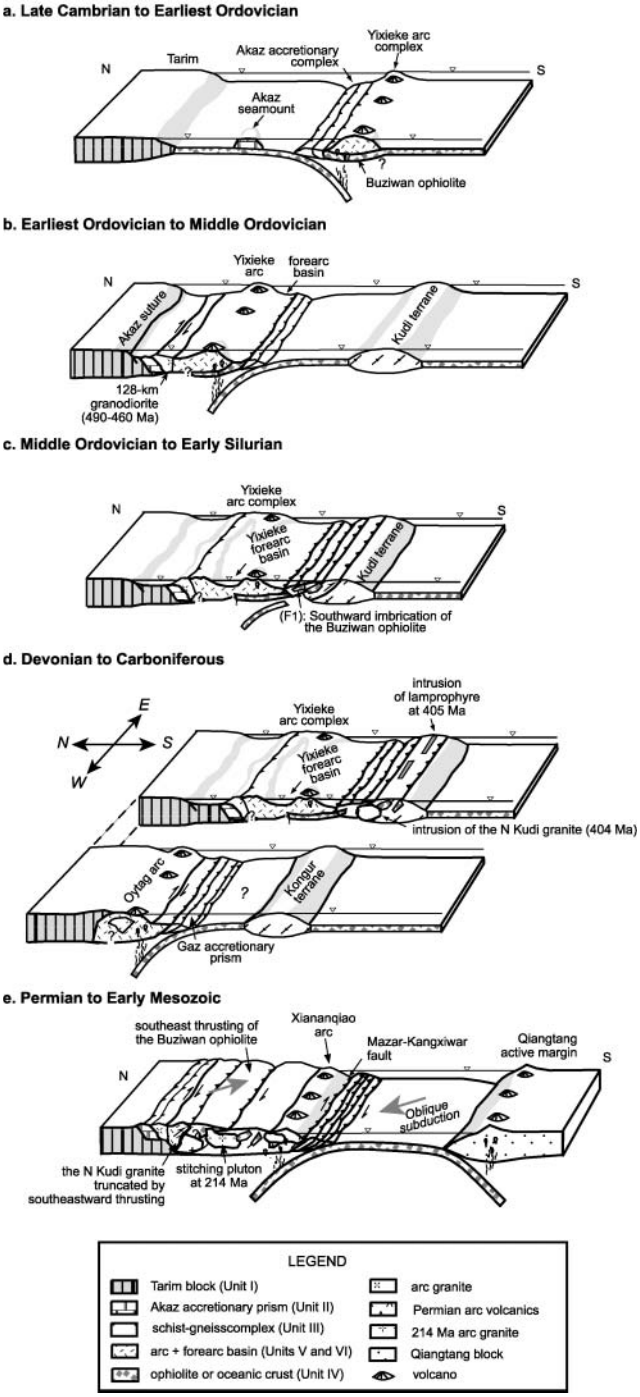


Fig. 9. Sequential diagram showing the Palaeozoic–Early Mesozoic tectonic evolution of the Western Kunlun Range. (**a**) Late Cambrian to Earliest Ordovician time; (**b**) Earliest Ordovician to Mid-Ordovician time; (**c**) Mid-Ordovician to Early Silurian time; (**d**) Devonian to Carboniferous time; (**e**) Permian to Early Mesozoic time. (See text for discussion.)

ary prism north of the arc in Cambrian–Early Ordovician time. The intervening ocean between the oceanic arc and the Tarim block was consumed, and the arc was emplaced northward onto the North Kunlun terrane, giving rise to the Akaz suture in Early to Mid-Ordovician time and subsequent northward thrusting of the Akaz prism over the Tarim block (Fig. 9b).

Earliest Ordovician to Mid-Ordovician time

North-dipping subduction beneath the southern margin of the accreted Yixieke arc may have started at *c*. 490 Ma in what had become an Andean-type continental margin (Fig. 9b). North-dipping subduction lasted for some 30 Ma (490–460 Ma) as documented by U/Pb dating of the 128 km granodiorite (Xu *et al*. 1996; Sobel & Arnaud 1999; Yuan 1999) and associated volcanic rocks in the Yixieke arc.

Mid-Ordovician to Early Silurian time

A continental fragment, the Kudi terrane, moved northward and at *c*. 452 Ma was incorporated into the subduction zone south of the Yixieke arc (Fig. 9c). The impingement process of the Kudi terrane lasted about 20 Ma (452–428 Ma, Zhou 1998). This convergence gave rise to southward thrusting of the Yixieke forearc in Ordovician–Early Silurian time, which then led to obduction of the Buziwan ultrabasic rocks southward over the Kudi terrane (F_1, Fig. 9c). This deformation caused high-grade metamorphism and ductile shearing within the Kudi gneiss. The convergent deformation may also have propagated further northward to the older Akaz suture, causing north-vergent thrusting and folding (Matte *et al*. 1996).

Devonian to Carboniferous time

From Early to Mid-Devonian time (404–380 Ma) the North Kudi granite intruded the northern border of the Kudi terrane, which underwent minor extension (Fig. 9d), allowing the intrusion of lamprophyre dykes dated by $^{40}Ar/^{39}Ar$ at 405 ± 3 Ma (Zhou 1998). Ophiolite obduction (F_1, Fig. 9c) may have initiated partial melting in the Kudi schists, a situation similar to anatexis of metasediments during late Caledonian ophiolite obduction in west Norway (Skjerlie *et al*. 2000). This could explain why trace element data of the North Kudi granite (Fig. 9d) indicate derivation by partial melting of sedimentary material (Yuan 1999).

The youngest turbidites in the Yixieke forearc basin (Fig. 9d) were deposited in Late Devonian–Early Carboniferous time. A lack of magmatic activity from 350 to 280 Ma (Yuan 1999) was probably related to cessation of subduction; this would be consistent with palaeomagnetic data indicating that the Tarim block was moving northward as a united plate in Devonian to Late Carboniferous time (Li 1990; Yin & Nie 1996) and collision between Tianshan and southern Siberia in Carboniferous–Permian times (Windley *et al*. 1990). The northward drift of the Tarim block decreased convergence with the Western Kunlun Range, which being submerged was overlain by a thick pile of marine deposits in Late Devonian to Early Carboniferous time (XBGMR 1993).

Whereas the Kudi area was tectonically quiescent, subduction took place in the Oytag area, giving rise to the Oytag arc and the Gaz forearc (Fig. 9d).

Permian to Early Mesozoic time

In Early Permian to Late Triassic time north-dipping subduction was generated under the southern margin of the accreted Kudi terrane (Fig. 9e). Early Permian volcanic rocks at Xiananqiao mark the start of subduction beneath the Andean-type margin (Fig. 2). Arc-related magmatism continued in Early Mesozoic time as demonstrated by granites in the Mazar–Kangxiwar area, which have isotopic ages in the range 231–190 Ma (K–Ar, Ar/Ar dates, Zhang & Xie 1989; Zhang *et al*. 1996) and at 214 Ma (zircon age, Yuan 1999). Geochemical data suggest that these are arc-collisional granites (Pan 1996; Zhang *et al*. 1996).

The 214 Ma arc granite intruded and stitched the tectonic contact between the Kudi arc ophiolite and the Kudi gneiss–schist complex. Near Xiananqiao to the south (Figs. 2 and 9e) a granite has a whole-rock $^{40}Ar/^{39}Ar$ age of 211 Ma and a K-feldspar $^{40}Ar/^{39}Ar$ age of 180 ± 10 Ma (Arnaud & Vidal 1990); associated rhyolite and porphyry yield a whole-rock Rb–Sr isochron of 193 ± 10 Ma (Arnaud & Vidal 1990). In this period hinterland-ward thrusting transported the Akaz seamount and the Tarim basement northwards over Permo-Triassic intermontane basin sediments.

Finally, in Late Triassic–Jurassic time the Western Kunlun Range collided with the northern active margin of the Qiangtang block. A foreland fold–thrust belt with a southwestward vergence formed south of the Mazar–Kangxiwar fault (Şengör & Okurogullari 1991; Matte *et al*. 1996; Pan 1996; Xiao *et al*. 1998, 2002).

Discussion and conclusions

Emplacement time and nature of the Kudi arc-ophiolite complex

There are no plagiogranite dykes to provide a radiometric age for the Kudi arc ophiolite. Sm–Nd isotopic analyses of basalts from the Yixieke Valley gave no geological meaning because of an MSWD value of 3.92 and a large error of 136 Ma (Yuan 1999). It is not surprising that there are contrasting suggestions for the age of the Kudi arc ophiolite: Late Neoproterozoic (Wang 1983), Proterozoic–Early Palaeozoic (Matte *et al*. 1996; Pan 1996) and Late Palaeozoic (Jiang *et al*. 1992; Yao & Hsü 1994; Yang *et al*. 1996; Yin & Harrison 2000).

Geochemical studies indicate that the island arc has an intra-oceanic, suprasubduction origin (Yang *et al*. 1996; Wang *et al*. 2001), and that the 490–460 Ma 128 km granodiorite (Fig. 2) (Wang 1983; Zhang & Xie 1989; Arnaud & Vidal 1990; Xu *et al*. 1994, 1996) formed in a continental magmatic arc (Fang 1998; Yuan 1999). This gives us key information on a geodynamic change by *c*. 490 Ma of an intra-oceanic arc to a continental margin arc. Furthermore, the Late Ordovician–Silurian radiolarian cherts in the Kudi arc ophiolite indicate that the suprasubduction zone was largely constructed before Late Ordovician time.

When did the southward obduction of the Kudi arc ophiolite take place? Figures 2 and 6 demonstrate that the ophiolite was imbricated with the gneiss–schist complex that was intruded by the North Kudi granite dated at 404 Ma. This provides a minimum age for the obduction. Our field data show that the fold axes of the Kudi gneiss below the basal thrust of the ophiolite plunge 35–55° towards 325–335°. This is coincident with the ductile hornblende–biotite lineation in the gneiss (Fig. 2), which was dated by Ar/Ar at 452–428 Ma (Zhou 1998). We interpret this as the obduction time of the Buziwan ophiolite (F_1 in Fig.

9c). Later southward thrusting of the Kudi arc ophiolite truncated the 404–380 Ma North Kudi granite (Figs. 6 and 9e) and the thrust was stitched by a 214 Ma granite (Fig. 2); this implies that a second phase of thrusting (F_2) of the arc occurred in the period 380–214 Ma.

Tectonic polarity in the Palaeozoic Western Kunlun Range

As discussed above, by *c*. 490 Ma an intra-oceanic arc changed into a continental magmatic arc. South-dipping subduction polarity before 490 Ma is indicated by the south-dipping Akaz suture, which separates the passive margin of the Tarim block to the north and the Yixieke oceanic arc to the south. This polarity was accepted by most workers, although the precise position of the suture they inferred is different from ours (Pan 1992; Matte *et al*. 1996). It is most likely that south-dipping subduction brought the Tarim block southwards to close the oceanic basin and to cause the arc to be thrust onto the Tarim block; it is unlikely that north-dipping subduction would cause this polarity. However, the 128 km granodiorite is an important indicator to mark the start of northward subduction of oceanic crust under an active continental margin by 490 Ma.

Citing molasse-like Devonian sediments as a post-collisional indicator, Matte *et al*. (1996) suggested that the western Kunlun is characterized by long-term south-dipping subduction of Proto-Tethys. Although we agree with the early stage of a south-dipping subduction of the Proto-Tethys beneath an intra-oceanic arc, we do not agree with a long-term south-dipping subduction until Silurian time. Neither foreland molasse basins betraying the front of the collisional orogen nor Silurian–Devonian foreland fold–thrust belts have ever been unambiguously confirmed, because the intense northward thrusting could be of Mesozoic (Arnaud & Vidal 1990) and/or Cenozoic age (Sobel & Arnaud 1999). In our model, the locally distributed Devonian sediments are better explained as deposits that were uplifted by tectonic extension of an Early Palaeozoic arc–accretionary prism.

Northward-dipping subduction is required to produce the Andean-type magmatic arc by 490 Ma and also to bring the Kudi continental block northwards to collide with and be thrust below the Yixieke arc and ophiolite at about 452–428 Ma. It is therefore unlikely that the high-grade metamorphism and ductile deformation of the Kudi terrane (452–428 Ma) can be related to the collision between the southern Tarim and Kudi terranes according to the south-dipping subduction model of Matte *et al*. (1996).

Correlation with the Altyn Tagh ophiolite belt

From comparison of lithologies and radiometric data, Sobel & Arnaud (1999) suggested that the Kudi–Oytag ophiolite belt and suture in the Western Kunlun Range is similar to and may be a lateral continuation of the Ordovician, south-dipping Lapeiquan suture and ophiolite belt in the Altyn–East Kunlun Range (Fig. 1). Later, He *et al*. (1999) described from the central segment of the Altyn Tagh orogen Late Devonian to Early Carboniferous radiolarians in cherts, which were previously assigned a Neoproterozoic age. The rocks are juxtaposed with a 1400 m thick sequence of lavas and pyroclastic rocks, and a 1400 m thick sequence of black siliceous slates and limestone interbedded with basic–intermediate tuffs and sandstone. They are in fault contact with a Lower Palaeozoic ophiolite. This Upper Palaeozoic radiolarian-bearing sequence has many similarities to the contemporaneous Yixieke turbidite sequence. Our new data confirm and place tighter constraints on correlations between the eastern and western Kunlun, as demonstrated in Fig. 10. Current models suggest that in the eastern and western Kunlun on the southern margin of the palaeo-Asian continent there was in Ordovician time oceanic crust, southward-dipping intra-oceanic subduction and island arcs, and in Late Devonian–Early Carboniferous time radiolarian-bearing carbonate and/or clastic sediments, overlying arc-type lavas and pyroclastic rocks. We do not wish to overstretch correlations, because we would expect local differences in

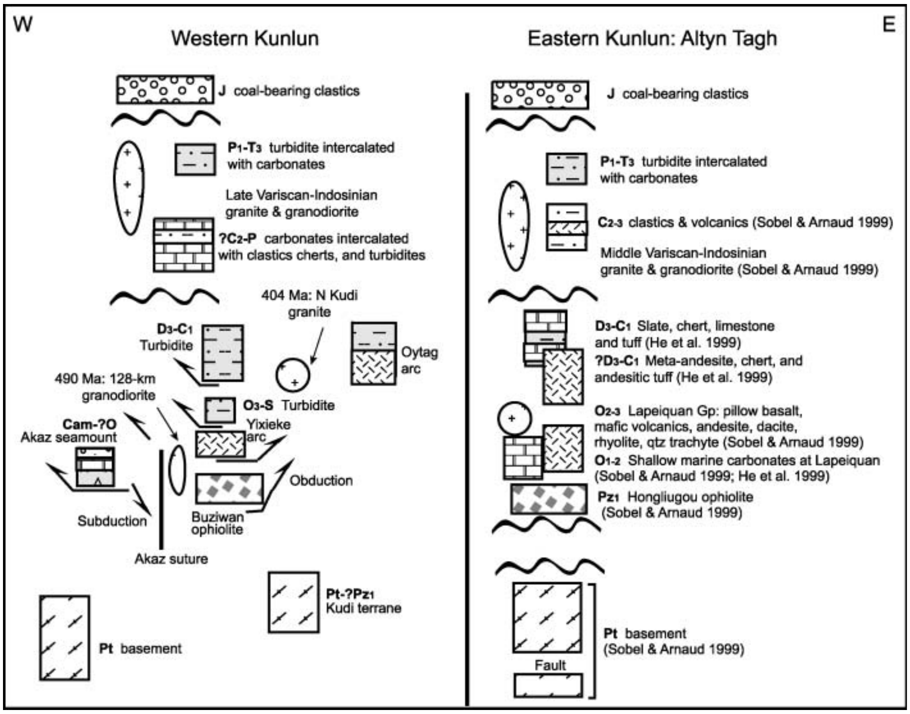


Fig. 10. Schematic comparative tectonostratigraphy of the Western Kunlun and Eastern Kunlun (Altyn Tagh) Ranges, compiled from our own work and that of Jiang *et al*. (1992), XBGMR (1993), He *et al*. (1999) and Sobel & Arnaud (1999).

stratigraphy and arc polarity; nevertheless, these similarities should be borne in mind in future investigations along the Kunlun Range. The possible Ordovician arc in the Altyn Tagh Range, mentioned by Sobel & Arnaud (1999), has yet to be studied in detail and its subduction polarity defined.

A north-dipping, active continental margin in Late Palaeozoic time along the Kunlun Range apparently initiated the tectonic framework for the palaeogeography of northern Tibet ever since. Heubeck (2001) showed that this active continental margin extended from the Qilian Shan to Turkey from at least Mid-Devonian to Late Permian time. The amalgamation of the southerly derived blocks that accreted to Asia in Mesozoic–Cenozoic time took place in this palaeogeographical framework (Dewey *et al*. 1988; Kapp *et al*. 2000). Peltzer & Tapponnier (1988) estimated that the eastern and western Kunlun were displaced by about 500 km by the Altyn Tagh fault. However, the Lapeiquan region in the eastern Kunlun (Zhou & Graham 1996; Sobel & Arnaud 1999) is situated north of the Altyn Tagh fault and south of the Ruoqiang–Xingxingxia fault (RXF in Fig. 1). Therefore the latter may have been responsible for the bulk of the displacement. Nevertheless, the shape of the Altyn Tagh and Ruoqiang–Xingxingxia fault system, wedge-shaped (Zhou & Graham 1996) or not, requires further study and reconstruction to constrain more precisely the displacement history.

Although our model of an early Palaeozoic arc–accretionary prism superimposed by a late Palaeozoic–Early Mesozoic arc–accretionary prism well explains the available data in the Western Kunlun Range, we recognize that the Kunlun orogen as a whole has been overprinted by Cenozoic and/or Mesozoic deformation (Arnaud *et al*. 1993; Brunel *et al*. 1994; Sobel & Arnaud 1999; Kao *et al*. 2001; Li *et al*. 2002). Further detailed studies are required to distinguish Palaeozoic structures such as thrusts, normal faults and sutures that were reactivated in Mesozoic–Cenozoic time.

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