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Cenozoic tectonic evolution of Qaidam basin and its surrounding regions (part 2): Wedge tectonics in southern Qaidam basin and the Eastern Kunlun Range

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ABSTRACT

Our inability to determine the growth history and growth mechanism of the Tibetan plateau may be attributed in part to the lack of detailed geologic information over remote and often inaccessible central Tibet, where the Eastern Kunlun Range and Qaidam basin stand out as the dominant tectonic features. The contact between the two exhibits the largest and most extensive topographic relief exceeding 2 km across their boundary inside the plateau. Thus, determining their structural relationship has important implications for unraveling the formation mechanism of the whole Tibetan plateau. To address this issue, we conducted field mapping and analysis of subsurface and satellite data across the Qimen Tagh Mountains, part of the western segment of the Eastern Kunlun Range, and the Yousha Shan uplift in southwestern Qaidam basin. Our work suggests that the western Eastern Kunlun Range is dominated by south-directed thrusts that carry the low-elevation Qaidam basin over the high-elevation Eastern Kunlun Range. Cenozoic contraction in the region initiated in the late Oligocene and early Miocene (28–24 Ma) and has accommodated at least

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48% upper-crustal shortening (i.e., ~150 km shortening) since that time. In order to explain both the high elevation of the Eastern Kunlun Range and the dominant south-directed thrusts across the range, we propose that the Cenozoic uplift of the range has been accommodated by large-scale wedge tectonics that simultaneously absorb southward subduction of Qaidam lower crust below and southward obduction of Qaidam upper crust above the Eastern Kunlun crust. In the context of this model, the amount of Qaidam lower-crust subduction should be equal to or larger than the amount of shortening across Qaidam upper crust in the north-tapering thrust wedge system, thus implying at least 150 km of Qaidam lower-crust subduction since the late Oligocene and early Miocene. The late Oligocene initiation of contraction along the southern margin of Qaidam basin is significantly younger than that for the northern basin margin in the Paleocene to early Eocene between 65 and 50 Ma. This temporal pattern of deformation indicates that the construction of the Tibetan plateau is not a simple process of northward migration of its northern deformation fronts. Instead, significant shortening has occurred in the plateau interior after the plateau margins were firmly established at or close to their current positions. If Cenozoic crustal deformation across the Eastern Kunlun and Qaidam regions was accommodated by pure-shear deformation, our observed >48% upper-crustal shortening strain is sufficient to explain the current elevation and crustal thickness of the region. However, if the deformation between the upper and lower crust was decoupled during the Cenozoic Indo-Asian collision, lower-crustal flow or thermal events in the mantle could be additional causes of plateau uplift across the Eastern Kunlun Range and Qaidam basin.

Keywords: Qaidam basin, Eastern Kunlun Range, Tibetan plateau, wedge tectonics, Qilian Shan-Nan Shan thrust belt.

INTRODUCTION

Despite its importance in determining dynamics of continental deformation, the growth mechanism and constructional history of the Tibetan plateau during the Cenozoic Indo-Asian collision remain poorly understood. This incomplete knowledge may be attributed in part to the lack of detailed geologic information about remote and inaccessible central Tibet between the Bangong-Nujiang suture in the south and the Qilian Shan in the north (Fig. 1). In this area, the Eastern Kunlun Range and Qaidam basin stand out as the most dominant Cenozoic tectono-geomorphological features; the former has an average elevation of ~5000 m with peaks exceeding 7000 m, whereas the latter has an average elevation of ~2800 m with little internal relief. The contact between the two tectonic features forms the most extensive topographic front (>1000 km long) and the largest relief (>2.5 km on average) inside the plateau (Fig. 2). Understanding structural relationships between the development of the Eastern Kunlun Range and Qaidam basin has important implications for unraveling the formation mechanism and growth history of the whole Tibetan plateau.

In the past two decades, several tectonic studies have addressed this question. Burchfiel et al. (1989a) propose that the uplift of the Eastern Kunlun Range was induced by motion on a major south-dipping thrust; the fault marks the southern boundary of a north-directed thrust belt across Qaidam basin and the Qilian Shan to the north. The concept of the Eastern Kunlun Range being thrust over Qaidam basin was later expanded by Mock et al. (1999), who speculated that northward thrusting across the Eastern Kunlun Range was associated with vertical-wedge extrusion starting ca. 30–20 Ma.

In contrast to the above models emphasizing the role of dip-slip faulting across the Eastern Kunlun Range, Meyer et al. (1998), Tapponnier et al. (2001), Jolivet et al. (2003), and Wang et al. (2006) suggest that Cenozoic left-slip deformation has dominated the region. Specifically, they suggest that the Eastern Kunlun Range consists of a large transpressional system with the left-slip Kunlun fault in the south and a north-directed thrust along the northern flank of the Eastern Kunlun Range.

Deep crustal structures below the Eastern Kunlun Range have been explored by seismological studies. Based on interpretation of fault-plane solutions, focal-depth distributions, and active fault distributions, Tapponnier et al. (1990) and Chen et al. (1999) suggest that the Qaidam crust has been subducted southward below the Eastern Kunlun Range along a low-angle south-dipping thrust to a mantle depth. Examination of teleseismic P-wave arrivals by Zhu and Helmberger (1998) reveals that the Moho depth decreases abruptly across the topographic front between the Eastern Kunlun Range and Qaidam basin near Golmud, from ~50 km below the Eastern Kunlun Range to ~35 km below Qaidam basin. They attribute this staircase-like sharp decrease in Moho depth to the presence of a ductile-flow channel in the lower crust of the Eastern Kunlun Range that terminates abruptly in the north below the range front. This

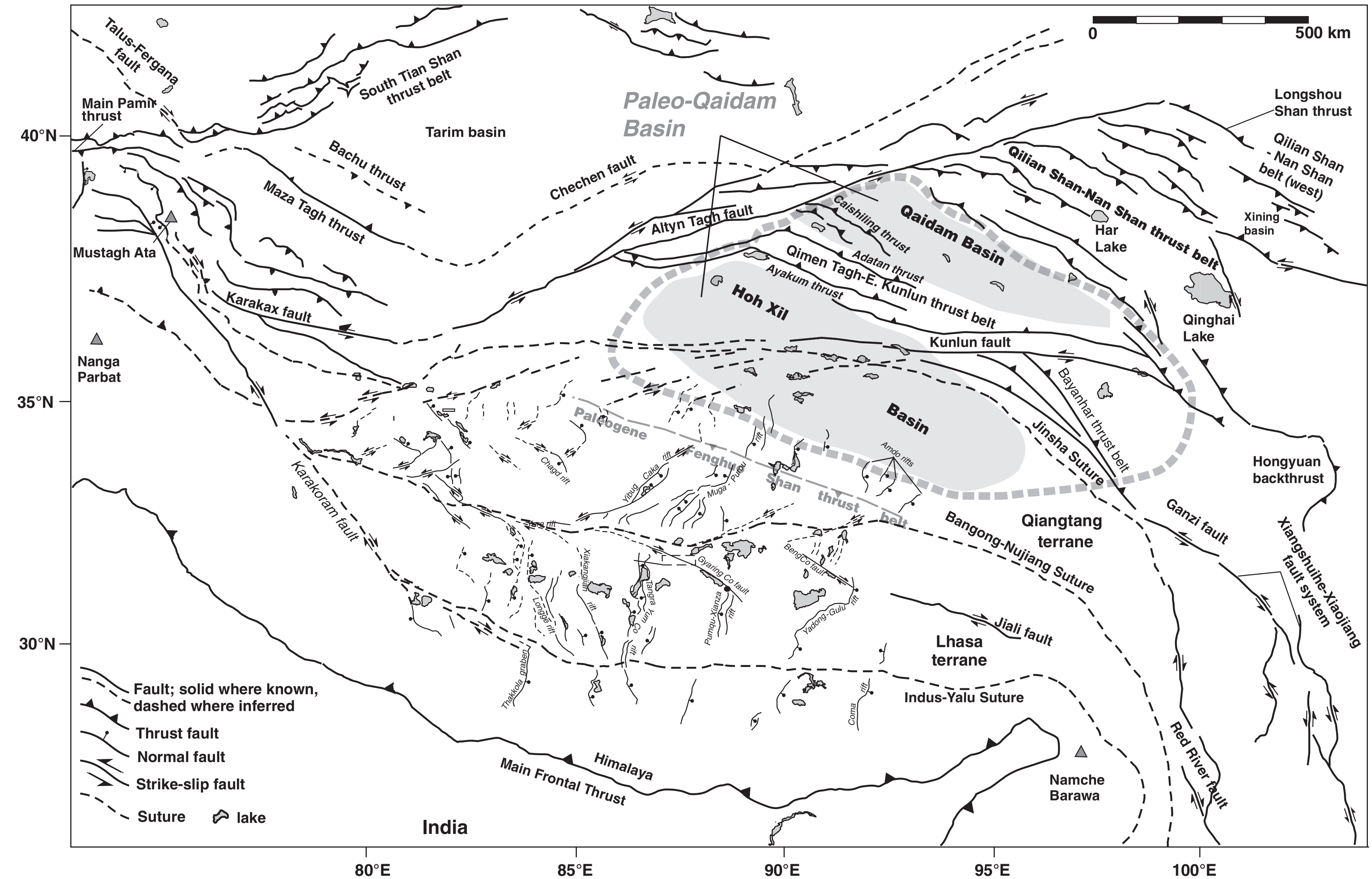


Figure 1. Tectonic map of major Cenozoic faults and sutures across the Tibetan plateau, modified after Taylor et al. (2003).

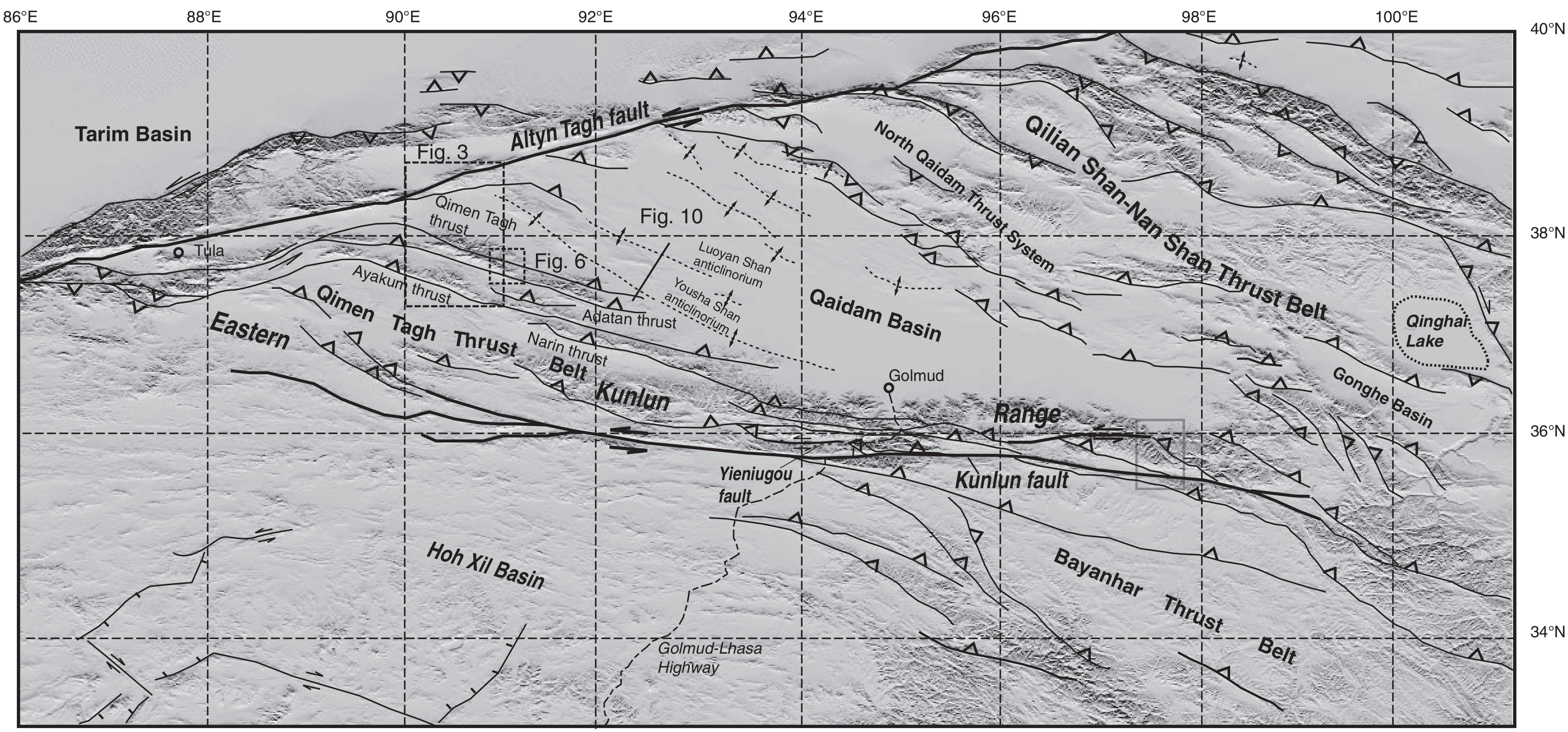


Figure 2. Digital topographic map of northern and central Tibet, showing major Cenozoic faults and locations of Figures 3, 6, and 10.

proposal is consistent with the predictions of the channel-flow model of Royden et al. (1997) and Clark and Royden (2000) for the development of the Tibetan plateau.

Except the model of Zhu and Helmberger (1998), all aforementioned structural models require the presence of a major south-dipping and north-directed thrust system that carries the Eastern Kunlun Range over Qaidam basin. This inference appears to be plausible, as it provides a simple explanation for the large elevation difference between the Eastern Kunlun Range and Qaidam basin. However, the existence of the *inferred* structure has never been established in the field. For example, the tectonic maps of Meyer et al. (1998) and Jolivet et al. (2003) place a south-dipping thrust along the northern front of the Eastern Kunlun Range, but these authors did not provide any field documentation of the structure. To the contrary, the existing regional geologic map (e.g., Liu, 1988) and fieldwork performed by Dewey et al. (1988) during the Sino-Anglo Geotraverse have all failed to document such a structure along the northern margin of the Eastern Kunlun Range.

Although focal mechanisms and focal-depth distribution have been used to support the presence of a south-dipping thrust below the Eastern Kunlun Range (Chen et al., 1999), it should be kept in mind that the data projected on the single cross section were collected along the whole Eastern Kunlun Range, which is more than 1000 km long. In addition, the fault plane solutions could not differentiate which of the two possible fault planes actually created the earthquakes.

The contradiction between having a major south-dipping range-bounding thrust along the northern margin of the Eastern Kunlun Range and the expected thickness distribution of Cenozoic strata across Qaidam basin has long been noted; Cenozoic strata and their individual units consistently thicken toward the basin center and thin toward the basin margins (Bally et al., 1986; Huang et al., 1996; Sobel et al., 2003; Wang et al., 2006; Yin et al., 2008a, 2008b). This isopach pattern contradicts the prediction of a classic foreland-basin model that requires the maximum thickness of foreland sedimentation to be restricted to the bounding thrust (e.g., Jordan, 1981). For this reason, Bally et al. (1986) speculated that the Cenozoic Qaidam basin formed during the development of a large synclinorium.

In order to determine the geologic relationship between the Cenozoic uplift of the Eastern Kunlun Range and the evolution of Qaidam basin, we conducted geologic research in the region in the past decade by integrating surface mapping with interpretations of subsurface seismic, drill-hole, and sedimentological data. Due to the large geographic extent of the area (the Eastern Kunlun Range alone is larger than California!), we report our results in three separate papers. The first paper by Yin et al. (2008a) deals with the Cenozoic structural evolution of the North Qaidam thrust system and the southern Qilian Shan-Nan Shan thrust belt. The second paper, presented here, documents the geology of the western segment of the Eastern Kunlun Shan and southwestern Qaidam basin and discusses its implications on the mode and timing of plateau construction across central Tibet. Our third paper by Yin et al. (2008b) examines Cenozoic sedimentation and structural evolution of the whole Qaidam basin and its relationship to slip distribution along the left-slip Altyn Tagh fault.

Our work in the western segment of the Eastern Kunlun Range and southern Qaidam basin is based on detailed field mapping, interpretation of subsurface data from petroleum drill holes and seismic reflection profiles, and systematic analysis of satellite images. Our work, in conjunction with the existing seismic reflection profiles across the region, suggests that (1) the contact between the western Eastern Kunlun Range and southwestern Qaidam basin is a north-dipping unconformity, (2) the major structures across the Eastern Kunlun Range are dominated by *south-directed* Cenozoic thrusts carrying the low-altitude Qaidam basin over the high-altitude Eastern Kunlun Range, and (3) Cenozoic contraction in the region initiated in the late Oligocene to early Miocene (28–24 Ma), much later than the Paleocene–early Eocene (65–50 Ma) initiation age of Cenozoic deformation along the northern margin of Qaidam basin. In the following sections, we outline the regional geologic framework of Qaidam basin and the Eastern Kunlun Range. This is followed by a detailed documentation of our field observations and subsurface data from our study area.

GEOLOGY OF QAIDAM BASIN AND THE EASTERN KUNLUN RANGE

The morphologically defined Eastern Kunlun Range is bounded by Qaidam basin to the north and the Hoh Xil basin to the south (Fig. 1). The boundary between the Hoh Xil basin and the Eastern Range is marked by the left-slip Kunlun fault. Qaidam basin is the largest topographic depression inside Tibet and contains an Eocene to Quaternary continental sedimentary sequence (Bally et al., 1986; Wang and Coward, 1990; Song and Wang, 1993; Huang et al., 1996; Zhang, 1997; Métivier et al., 1998; Xia et al., 2001; Yin et al., 2002; Dang et al., 2003; Sobel et al., 2003; Sun et al., 2005; Rieser et al., 2005, 2006a, 2006b; Zhou et al., 2006). The thickest Cenozoic strata are located in the basin center with a depth >15 km; the strata thin toward the basin margins to ~<3 km (Huang et al., 1996). Sedimentological development of the basin has been established by analyzing thickness distribution (Huang et al., 1996), paleocurrent directions (Hanson, 1998), lithofacies patterns (e.g., Zhang, 1997), sandstone petrology (Rieser et al., 2005), ^{40}Ar/^{39}Ar ages of detrital micas (Rieser et al., 2006a, 2006b), and fission-track ages of detrital apatites (Qiu, 2002). These studies suggest that the Cenozoic Qaidam basin has expanded eastward since the Eocene, with its depocenters consistently located along the axis of the basin.

Cenozoic stratigraphic division and age assignments across Qaidam basin are based on the correlation of outcrop geology with subsurface data (seismic profiles and drill cores), terrestrial fossils (i.e., spores, ostracods, and pollen), basin-wide stratigraphic correlation via a dense network of seismic reflection profiles, magnetostratigraphic studies, and fission-track and ^{40}Ar/^{39}Ar dating of detrital grains (Huo, 1990; Qinghai, B.G.M.R., 1991; Yang et al., 1992; Song and Wang, 1993; Huang et al., 1996; Xia et al., 2001; Qiu, 2002; Sun et al., 2005; Rieser et al., 2006a, 2006b). Major Cenozoic stratigraphic units in Qaidam basin include (Table 1): Paleocene (?) and early Eocene Lulehe Formation (E1+2; >54–49 Ma) (Yang, 1988; Huo, 1990; Yang et al., 1992; Rieser et al., 2006a, 2006b), middle and late Eocene Lower Xiaganchaigou Formation (E3-1; 49–34 Ma) (Yang et al., 1992; Sun et al., 2005), early Oligocene Upper Xiaganchaigou Formation (E3-2; 34–28.5 Ma) (Sun et al., 1999), late Oligocene Shanggancaigou Formation (N1; 28.5–24 Ma) (Sun et al., 1999), early to middle Miocene Xiayoushashan Formation (N2-1; 24–11 Ma) (Sun et al., 1999), late Miocene Shangyoushashan Formation (N2-2; 11–5.3 Ma), Pliocene Shizigou Formation (N2-3; 5.3–1.8 Ma) (Sun et al., 1999), and Quaternary Qigequan and Dabuxun Yanqiao Formations (Q2) (Yang et al., 1997; Sun et al., 1999). Our age division closely follows that of Rieser et al. (2006a, 2006b) except the age assignment of the Xiaganchaigou Formation, for which we rely on the result of a more recent magnetostratigraphic study by Sun et al. (2005).

The Kunlun fault was initiated at 15–7 Ma, with a Quaternary slip rate of 11–16 mm/yr and a total displacement of ~75 km (Kidd and Molnar, 1988; van Der Woerd et al., 2002; Jolivet et al., 2003; Lin et al., 2006). The bedrock of the Eastern Kunlun Range is dominated by two phases of plutonism at the Ordovician-Silurian and Permian-Triassic (Liu, 1988). Due to the extensive exposure of plutons, the area is often referred to as the Kunlun Batholith Belt (e.g., Chang and Zheng, 1973; Allègre et al., 1984; Harris et al., 1988; Dewey et al., 1988). The Paleozoic and early Mesozoic igneous rocks were intruded into Precambrian gneiss, Neoproterozoic metasediments, and Devonian-Carboniferous marine strata; they were in turn overlain by Jurassic to Cenozoic continental deposits (Liu, 1988; Coward et al., 1988; Harris et al., 1988; Mock et al., 1999; Cowgill et al., 2003; Robinson et al., 2003; Roger et al., 2003). The Sino-Anglo Geotraverse along the Golmud-Lhasa Highway (Dewey et al., 1988; Coward et al., 1988; Harris et al., 1988) and the reconnaissance work of others at the western end of the Eastern Kunlun Range (Molnar et al., 1987; Burchfiel et al., 1989b; McKenna and Walker, 1990) have revealed the general style of deformation, extent of major Mesozoic sutures, and existence of Cenozoic igneous activities across the region. $^{40}Ar/^{39}Ar$ thermochronological studies reveal widespread Mesozoic cooling events across the range, which were overprinted locally by a prominent Cenozoic cooling event at 30–20 Ma (Mock et al., 1999; Liu et al., 2005). Apatite fission-track studies suggest that the Eastern Kunlun region experienced rapid and widespread cooling ca. 20–10 Ma, possibly related to the initiation of Cenozoic uplift (Jolivet et al., 2001; Wang et al., 2004; Liu et al., 2005; Yuan et al., 2006). Due to the reconnaissance nature of the above investigations and their strong emphasis on thermochronology, the structural relationships and the evolution of the geologic contact between the Eastern Kunlun Range and Qaidam basin are essentially unconstrained. Below we address this issue by presenting new field observations and interpretation of newly available subsurface data from the Qimen Tagh Mountains of the western Eastern Kunlun Range and southwestern Qaidam basin (Fig. 2).

TABLE 1. CENOZOIC STRATIGRAPHY OF QAIDAM BASIN

Unit name	Symbol	Geologic time	Age	Reflectors
Dabuxun Yanqiao Formation	Q2	Holocene	0.01–present	
Qigequan Formation	Q1	Pleistocene	1.8–0.01 Ma	T0
Shizigou Formation	N2-3	Pliocene	5.3–1.8 Ma	T1
Shangyoushashan Formation	N2-2	Late Miocene	11.2–5.3 Ma	T2'
Xiayoushashan Formation	N2-1	Early and middle Miocene	23.8–11.2 Ma	T2
Shangganchaigou Formation	N1	Late Oligocene	28.5–23.8 Ma	T3
Upper Xiaganchaigou Formation	E3-2	Early Oligocene	37–28.5 Ma	T4
Lower Xiaganchaigou Formation	E3-1	Middle Eocene to late Eocene	49–37 Ma	T5
Lulehe Formation	E1+2	Paleocene to early Eocene	>54.8–49 Ma	TR
(Dominantly Jurassic strata locally with Cretaceous beds on top)	Jr	Jurassic-Cretaceous	206–65 Ma	T6

THE QIMEN TAGH AND SOUTHWEST QAIDAM BASIN

Structural Geology from Surface Mapping

The Qimen Tagh Mountains and southwestern Qaidam basin expose from north to south the following major Cenozoic structures: (1) the active left-slip Altyn Tagh fault, (2) the north-dipping Yiematan thrust, (3) the north-dipping Caishiling thrust, (4) the south-verging and eastward-plunging Yousha Shan anticlinorium, (5) the Gas Hure syncline, (6) the north-dipping Qimen Tagh imbricate thrust zone, (7) the north-dipping Adatan thrust, and (8) the north-dipping Ayakum thrust (Figs. 3 and 4).

The left-slip Altyn Tagh fault makes a right step in our study area and forms a prominent restraining bend. Several south-directed thrusts and folds are developed in this transpressional zone, including the Yiematan and Caishiling thrusts and the Yousha Shan anticlinorium. The Yiematan thrust juxtaposes Proterozoic gneisses over Neogene strata, whereas the Caishiling thrust places Ordovician metavolcanics and metagraywacke over Jurassic fluvial and lacustrine deposits and Cenozoic red beds (Fig. 3).

The Yousha Shan anticlinorium is a south-verging fold, with a steep to overturned southern limb (Figs. 4 and 5). Contractional structures in this fold complex have an eastward decreasing magnitude of shortening, which is expressed by a progressive decrease in stratigraphic throw across thrusts and eastward plunging fold axes (Figs. 3 and 5). The fold is active and has been propagating eastward in the Quaternary, which is expressed by sequential eastward uplift and tilting of Quaternary terrace surfaces (Fig. 5). In addition, the eastward growth of the anticline has caused a systematic deflection of drainages that flow around the fold nose (Fig. 5).

The Gas Hure syncline is the southern continuation of the active Yousha Shan anticlinorium and controls an active depocenter zone expressed by the development of Gas Hure Lake (Figs. 3 and 5). The Cenozoic development of the syncline has produced a northward-thickening sequence across its southern limb, which is evident from well data indicating a systematic northward increase in depth to crystalline basement (Fig. 4). The north-directed Arlar thrust is a minor blind structure well-imaged seismically below the Gas Hure syncline (Fig. 4). Motion on the thrust has produced a fault-propagation fold in its hanging wall and an early Miocene to Quaternary growth-strata sequence, indicating the thrust initiated in the early Miocene and Pliocene (Fig. 4).

The northern Qimen Tagh Mountains are dominated by south-directed imbricate thrusts, which juxtapose Proterozoic gneiss and early Paleozoic granites over Ordovician and Carboniferous strata, and locally place Precambrian and Paleozoic rocks directly over Eocene strata (Figs. 3 and 4). Due to the lack of matching units across these faults, the exact slip on these faults is unknown. In contrast to the thrusts to the north that are mainly developed in the bedrock of the range, the southern Qimen Tagh Mountains are dominated by the Adatan and Ayakum thrusts that place Proterozoic, Paleozoic, and Triassic rocks directly over Quaternary sediments. The morphological expression of the active Adatan fault is particularly striking in Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images and in the field; it cuts alluvial fan surfaces, forming prominent fault scarps (Figs. 6, 7, and 8A). Ordovician graywacke in the Adatan hanging wall experienced two phases of folding. The first was isoclinal folding that transposed bedding and was associated with well-developed slaty cleavage. The second phase of folding is tight and commonly associated with brittle thrusting forming fault-bend or fault-propagation folds (Fig. 8D). These folds are more widely spaced and are defined by warping of the slaty cleavage from the first-phase folding (Fig. 7). The style of the deformation for the second-phase folding is compatible with that in the Cenozoic strata of southern Qaidam basin. For this reason, we suggest that the later folding event was caused by Cenozoic tectonics.

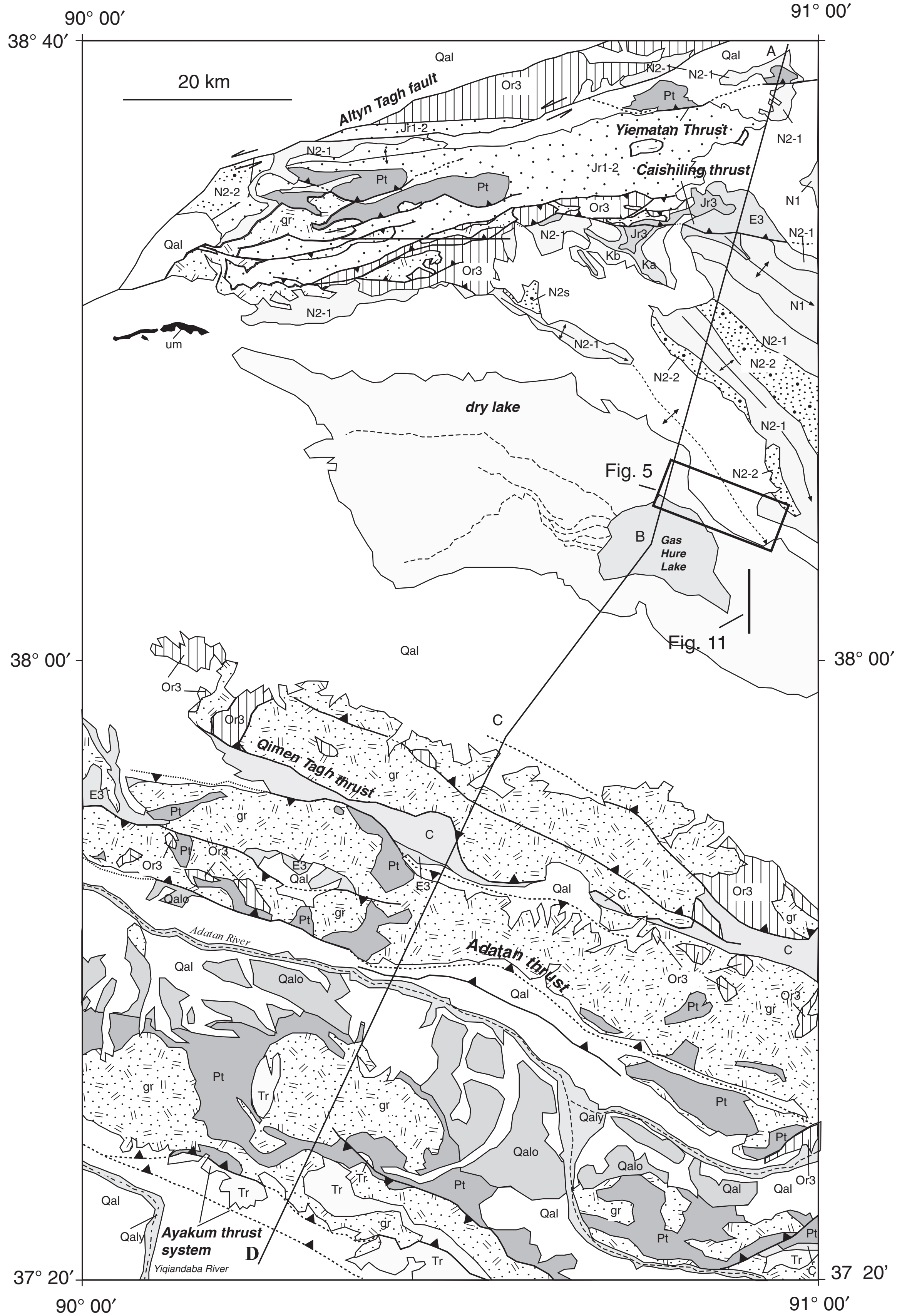
The Ayakum thrust zone is an active structure and has a strong topographic expression (Fig. 2). It consists of two fault branches in the study area (Figs. 3 and 4), with a northern thrust placing Paleozoic granite over Triassic strata and a southern thrust placing Triassic rocks over Neogene-Quaternary strata. The Ayakum fault strikes east and makes a sharp turn to the southwest at its western end; the southwest-trending fault segment in turn is linked with a north-directed Cenozoic thrust system to the south near Tula (Robinson et al., 2003; Dupont-Nivet et al., 2004) (Figs. 2 and 3).

To determine the contact relationship between the western Eastern Kunlun Range and Qaidam basin, we systematically examined the geology across the topographic boundary between the two tectonic features. Our field observations reveal no disrupted Quaternary fans along the range front, indicating no Quaternary active faults that bound the Eastern Kunlun Range, as speculated by many early workers in the region. This observation applies to the whole northern front of the Eastern Kunlun Range.

The contact between the range and Qaidam basin is concealed in most places by Quaternary fan deposits that overlap bedrock of the Eastern Kunlun Range. In a few places, the contact between the Paleozoic rocks of the Eastern Kunlun Range and Cenozoic strata of southern Qaidam basin is exposed in deeply cut canyons, where we observed that north-dipping Cenozoic strata rest unconformably on top of Paleozoic rocks (Fig. 8B). The Cenozoic strata above the unconformity are folded and cut by south-directed thrusts (Fig. 9). Locally, the contact between the Eastern Kunlun Range and Qaidam basin is defined by gentle north-dipping Pliocene strata overlapping north-dipping Carboniferous beds (Fig. 8C). Similar relationships are also seen from seismic reflection profiles across the southern margin of Qaidam basin (Fig. 10).

Structural Geology from Subsurface Data

We have examined a series of seismic-reflection profiles and drill-hole data from southwestern Qaidam basin provided to us by the Qinghai Oilfield Company. These data help constrain the geometry of major structures in the basin and their relationship to the Eastern Kunlun uplift. Figure 10 shows an example



90° 00′
91° 00′
38° 40′
38° 00′
37° 20′
37 20′
20 km
Altyn Tagh fault
Yiematan Thrust
Caishiling thrust
dry lake
Gas Hure Lake
Fig. 5
Fig. 11
Qimen Tagh thrust
Adatan thrust
Adatan River
Ayakum thrust system
Yiqiandaba River
A
B
C
D
Qal
Or3
N2-1
N2-2
Pt
Jr1-2
gr
Jr3
E3
N1
Kb
Ka
N2s
um
C
Qalo
Tr
Qaly

Figure 3. Geologic map of the Qimen Tagh and Yousha Shan area; see Figure 2 for location. Major lithologic units: Qaly—active fluvial channel deposits; Qal—Quaternary alluvial deposits; Qalo—older Quaternary alluvial deposits; N1—late Oligocene strata; N2-1 and N2-2—older and younger Pliocene sedimentary units; E3—Eocene-Oligocene strata; Ka—older Cretaceous unit; Kb—younger Cretaceous unit that also includes Paleocene–early Eocene strata; Jr1-2 and Jr3—Jurassic sedimentary units; Tr—Triassic sedimentary and volcanic rocks; C—Carboniferous sedimentary unit; Or3—Upper Ordovician metavolcanic and metagraywacke sequences; Pt—Proterozoic gneisses; gr—early Paleozoic granites; um—ultramafic rocks. The map also shows locations of Figures 5 and 11.

of such seismic profiles, this one lying across the eastern tip of the north-dipping Qimen Tagh thrust zone that we mapped in the field to the west (Fig. 2). The thrust fault in the seismic section offsets the base of the Cenozoic strata for ~5 km. Displacement on this fault induced a south-verging fault-bend fold in the hanging wall. The north-dipping Cenozoic strata shown in the seismic line along the southern basin margin are consistent with our field observations discussed earlier, and so is the folding of the Cenozoic strata (cf. Figs. 8B and 9). More complete data sets on seismic-reflection profiles across the whole Qaidam basin are reported in Yin et al. (2008b).

In addition to the seismic profiles we obtained from Qinghai Oilfield Company, we also reinterpret a published seismic profile by Song and Wang (1993) (Fig. 11). In the original interpretation, Song and Wang (1993) failed to recognize the presence of a fault-bend fold above the Arlar thrust. This thrust is a backthrust in the forelimb of the south-verging Yousha Shan anticlinorium. A similar backthrust is also shown in Figure 10 across the eastern end of the Yousha Shan anticlinorium.

Across the eastern segment of the Yousha Shan anticlinorium, the backlimbs of the south-directed Yousha Shan and north-directed Luoyan Shan anticlinoriums are flat. Based on the classic fault-bend fold model of Suppe (1983), this suggests the presence of a flat décollement in the middle crust when the detailed geometric relationships between the two high-angle thrusts and their related fold complexes in the respective hanging wall are considered (Fig. 10). Across the western segment of the Yousha Shan anticlinorium, surface geology and its downward projection requires the presence of a major thrust ramp below the anticlinorium when cross section balance is considered. This thrust ramp is also exposed in the eastern section in Figure 10, but it lies at a much shallower depth.

Our inferred décollement at a middle crustal level below Qaidam basin is consistent with the early proposal of Burchfiel et al. (1989a) based on two lines of argument: (1) there are no lower crustal rocks exposed across Qaidam basin and the Qilian Shan–Nan Shan thrust belt, and (2) continental middle crust tends to localize ductile shear zones, as exemplified by many extensional detachment fault zones around the world. We admit that our location of the décollement is highly tentative. For example, the fault could be located at greater depth than we assume here, such as along the base of the lower crust immediately above the Moho, where the crustal strength is presumably weakest, as inferred from depth-dependent crustal rheology (e.g., Chen and Molnar, 1983). However, determining the existence and depth of the proposed middle or lower crustal décollement is beyond the scope of this study; we hope our proposal will inspire more geophysical research across the area to resolve this issue.

Magnitude of Cenozoic Shortening

Due to the lack of matching units across many Cenozoic thrusts within the Qimen Tagh Mountains, it is difficult to estimate their exact offsets and thus the Cenozoic shortening strain across the range. However, a relatively accurate estimate of crustal shortening can be obtained across southwestern Qaidam basin, where surface geology is well mapped and seismic-reflection profiles provide tight constraints on the geometry of the deeper structures. The cross section of southwest Qaidam basin, from point A to point B on Figure 4, was constructed using the kink-bend method of Suppe (1983) and reinterpretation of a seismic profile published by Song and Wang (1993). Line balancing and summation of minimum fault slips across this section suggest shortening of >58 km, which yields a shortening strain of >48%. Given the significantly higher elevation of the Qimen Tagh Mountains (~5000 m) relative to the Yousha Shan anticlinorium (~3200 m) and field evidence for a denser distribution of Cenozoic thrusts and folds across the range, the shortening strain from southwest Qaidam basin may only be a lower bound for the shortening strain across the Qimen Tagh Mountains to the south.

Timing of Cenozoic Deformation

Three lines of evidence suggest that Cenozoic deformation across the Qimen Tagh Mountains and southwestern Qaidam basin was initiated in or after the latest Oligocene–early Miocene. First, Oligocene lacustrine deposits are scattered in the Qimen Tagh Mountains and have been correlated with coeval deposition of lacustrine strata in southwestern Qaidam (Zhong et al., 2004; Guo et al., 2006) (Fig. 3). This observation implies the presence of a unified but much larger basin extending from the present southwestern Qaidam basin into the Qimen Tagh Mountains. The basin did not become fragmented until after Oligocene lacustrine deposition across the region, which implies that the Qimen Tagh was not uplifted until after the end of the Oligocene.

The second line of evidence for a Neogene initiation of contraction in the region comes from growth strata relationships imaged in seismic-reflection profiles (Figs. 10 and 11). In Figure 10, stratigraphic thickening occurs in unit N2-1 (early and middle Miocene; see Table 1) and the younger strata above it in a synclinal position, whereas the thickness of unit N1 (late Oligocene; see Table 1) and older strata are not affected by folding. This suggests that the eastern segment of the Yousha Shan anticlinorium did not start to develop until after the early Miocene. In contrast to the eastern section, the seismic section across the western Yousha

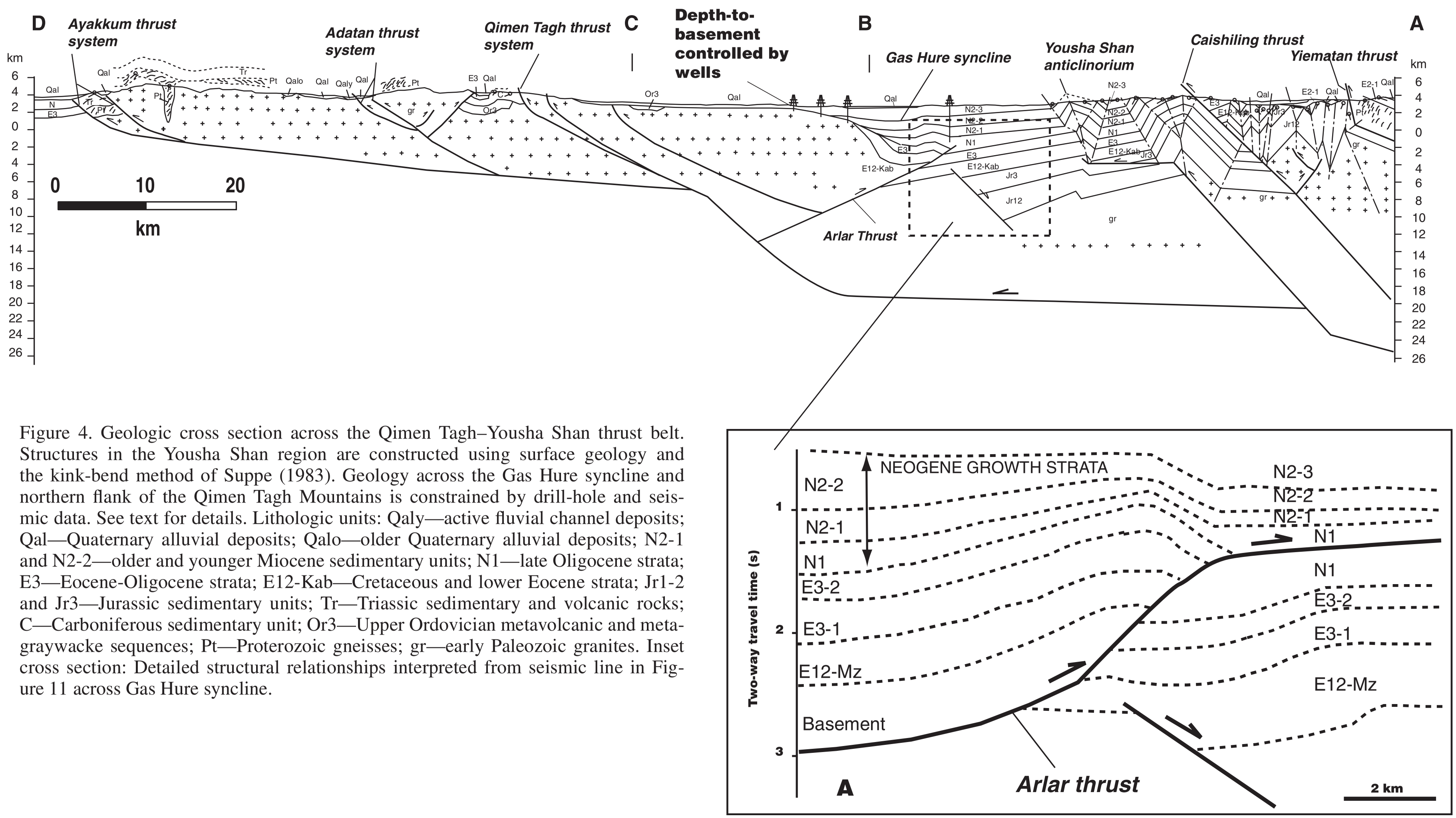
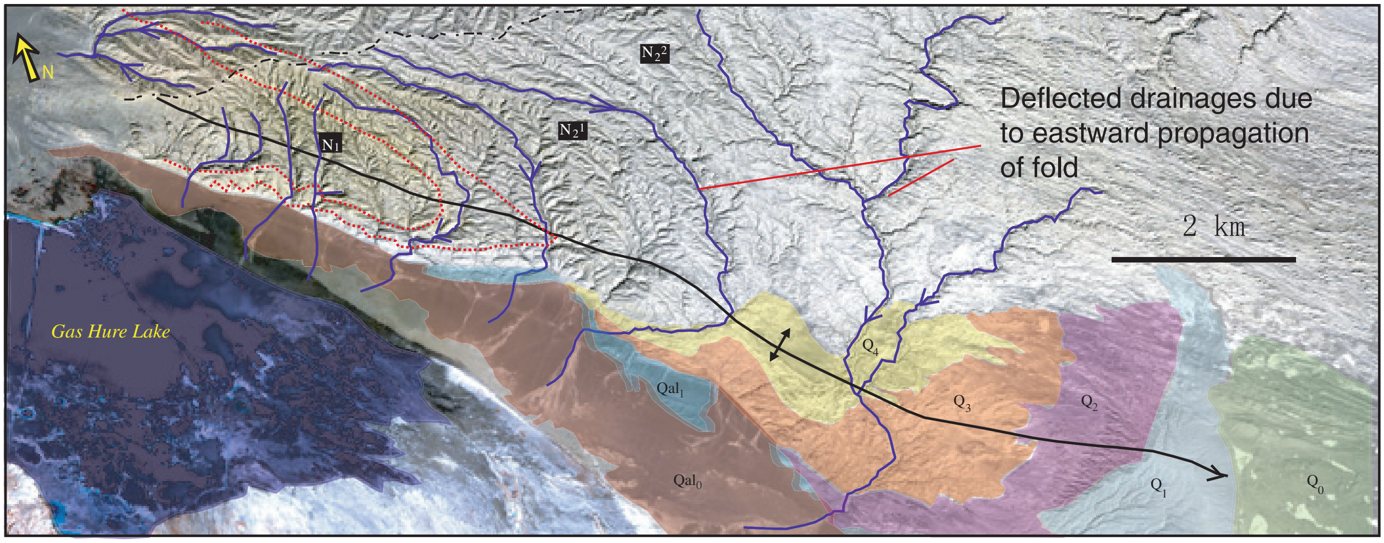


Figure 4. Geologic cross section across the Qimen Tagh–Yousha Shan thrust belt. Structures in the Yousha Shan region are constructed using surface geology and the kink-bend method of Suppe (1983). Geology across the Gas Hure syncline and northern flank of the Qimen Tagh Mountains is constrained by drill-hole and seismic data. See text for details. Lithologic units: Qaly—active fluvial channel deposits; Qal—Quaternary alluvial deposits; Qalo—older Quaternary alluvial deposits; N2-1 and N2-2—older and younger Miocene sedimentary units; N1—late Oligocene strata; E3—Eocene-Oligocene strata; E12-Kab—Cretaceous and lower Eocene strata; Jr1-2 and Jr3—Jurassic sedimentary units; Tr—Triassic sedimentary and volcanic rocks; C—Carboniferous sedimentary unit; Or3—Upper Ordovician metavolcanic and metagraywacke sequences; Pt—Proterozoic gneisses; gr—early Paleozoic granites. Inset cross section: Detailed structural relationships interpreted from seismic line in Figure 11 across Gas Hure syncline.



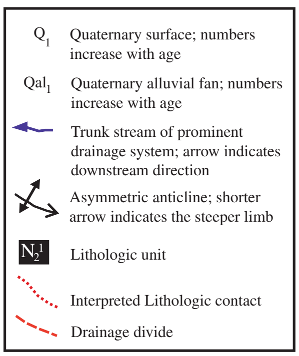


Figure 5. Advanced Spaceborne Thermal Emission and Reflection Radiometer image of the Yousha Shan anticlinorium. Note that south-flowing drainages are systematically deflected and make U-shaped turns around the anticlinal nose. The tightness of the turns decreases eastward, which is associated with eastward younging of tilted Quaternary fan surfaces as indicated by an eastward decrease in drainage density and incision. We interpret the above observations as results of eastward propagation of the Yousha Shan anticlinorium. Also note that the drainage divide does not coincide with the anticline axis. This may be caused by a lower base level on the south side of the anticline than that on the north side, forcing the drainage divide to have propagated northward as the anticline grew to the east.

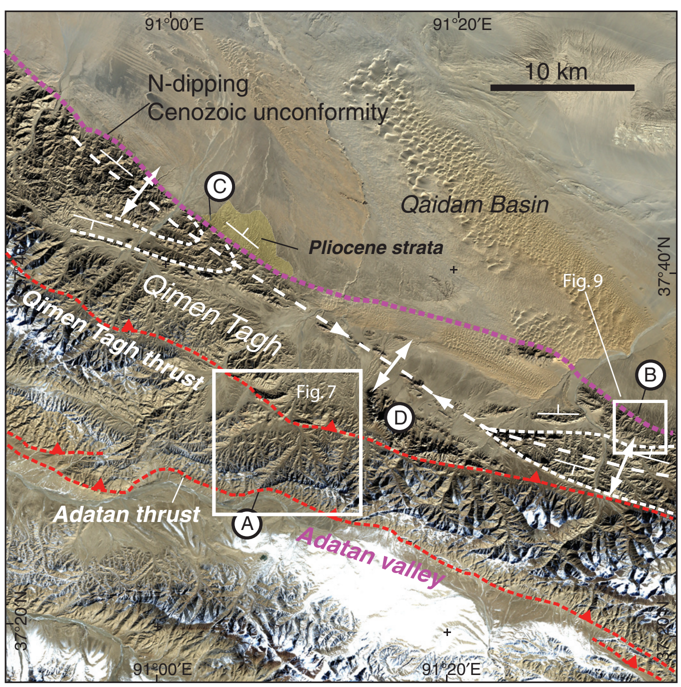


Figure 6. Advanced Spaceborne Thermal Emission and Reflection Radiometer image of the central Qimen Tagh area. The sharp contact between Qaidam basin and bedrock in the range to the south has been interpreted as evidence for active north-directed thrusting (e.g., Meyer et al., 1998; Jolivet et al., 2003). However, field examination indicates that this is a steeply north-dipping unconformity between a resistant Carboniferous marble unit in the south- and north-dipping Cenozoic strata in the north. The image also shows the trace of the active Adatan thrust. Locations of field photos in Figure 8 are indicated on this image as A, B, C, and D. Locations of Figures 7 and 9 are also indicated.

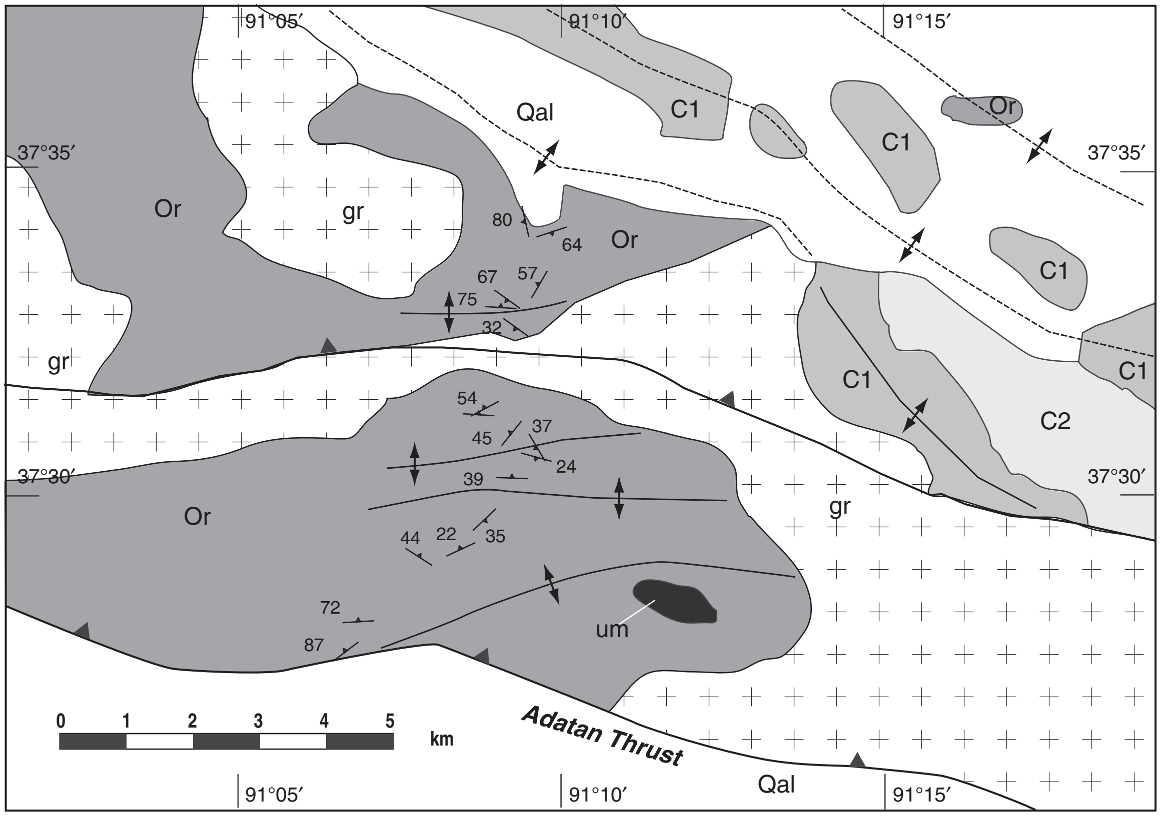


Figure 7. Detailed geologic map of the Adatan thrust hanging wall. Qal—Quaternary alluvial deposits; C1 and C2—Carboniferous units; gr—early Paleozoic granites; Or—Ordovician unit; um—ultramafic rocks. The major folds shown in the map are defined by cleavage that was developed during an early phase of isoclinal folding that transposed most of the original bedding.

Shan anticlinorium indicates an earlier initiation age of deformation. This is shown by synfolding and synthrusting deposition of unit N1; its thickness changes across the fault-bend fold above the Arlar thrust. Because the Arlar thrust is part of the forelimb structure of the Yousha Shan anticlinorium, we suggest that Cenozoic contraction across the western segment of the anticlinorium did not begin until the late Oligocene. The combination of these age interpretations brings us to the conclusion that the Yousha Shan anticlinorium has grown from west to east. This interpretation is consistent with the conclusion reached by our independent geomorphologic arguments (as discussed earlier; see Fig. 5).

The third line of evidence comes from $^{40}Ar/^{39}Ar$ and apatite fission-track thermochronology across the Eastern Kunlun Range. Existing $^{40}Ar/^{39}Ar$ mica and biotite ages indicate that the range experienced a profound Mesozoic cooling, but no Cenozoic signals were detected (Wang et al., 2004; Liu et al., 2005). By conducting $^{40}Ar/^{39}Ar$ multidomain analysis of K-feldspar samples collected across the central Eastern Kunlun Range, Mock et al. (1999) revealed a highly localized rapid cooling event at 30–20 Ma (late Oligocene and early Miocene). In contrast to the general lack of Cenozoic cooling signals from high-temperature thermochronology, apatite fission-track studies across the Eastern Kunlun region consistently point to a Neogene initiation of range uplift. Jolivet et al. (2001) show that rapid cooling in the western segment of the Eastern Kunlun Range did not begin until after 15 Ma. Similarly, Yuan et al. (2006) show initial rapid cooling to have occurred in the eastern segment of the Eastern Kunlun Range between 20 and 10 Ma. If Cenozoic cooling detected by apatite fission-track thermochronology reflects crustal thickening and its induced exhumation, then these thermochronological data suggest that the Eastern Kunlun Range has been uplifted since 20–10 Ma, with local areas uplifted slightly earlier, ca. 30–20 Ma This age range is significantly younger than the initiation age of contractional deformation along the northern margin of Qaidam basin (Jolivet et al., 2001; Yin et al., 2002).

DISCUSSION

Our field studies, together with the existing observations, lead to the following findings: (1) the western segment of the Eastern Kunlun Range is dominated by south-directed thrusts carrying the low-elevation Qaidam basin over the high-elevation Eastern Kunlun Range; (2) shortening strain across southwestern Qaidam basin exceeds 48%; and (3) Cenozoic contraction in

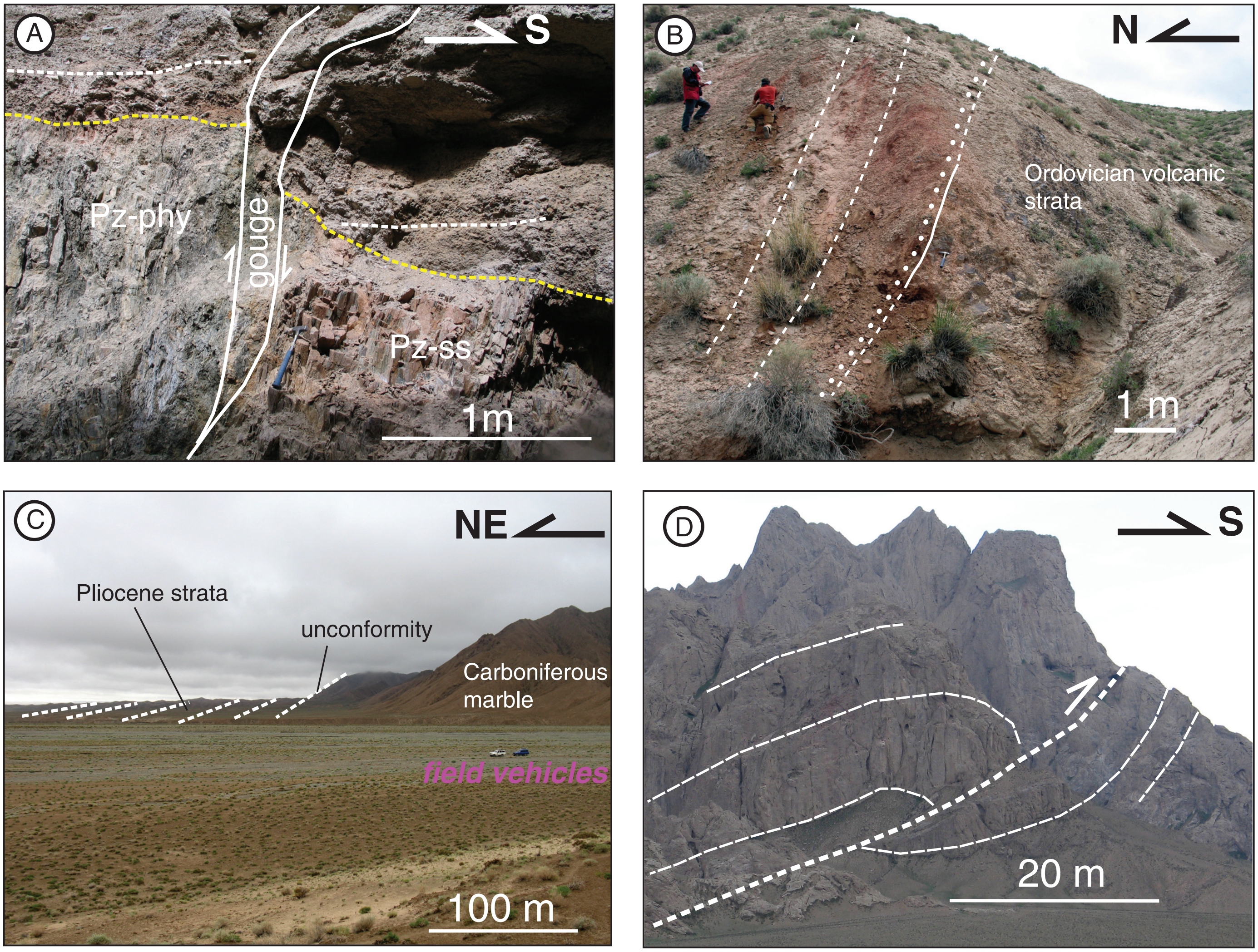


Figure 8. Field photos from the Qimen Tagh area. (A) Active Adatan thrust zone, which cuts Quaternary alluvial deposits. Pz-phy—Paleozoic phyllite; Pz-ss—Paleozoic sandstone. (B) Unconformity between north-dipping Cenozoic strata of Qaidam basin and Ordovician metavolcanic rocks of the Eastern Kunlun Range. (C) Pliocene-Quaternary sedimentary strata unconformably rest on top of a Carboniferous marble unit. Due to the resistant nature of the marble unit below, this contact forms a prominent linear topographic feature, as imaged in Figure 6. (D) Fault-bend fold in Carboniferous limestone in the Qimen Tagh Mountains.

the Qimen Tagh Mountains and southwestern Qaidam basin was initiated in the late Oligocene and early Miocene. We address the implications of these findings with respect to the history and mechanism of Cenozoic Tibetan uplift in the following sections.

Wedge Tectonics across the Eastern Kunlun Range

The discovery of a north-dipping unconformity along the northern edge of the Eastern Kunlun Range and dominant south-directed thrusts across the Qimen Tagh–Yousha Shan thrust belt is counterintuitive and contrary to the existing structural models reviewed in this paper. However, this type of structure is not uncommon in fold-thrust belts around the world; it is typically associated with the development of large triangle zones as a result of flake or wedge tectonics either during continental collision or intracontinental deformation (Oxburgh, 1972; Price, 1981, 1986). We propose that the development of the south-directed thrusts across the Qimen Tagh and southern Qaidam regions were induced by a similar tectonic process. Specifically, we envision that the lower crust and mantle lithosphere of Qaidam basin has been subducting southward below the Eastern Kunlun Range since the late Oligocene and early Miocene, whereas Qaidam upper crust has been carried over the range by southward thrusting (Fig. 12). This model is not only consistent with the observed structural geometry across the western Eastern Kunlun Range but also predicts simultaneous uplift of the range in both the footwall and hanging wall of the Qimen Tagh–Yousha Shan thrust belt. An important geometric property of this model is that crustal shortening across

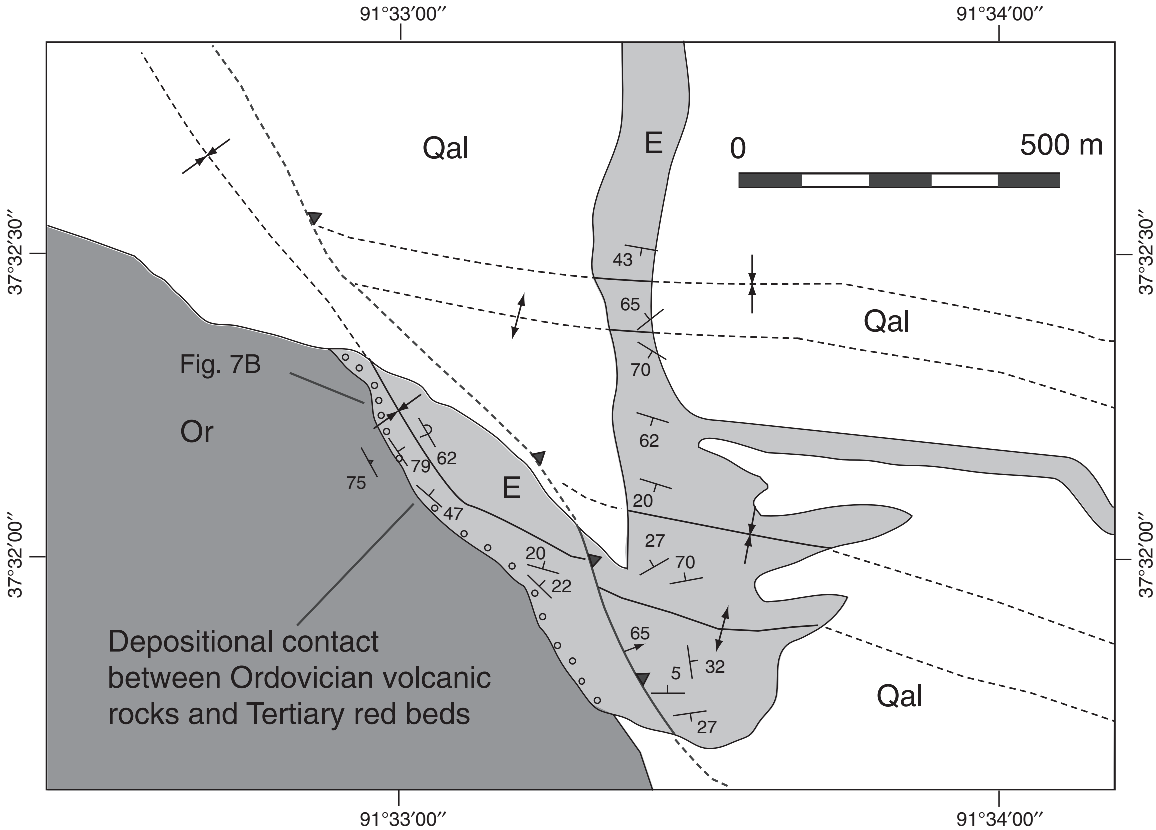
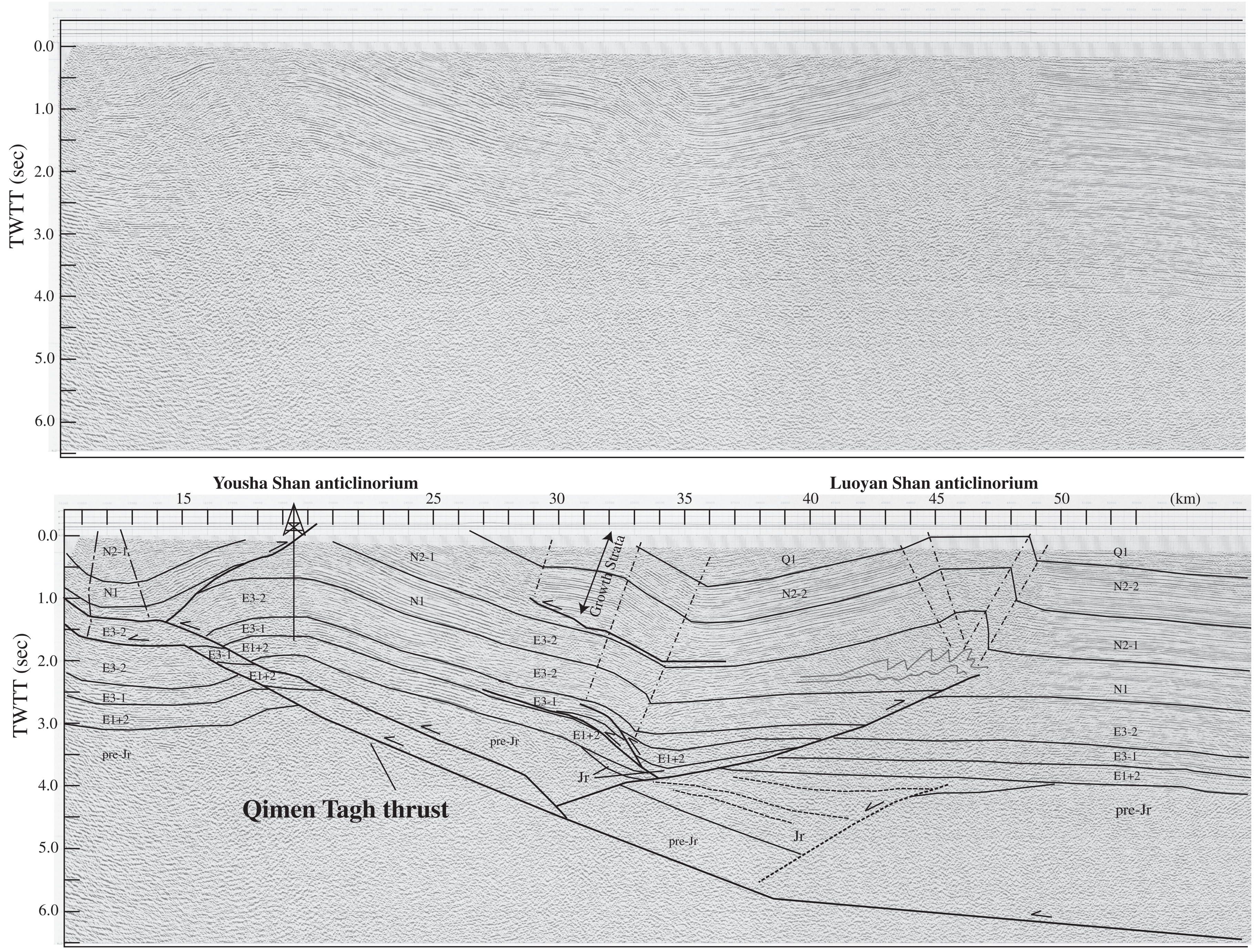


Figure 9. Detailed geologic map showing the unconformity between Paleogene strata (E) and Ordovician metavolcanics (Or). The area is mostly covered by Quaternary alluvial and loess deposits (Qal), except the deep-cut gullies. Note that the Cenozoic strata themselves are folded and cut by south-directed thrusts.

the Qimen Tagh–Yousha Shan thrust belt provides a minimum estimate for the amount of southward subduction of the Qaidam basement. That is, if the Eastern Kunlun tectonic wedge terminates below the range front where the basal thrust and backthrust meet, then the amount of fault slip on the two faults above and below the wedge must be the same. However, if a frontal décollement is present and extends beyond the tip point of the wedge, as shown in Figure 12, then slip on the basal thrust could be much greater than that on the backthrust above. If we assume that the calculated 48% Cenozoic shortening strain from southwestern Qaidam basin has been applied uniformly across the 150-km-wide Qimen Tagh–Yousha Shan thrust belt, then the minimum amount of southward overthrusting of the Qaidam basement is ~150 km. Because the total amount of shortening across the western end of the Eastern Kunlun Range is 250–300 km, as deduced from Yin and Harrison (2000) based on differential Cenozoic slip along the Altyn Tagh fault, the difference suggests that the frontal décollement below Qaidam basin has a total slip of ~100–150 km (i.e., $S2 = S - S1$, where S = 250–300 km and $S1$ = 150 km; see inset in Figure 12 for this geometric relationship).

There are at least two possible kinematic histories that could lead to the currently observed structural configuration across the Qimen Tagh Mountains and southwestern Qaidam basin. The first scenario is that the initial Cenozoic uplift of the Eastern Kunlun Range was produced by north-directed thrusting and associated with foreland-basin development (Fig. 13). Later development of a south-directed thrust in the foreland caused partitioning and progressive closure of the early foreland basin. Continuous motion on the younger south-directed thrust allowed its hanging wall to override the older north-directed thrusts and to create a new foreland basin at a high altitude on top of the older north-directed

Figure 10. Interpreted seismic line across the eastern tip of the north-dipping Qimen Tagh thrust zone and the eastern segments of the Yousha Shan anticlinorium. The main thrust offsets the base of Cenozoic strata for ~5 km; its motion induced the development of the south-verging fault-bend fold in the hanging wall, expressed as the Yousha Shan anticlinorium on the surface. The north-dipping geometry of Cenozoic strata shown in the seismic line along the southern margin of Qaidam basin is consistent with our field observations. E1+2—Paleocene–early Eocene strata; E3-1—middle to late Eocene strata; E3-2—early Oligocene strata; Jr—Jurassic strata; pre-Jr—pre-Jurassic rocks; N1—late Oligocene strata; N2-1 and N2-2—Miocene strata sedimentary units; TWTT—two-way travel time.


TWTT (sec)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Yousha Shan anticlinorium
Luoyan Shan anticlinorium
15
25
30
35
40
45
50
(km)
N2-1
N1
E3-2
E3-1
E1+2
pre-Jr
Growth Strata
Q1
N2-2
Jr
Qimen Tagh thrust

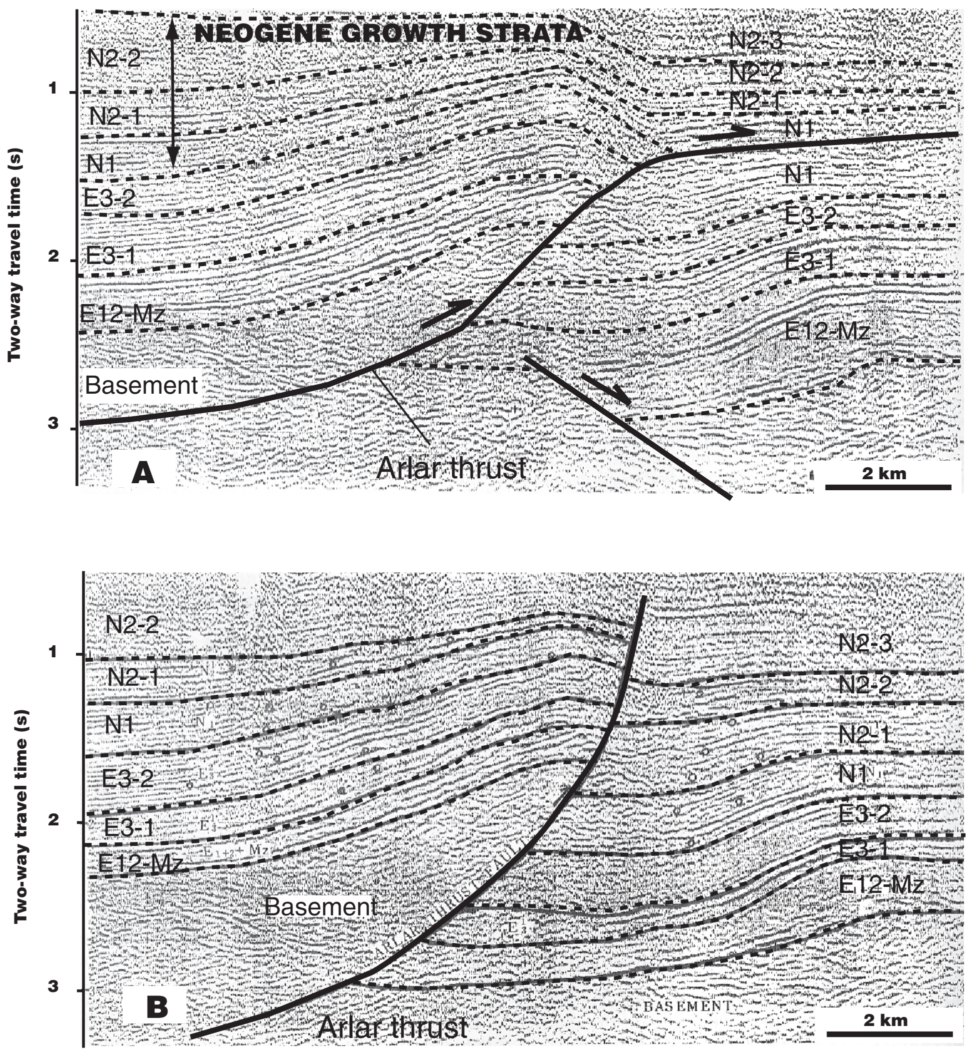


Figure 11. Seismic profile of Song and Wang (1993) along the eastern edge of Gas Hure Lake; see Figure 3 for location. (A) Reinterpreted seismic section of Song and Wang (1993). Note that growth strata started to develop during initial deposition of late Oligocene unit N1, which suggests that the Arlar thrust initiated during the deposition of this unit. The abrupt thickness change in Mesozoic strata is induced by a north-dipping normal fault. (B) Originally interpreted seismic section by Song and Wang (1993). This interpretation forces the Arlar thrust to cut through a series of continuous reflectors in the upper stratigraphic units and implies that the thrust is exposed at the surface. The latter is inconsistent with our field observations. N1—late Oligocene strata; N2-1—early and middle Miocene strata; N2-2—late Miocene sedimentary units; N2-3—Pliocene strata; E3-1—middle to late Eocene strata; E3-2—early Oligocene strata; E12-Mz—Middle to late Eocene strata.

thrust. This may explain the development of active foreland basins in the footwalls of the Ayakum and Adatan thrusts at elevations >4500 m, some 1500 m higher than Qaidam basin. We refer to this kinematic history as the *push-together process*. The model implies that large-magnitude upper-crustal shortening could be completely concealed due to long-distance travel of large thrusts.

Alternatively, the uplift of the Eastern Kunlun Range may have been accomplished by accretion of the Qaidam crust in a piecemeal fashion. We refer to this kinematic history as the *piecemeal-accretion process* (Fig. 14). That is, the uplift of the Eastern Kunlun Range was accomplished by northward motion of a tectonic wedge below, with the wedge tip line propagating northward. The tip-line propagation resulted in sequential northward creation of south-directed thrusts in southern Qaidam basin. These thrusts accreted Qaidam crust incrementally onto the Eastern Kunlun Range, causing the range to be uplifted and enlarged progressively northward with time.

The Youshan Shan anticlinorium and its underlying south-directed blind thrust system could be regarded as an incipient south-directed thrust in our models; that is, its development could

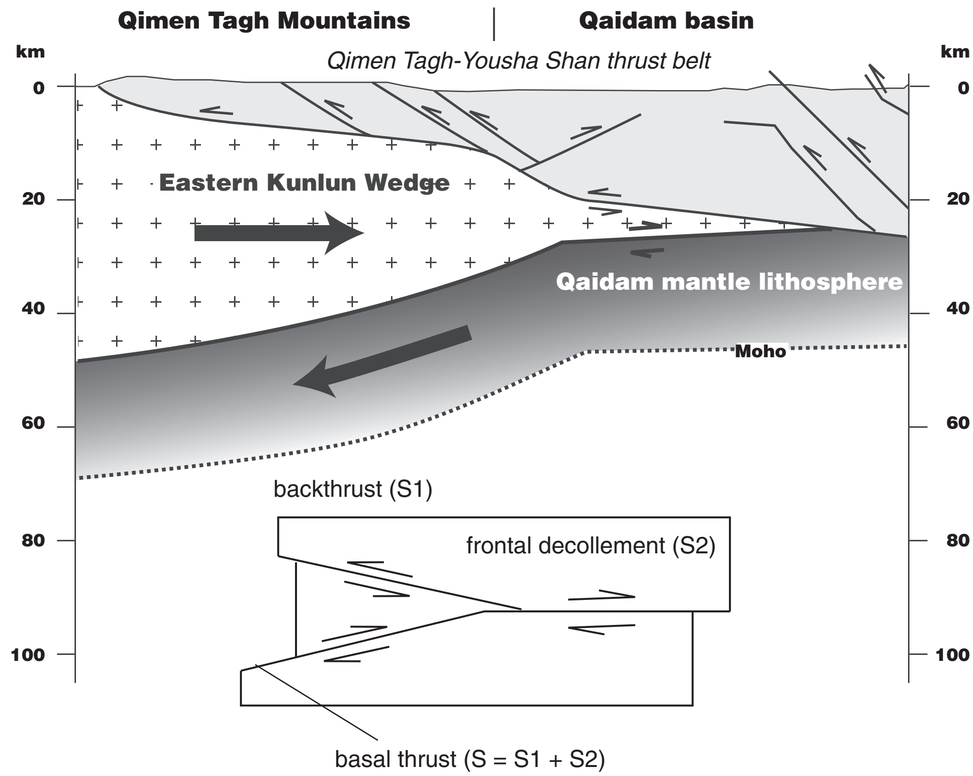


Figure 12. Conceptual model for the structural geometry of the Qimen Tagh–Yousha Shan thrust belt. We infer the presence of a large tectonic wedge below the Eastern Kunlun Range. Its northward extrusion is accommodated by south-directed thrusting in the upper crust and north-directed thrusting in lower crust. This model predicts synchronous uplift of the footwall and hanging wall of the south-directed Qimen Tagh–Yousha Shan thrust belt. Inset shows the relationship between total slip on the basal thrust ($S = S1 + S2$) and slip on the backthrust ($S1$) and frontal décollement ($S2$).

follow either of the kinematic paths shown in Figures 13 and 14. The ultimate test of the two models is elucidation of the deep structures below the Eastern Kunlun Range by either projecting map-view relationships onto deep crustal sections, or more directly, by conducting deep seismic studies to examine if low-density and low-velocity sedimentary basins are buried below major thrust sheets.

It has been long noted that Cenozoic depocenters of Qaidam basin have been persistently located near the axis of the basin rather than along its edges (Bally et al., 1986; Huang et al., 1996; Wang et al., 2006). The modern expression of this situation is the presence of a series of large basins along the basin axis, where all large rivers flowing out of the Eastern Kunlun Range and Qilian Shan terminate. Our observation that Cenozoic strata thicken toward basin centers is consistent with this early conclusion but is inconsistent with the classic foreland-basin model that predicts flexural bending of the foreland basement toward basin-bounding thrusts and thickening of foreland sediments toward the basin margins. The presence of the south-directed thrusts across the western Eastern Kunlun Range and a triangle zone along the northern edge of Qaidam basin (Yin et al., 2008a) indicate that the development of the synclinal trough across Qaidam basin is caused by the uplift of the two structural systems on the basin margins. This deformational process produces an apparent synclinorium across Qaidam basin, as first recognized by Bally et al. (1986).

Out-of-Sequence Thrusting and Growth History of the Tibetan Plateau

Studies along the northern margin of Qaidam basin indicate that its bounding contractional structures started to develop in the early to middle Eocene, ca. 55–45 Ma (Jolivet et al., 2001; Yin et al., 2002, 2008a). This timing of deformation is significantly older than the late Oligocene–early Miocene initiation of deformation along the southern margin of Qaidam basin. Neogene initiation of contraction at 20–10 Ma appears to be a widespread phenomenon across the whole Eastern Kunlun Range as well, which is revealed by low-temperature fission-track thermochronometry (Jolivet et al., 2003; Yuan et al., 2006). Even the locally determined older initiation age of 30–20 Ma (Mock et al., 1999) is significantly younger than the age of initial Cenozoic deforma-

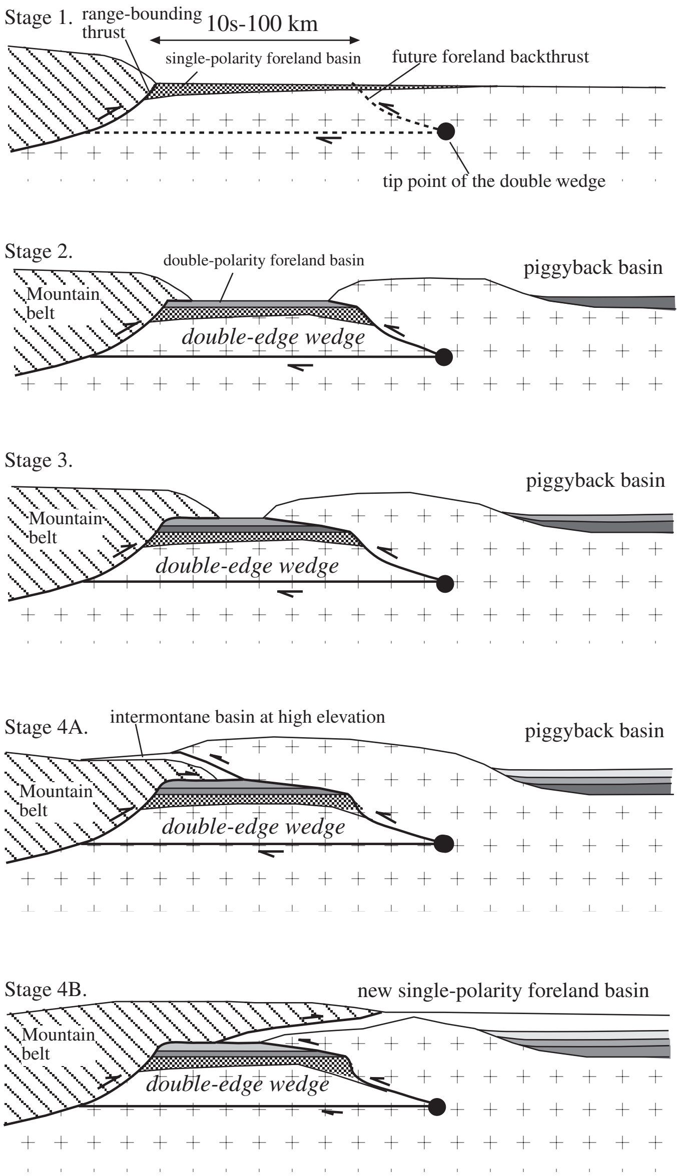


Figure 13. A push-together model for the development of the south-directed Qimen Tagh–Yousha Shan thrust belt. This model predicts that early north-directed thrusts are overridden by later south-directed thrusts across the Eastern Kunlun Range. Stage 1: A north-directed thrust is developed, generating a southward-thickening foreland basin. Stage 2: A south-directed thrust is developed above the tip line of a north-extruding wedge. As a result, the original single-polarity foreland basin is modified to become a double-polarity foreland basin, with its strata thickening to the basin edges toward the two bounding thrusts. Corresponding to the double-polarity basin is the double-edge wedge block below, which is extruding northward with northward migration of its tip line. Stage 3: Continuous motion on the south-directed thrust progressively closes the double-polarity foreland basin. Stage 4A: The south-directed thrust may eventually override the north-directed thrust, placing the older foreland basin entirely below its footwall. Stage 4B: Alternatively, if motion on the north-directed thrust has been active coevally with the south-directed backthrusting, the north-directed thrust could override the south-directed thrust. The most important implication of this model is that a large amount of crustal shortening may not be detectable by surface mapping only.

tion along the northern margin of Qaidam basin. This leads us to conclude that the northern and southern bounding structures of Qaidam basin were initiated diachronously, with the north started first followed by the south. This inference raises the question of where the southern margin of the Eocene Qaidam basin was located. Eocene lacustrine sediments are stranded and scattered across the Eastern Kunlun Range (Fig. 3), so it is possible that the Eocene to early Oligocene southern boundary of Qaidam basin was located south of the Eastern Kunlun Range. If this is the case, then it is highly likely that the Eocene Qaidam basin and the Eocene Hoh Xil basin of Liu et al. (2001, 2003) were parts of a once contiguous basin that was later partitioned by the Neogene uplift of the Eastern Kunlun Range. This size of this basin is comparable to that of Tarim basin between the Tian Shan and Tibetan plateau, and we refer to this inferred large Eocene basin across central Tibet as the *Paleo-Qaidam basin* (Fig. 1).

Our inferred late Oligocene and early Miocene age of initial deformation for the south-directed thrust belt across the western Eastern Kunlun Range is older than the initiation age of the Kunlun fault at 15–7 Ma (Kidd and Molnar, 1988; Jolivet et al., 2003). If southward thrusting was related to left-slip deformation along the Kunlun fault, then deformation must have been propagated from the west to the east. This implies a more complicated deformation history for the development of the Eastern Kunlun transpressional system. That is, the Qimen Tagh thrust belt propagated eastward first and was later linked with the nearly nucleated Kunlun fault that serves as a transfer zone to pass on the contraction to the thrust belt in the Bayanhar Mountains south of the Kunlun fault (Fig. 2).

The younger age of initiation of deformation along the southern margin of Qaidam basin relative to the northern margin suggests that the development of contractional structures across the basin is *out of sequence*, following the terminology of thrust tectonics (e.g., Boyer and Elliott, 1982). This temporal pattern of deformation is inconsistent with the prediction of the thin-viscous-sheet model, at least in its original form, assuming uniform material properties across the whole Tibetan plateau (England and Houseman, 1986). A revised thin-viscous-sheet model, allowing heterogeneous distribution of mechanical strength and the presence of preexisting weakness, may explain the irregular deformation across northern Tibet as we observed across Qaidam basin (e.g., Neil and Houseman, 1997; Kong et al., 1997).

Mechanisms of Tibetan-Plateau Uplift

Determining the magnitude of Cenozoic shortening is a key to evaluating whether lower-crustal flow or thermal events in the upper mantle were responsible for the uplift of the Tibetan plateau (Royden et al., 1997; Clark and Royden, 2000; Molnar et al., 1993). Our estimated crustal shortening in southwestern Qaidam basin is >48%. As discussed above, a similar or even larger magnitude of shortening is expected across the Eastern Kunlun Range. The crustal thickness of Qaidam basin is ~45 km, which is 15–20 km thinner than that for the Eastern Kunlun Range (Zhu

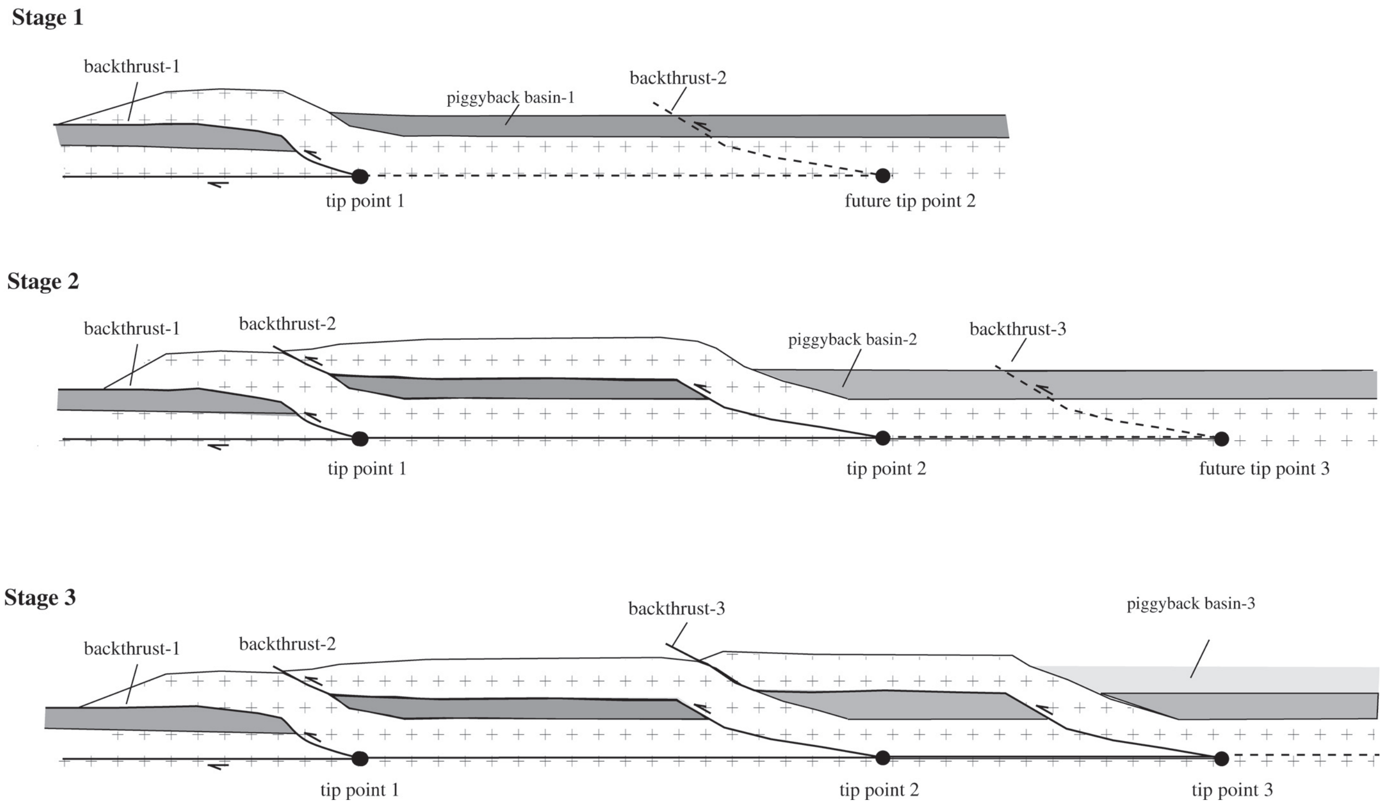


Figure 14. A piece-meal accretion model for the uplift history of the Qimen Tagh Mountains and the development of the south-directed Qimen Tagh–Yousha Shan thrust belt. In this model, a large piggyback basin was first developed on the backlimb of a large backthrust that had climbed up the range front. The piggyback basin was subsequently fragmented by younger backthrusts developed to the north in the foreland as a result of northward propagation of a wedge tip.

and Helmberger, 1998; Zhao et al., 2006; S.L. Li et al., 2006; Y.H. Li et al., 2006). Thickening crust from an original thickness of 35 km to the present 45 km requires shortening strain of 29% (i.e., assuming Qaidam basin was at sea level prior to Cenozoic deformation). If upper crustal shortening, as we observed in the field and inferred from the subsurface data, is accommodated by pure-shear contraction in the Qaidam lower crust, then there is no need for lower crustal channel flow or thermal events in the mantle to raise the Eastern Kunlun Range and southern Qaidam basin. However, if there is a detachment surface separating deformation between the upper and lower crust across the Qaidam and Eastern Kunlun regions, other complicated processes not detectable by surface geologic investigations, such as channel flow or mantle thermal events, need to be considered.

CONCLUSIONS

Our field mapping and analysis of satellite and subsurface data suggest that the western segment of the Eastern Kunlun Range is dominated by south-directed thrusts, carrying the low-elevation Qaidam basin over the high-elevation Eastern Kunlun Range. Contractional deformation initiated in the late Oligocene to early Miocene (28–24 Ma) and has accommodated at least 48% upper-crustal shortening. We suggest that south-directed thrusting is an expression of a large-scale wedge tectonic system across the Eastern Kunlun region; the operation of this system has simultaneously accommodated southward subduction of the Qaidam lower crust and mantle lithosphere and southward thrusting of Qaidam basin over the Eastern Kunlun Range. The early Neogene initiation of deformation along the southern margin of Qaidam basin is significantly younger than that for the northern basin margin. This temporal pattern of deformation suggests that the construction of the Tibetan plateau was not by focusing deformation along its northward expanding margin. Instead, high strain zones were developed inside the Tibetan plateau and remained active during late stages of the Indo-Asian collision after the plateau margins had already been established. If Cenozoic deformation across the Eastern Kunlun and Qaidam regions has been accommodated by pure shear deformation over the whole crust, then our observed > 48% upper-crustal shortening strain is more than sufficient to explain the current elevation and crustal thickness of the region. However, if contraction between the upper and lower crust has been decoupled, then lower crustal flow and thermal events in the upper mantle could be additional causes of plateau uplift across the Eastern Kunlun Range and Qaidam basin.

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REFERENCES CITED

Allègre, C.J., and 34 others, 1984, Structure and evolution of the Himalayan-Tibet orogenic belt: Nature, v. 307, p. 17–22, doi: 10.1038/307017a0.

Bally, A.W., Chou, I.-M., Clayton, R., Eugster, H.P., Kidwell, S., Meckel, L.D., Ryder, R.T., Watts, A.B., and Wilson, A.A., 1986, Notes on sedimentary basins in China—Report of the American Sedimentary Basins delegation to the People's Republic of China: U.S. Geological Survey Open-File Report 86-327, 108 p.

Boyer, S.E., and Elliott, D., 1982, Thrust systems: AAPG Bulletin, v. 66, p. 1196–1230.

Burchfiel, B.C., Deng, Q., Molnar, P., Royden, L.H., Wang, Y., Zhang, P., and Zhang, W., 1989a, Intracrustal detachment with zones of continental deformation: Geology, v. 17, p. 748–752, doi: 10.1130/0091-7613(1989)017<0448:IDWZOC>2.3.CO;2.

Burchfiel, B.C., Molnar, P., Zhao, Z., Liang, K., Wang, S., Huang, M., and Sutter, J., 1989b, Geology of the Ulugh Muztagh area, northern Tibet: Earth and Planetary Science Letters, v. 94, p. 57–70, doi: 10.1016/0012-821X(89)90083-6.

Chang, C.-F., and Zheng, S.-L., 1973, Tectonic features of the Mount Jolmo Lungma region in southern Tibet, China: Scientia Geologica Sinica, v. 16, p. 1–12.

Chen, W.P., and Molnar, P., 1983, Focal depths of intracontinental and intraplate earthquakes and their implications for the thermal and mechanical properties of the lithosphere: Journal of Geophysical Research, v. 88, p. 4183–4214.

Chen, W.P., Chen, C.Y., and Nabelek, J.L., 1999, Present-day deformation of the Qaidam basin with implications for intra-continental tectonics: Tectonophysics, v. 305, p. 165–181, doi: 10.1016/S0040-1951(99)00006-2.

Clark, M.K., and Royden, L.H., 2000, Topographic ooze: Building the eastern margin of Tibet by lower crustal flow: Geology, v. 28, p. 703–706, doi: 10.1130/0091-7613(2000)28<703:TOBTEM>2.0.CO;2.

Coward, M.P., Kidd, W.S.F., Yun, P., Shackleton, R.M., and Hu, Z., 1988, Folding and imbrication of the Indian crust during Himalayan collision: Philosophical Transactions of the Royal Society of London Series A, v. 327, p. 89–116.

Cowgill, E., Yin, A., Harrison, T.M., and Wang, X.-F., 2003, Reconstruction of the Altyn Tagh fault based on U-Pb geochronology: Role of back thrusts, mantle sutures, and heterogeneous crustal strength in forming the Tibetan plateau: Journal of Geophysical Research, v. 108, p. 2346, doi: 10.1029/2002JB002080

Dang, Y., Hu, Y., Yu, H., Song, Y., and Yang, F., 2003, Petroleum geology of northern Qaidam basin: Beijing, Geological Publishing House, 187 p.

Dewey, J.F., Shackleton, R.M., Chang, C., and Sun, Y., 1988, The tectonic evolution of the Tibetan Plateau: Philosophical Transactions of the Royal Society of London Series A, v. 327, p. 379–413.

Dupont-Nivet, G., Robinson, D., Butler, R.F., Yin, A., and Melosh, H.J., 2004, Concentration of crustal displacement along a weak Altyn Tagh fault: Evidence from paleomagnetism of the northern Tibetan Plateau: Tectonics, v. 23, TC1020, doi: 10.1029/2002TC001397.

England, P., and Houseman, G., 1986, Finite strain calculations of continental deformation 2; Comparison with the India-Asia collision zone: Journal of Geophysical Research, v. 91, p. 3664–3676.

Guo, X.P., Wang, N.W., Ding, X.Z., Zhao, M., and Wang, D.N., 2006, Discovery of Paleogene palynological assemblages from the Wanbaogou Group-complex in western part of the Eastern Kunlun orogenic belt and its geological significance: Science in China Series D—Earth Sciences, v. 49, p. 358–367, doi: 10.1007/s11430-006-0358-9.

Hanson, A.D., 1998, Organic geochemistry and petroleum geology, tectonics and basin analysis of southern Tarim and northern Qaidam basins, northwest China [Ph.D. thesis]: Palo Alto, California, Stanford University, 316 p.

Harris, N.B.W., Xu, R., Lewis, C.L., Hawkeworth, C.J., and Zhang, Y., 1988, Isotope geochemistry of the 1985 Tibet Geotraverse, Lhasa to Golmud: Philosophical Transactions of the Royal Society of London Series A, v. 327, p. 263–285.

Huang, H., Huang, Q., and Ma, Y., 1996, Geology of Qaidam Basin and its petroleum prediction: Beijing, Geological Publishing House, 257 p.

Huo, G.M., ed., 1990, Petroleum geology of China: Oil fields in Qianghai and Xizang: Chinese Petroleum Industry Press, v. 14, 483 p.

Jolivet, M., Brunel, M., Seward, D., Xu, Z., Yang, J., Roger, F., Tapponnier, P., Malavieille, J., Arnaud, N., and Wu, C., 2001, Mesozoic and Cenozoic tectonics of the northern edge of the Tibetan plateau: Fission-track constraints: Tectonophysics, v. 343, p. 111–134, doi: 10.1016/S0040-1951(01)00196-2.

Jolivet, M., Brunel, M., Seward, D., Xu, Z., Yang, J., Malavieille, J., Roger, F., Leyreloup, A., Arnaud, N., and Wu, C., 2003, Neogene extension and volcanism in the Kunlun Fault Zone, northern Tibet: New constraints on the age of the Kunlun Fault: Tectonics, v. 22, p. 1052, doi: 10.1029/2002TC001428

Jordan, T.E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: AAPG Bulletin, v. 65, p. 2506–2520.

Kidd, W.S.F., and Molnar, P., 1988, Quaternary and active faulting observed on the 1985 Academia Sinica-Royal Society Geotraverse of Tibet: Philosophical Transactions of the Royal Society of London Series A, v. 327, p. 337–363.

Kong, X., Yin, A., and Harrison, T.M., 1997, Evaluating the role of pre-existing weakness and topographic distributions in the Indo-Asian collision by use of a thin-shell numerical model: Geology, v. 25, p. 527–530, doi: 10.1130/0091-7613(1997)025<0527:ETROPW>2.3.CO;2.

Li, S.L., Mooney, W.D., and Fan, J.C., 2006, Crustal structure of mainland China from deep seismic sounding data: Tectonophysics, v. 420, p. 239–252, doi: 10.1016/j.tecto.2006.01.026.

Li, Y.H., Wu, Q.J., An, Z.H., Tian, X.B., Zeng, R.S., Zhang, R.Q., and Li, H.G., 2006, The Poisson ratio and crustal structure across the NE Tibetan Plateau determined from receiver functions: Chinese Journal of Geophysics—Chinese Edition, v. 49, p. 1359–1368.

Lin, A.M., Guo, J.M., Kano, K., and Awata, Y., 2006, Average slip rate and recurrence interval of large-magnitude earthquakes on the western segment of the strike-slip Kunlun fault, northern Tibet: Bulletin of the Seismological Society of America, v. 96, p. 1597–1611, doi: 10.1785/0120050051.

Liu, Y.J., Genser, J., Neubauer, F., Jin, W., Ge, X.H., Handler, R., and Takasu, A., 2005, ^{40}Ar/^{39}Ar mineral ages from basement rocks in the Eastern Kunlun Mountains, NW China, and their tectonic implications: Tectonophysics, v. 398, p. 199–224, doi: 10.1016/j.tecto.2005.02.007.

Liu, Z.F., Wang, C.S., and Yi, H.S., 2001, Evolution and mass accumulation of the Cenozoic Hoh Xil basin, northern Tibet: Journal of Sedimentary Research, v. 71, p. 971–984.

Liu, Z.F., Zhao, X.X., Wang, C.S., Liu, S., and Yi, H.S., 2003, Magnetostratigraphy of Tertiary sediments from the Hoh Xil Basin: Implications for the Cenozoic tectonic history of the Tibetan Plateau: Geophysical Journal International, v. 154, p. 233–252, doi: 10.1046/j.1365-246X.2003.01986.x.

Liu, Z.Q., 1988, Geologic Map of the Qinghai-Xizhang Plateau and its Neighboring Regions: Beijing, Chengdu Institute of Geology and Mineral Resources, Geologic Publishing House, scale 1:1,500,000.

McKenna, L.W., and Walker, J.D., 1990, Geochemistry of crustally derived leucogranitic igneous rocks from the Ulugh Muztagh area, northern Tibet and their implications for the formation of the Tibetan Plateau: Journal of Geophysical Research, v. 95, p. 21,483–21,502.

Métivier, F., Gaudemer, Y., Tapponnier, P., and Meyer, B., 1998, Northeastward growth of the Tibet plateau deduced from balanced reconstruction of two depositional areas: The Qaidam and Hexi Corridor basins, China: Tectonics, v. 17, p. 823–842, doi: 10.1029/98TC02764.

Meyer, B., Tapponnier, P., Bourjot, L., Métivier, F., Gaudemer, Y., Peltzer, G., Shunmin, G., and Zhitai, C., 1998, Crustal thickening in Gansu-Qinghai, lithospheric mantle subduction, and oblique, strike-slip controlled growth of the Tibet plateau: Geophysical Journal International, v. 135, p. 1–47, doi: 10.1046/j.1365-246X.1998.00567.x.

Mock, C., Arnaud, N.O., and Cantagrel, J.M., 1999, An early unroofing in northeastern Tibet? Constraints from $^{40}Ar/^{39}Ar$ thermochronology on granitoids from the eastern Kunlun range (Qianghai, NW China): Earth and Planetary Science Letters, v. 171, p. 107–122, doi: 10.1016/S0012-821X(99)00133-8.

Molnar, P., Burchfiel, B.C., Zhao, Z., Lian, K., Wang, S., and Huang, M., 1987, Geologic Evolution of Northern Tibet: Results of an expedition to Ulugh Muztagh: Science, v. 235, p. 299–305, doi: 10.1126/science.235.4786.299.

Molnar, P., England, P., and Martinod, J., 1993, Mantle dynamics, the uplift of the Tibetan Plateau, and the Indian monsoon: Review of Geophysics, v. 31, p. 357–396, doi: 10.1029/93RG02030.

Neil, E.A., and Houseman, G.A., 1997, Geodynamics of the Tarim Basin and the Tian Shan in central Asia: Tectonics, v. 16, p. 571–584, doi: 10.1029/97TC01413.

Oxburgh, E.R., 1972, Flake Tectonics and continental collision: Nature, v. 239, p. 202–205, doi: 10.1038/239202a0.

Price, R.A., 1981, The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains, *in* Coward, M.P., and McClay, K.R., eds., Thrust and Nappe Tectonics: London, Geological Society Special Publication 9, p. 427–448.

Price, R.A., 1986, The southeastern Canadian Cordillera: Thrust faulting, tectonic edging, and delamination of the lithosphere: Journal of Structural Geology, v. 8, p. 239–254, doi: 10.1016/0191-8141(86)90046-5.

Qinghai, B.G.M.R., 1991, Regional Geology of Qinghai Province: Beijing, Qinghai Bureau of Geology and Mineral Resources, Geological Publishing House, 662 p.

Qiu, N., 2002, Tectono-thermal evolution of the Qaidam Basin, China: Evidence from Ro and apatite fission track data: Petroleum Geoscience, v. 8, p. 279–285.

Rieser, A.B., Neubauer, F., Liu, Y.J., and Ge, X.H., 2005, Sandstone provenance of north-western sectors of the intracontinental Cenozoic Qaidam basin, western China: Tectonic vs. climatic control: Sedimentary Geology, v. 177, p. 1–18, doi: 10.1016/j.sedgeo.2005.01.012.

Rieser, A.B., Liu, Y.J., Genser, J., Neubauer, F., Handler, R., Friedl, G., and Ge, X.H., 2006a, $^{40}Ar/^{39}Ar$ ages of detrital white mica constrain the Cenozoic development of the intracontinental Qaidam Basin: Geological Society of America Bulletin, v. 118, p. 1522–1534, doi: 10.1130/B25962.1.

Rieser, A.B., Liu, Y.J., Genser, J., Neubauer, F., Handler, R., and Ge, X.H., 2006b, Uniform Permian $^{40}Ar/^{39}Ar$ detrital mica ages in the eastern Qaidam Basin (NW China): Where is the source?: Terra Nova, v. 18, p. 79–87, doi: 10.1111/j.1365-3121.2005.00666.x.

Robinson, D.M., Dupont-Nivet, G., Gehrels, G.E., and Zhang, Y.Q., 2003, The Tula uplift, northwestern China: Evidence for regional tectonism of the northern Tibetan Plateau during late Mesozoic-early Cenozoic time: Geological Society of America Bulletin, v. 115, p. 35–47, doi: 10.1130/0016-7606(2003)115<0035:TTUNCE>2.0.CO;2.

Roger, F., Arnaud, N., Gilder, S., Tapponnier, P., Jolivet, M., Brunel, M., Malavieille, J., Xu, Z.Q., and Yang, J.S., 2003, Geochronological and geochemical constraints on Mesozoic suturing in east central Tibet: Tectonics, v. 22, 1037, doi:10.1029/ 2002TC001466.

Royden, L.H., Burchfiel, B.C., King, R.W., Wang, E., Chen, Z., Shen, F., and Liu, Y., 1997, Surface deformation and lower crustal flow in eastern Tibet: Science, v. 276, p. 788–790, doi: 10.1126/science.276.5313.788.

Sobel, E.R., Hilley, G.E., and Strecker, M.R., 2003, Formation of internally drained contractional basins by aridity-limited bedrock incision: Journal of Geophysical Research, v. 108, p. 2344, doi: 10.1029/2002JB001883

Song, T., and Wang, X., 1993, Structural styles and stratigraphic patterns of syndepositional faults in a contractional setting: Examples from Qaidam basin, northwestern China: AAPG Bulletin, v. 77, p. 102–117.

Sun, Z., Feng, X., Li, D., Yang, F., Qu, Y., and Wang, H., 1999, Cenozoic Ostracoda and palaeoenvironments of the northeastern Tarim Basin, western China: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 148, p. 37–50, doi: 10.1016/S0031-0182(98)00174-6.

Sun, Z.M., Yang, Z.Y., Pei, J.L., Ge, X.H., Wang, X.S., Yang, T.S., Li, W.M., and Yuan, S.H., 2005, Magnetostratigraphy of Paleogene sediments from northern Qaidam basin, China: Implications for tectonic uplift and block rotation in northern Tibetan plateau: Earth and Planetary Science Letters, v. 237, p. 635–646, doi: 10.1016/j.epsl.2005.07.007.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: American Journal of Science, v. 283, p. 684–721.

Tapponnier, P., Meyer, B., Avouac, J.P., Peltzer, G., Gaudemer, Y., Guo, S., Xiang, H., Yin, K., Chen, Z., Cai, S., and Dai, H., 1990, Active thrusting and folding in the Qilian Shan, and decoupling between upper crust and mantle in northeastern Tibet: Earth and Planetary Science Letters, v. 97, p. 382–403, doi: 10.1016/0012-821X(90)90053-Z.

Tapponnier, P., Xu, Z.Q., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., and Yang, J.S., 2001, Oblique stepwise rise and growth of the Tibet plateau: Science, v. 294, p. 1671–1677, doi: 10.1126/science.105978.

Taylor, M., Yin, A., Ryerson, F.J., Kapp, P., and Ding, L., 2003, Conjugate strike-slip faulting along the Bangong-Nujiang suture zone accommodates coeval east-west extension and north-south shortening in the interior of the Tibetan Plateau: Tectonics, v. 22, p. 1044, doi: 10.1029/2002TC001361.

van Der Woerd, J., Tapponnier, P., Ryerson, F.J., Meriaux, A.S., Meyer, B., Gaudemer, Y., Finkel, R.C., Caffee, M.W., Zhao, G.G., and Xu, Z.Q., 2002, Uniform postglacial slip-rate along the central 600 km of the Kunlun Fault (Tibet), from ^{26}Al, ^{10}Be, and ^{14}C dating of riser offsets, and climatic origin of the regional morphology: Geophysical Journal International, v. 148, p. 356–388, doi: 10.1046/j.1365-246x.2002.01556.x.

Wang, E., Xu, F.Y., Zhou, J.X., Wan, J.L., and Burchfiel, B.C., 2006, Eastward migration of the Qaidam basin and its implications for Cenozoic evolution of the Altyn Tagh fault and associated river systems: Geological Society of America Bulletin, v. 118, p. 349–365, doi: 10.1130/B25778.1.

Wang, F., Lo, C.H., Li, Q., Yeh, M.W., Wan, J.L., Zheng, D.W., and Wang, E.Q., 2004, Onset timing of significant unroofing around Qaidam basin, northern Tibet, China: constraints from $^{40}Ar/^{39}Ar$ and FT thermochronology on granitoids: Journal of Asian Earth Sciences, v. 24, p. 59–69, doi: 10.1016/j.jseaes.2003.07.004.

Wang, Q., and Coward, M.P., 1990, The Chaidam Basin (NW China): Formation and hydrocarbon potential: Journal of Petroleum Geology, v. 13, p. 93–112.

Xia, W., Zhang, N., Yuan, X., Fan, L., and Zhang, B., 2001, Cenozoic Qaidam basin, China: A stronger tectonic inversed, extensional rifted basin: AAPG Bulletin, v. 85, p. 715–736.

Yang, F., 1988, Distribution of the brackish-salt water ostracod in northwestern Qinghai Plateau and its geological significance, *in* Hanai, T., Ikeya, T., and Ishizaki, K., eds., Evolutionary biology of ostracoda: Shizuoka, Japan, Proceedings of the 9th International Symposium on Ostracoda, p. 519–530.

Yang, F., Ma, Z., Xu, T., and Ye, S., 1992, A Tertiary paleomagnetic stratigraphic profile in Qaidam basin: Acta Petrologica Sinica, v. 13, p. 97–101.

Yang, F., Sun, Z., Cao, C., Ma, Z., and Zhang, Y., 1997, Quaternary fossil ostracod zones and magnetostratigraphic profile in the Qaidam basin: Acta Micropalaeontologica Sinica, v. 14, p. 378–390.

Yin, A., and Harrison, T.M., 2000, Geologic evolution of the Himalayan-Tibetan orogen: Annual Review of Earth and Planetary Sciences, v. 28, p. 211–280, doi: 10.1146/annurev.earth.28.1.211.

Yin, A., Rumelhart, P., Cowgill, E., Butler, R., Harrison, T.M., Ingersoll, R.V., Cooper, K., Zhang, Q., and Wang, X.-F., 2002, Tectonic history of the Altyn Tagh fault in northern Tibet inferred from Cenozoic sedimentation: Geological Society of America Bulletin, v. 114, p. 1257–1295, doi: 10.1130/0016-7606(2002)114<1257:THOTAT>2.0.CO;2.

Yin, A., Chen, X., McRivette, M.W., Wang, L., and Jiang, W., 2008a, Cenozoic tectonic evolution of Qaidam Basin and its surrounding regions (part 1): The Southern Qilian Shan-Nan Shan Thrust Belt and Northern Qaidam Basin: Geological Society of America Bulletin, (in press).

Yin, A., Chen, X., McRivette, M.W., Wang, L., and Jiang, W., 2008b, Cenozoic tectonic evolution of Qaidam Basin and its surrounding regions (part 3): Structural geology, sedimentation, and tectonic reconstruction (in press).

Yuan, W.M., Dong, J.Q., Wang, S.C., and Carter, A., 2006, Apatite fission track evidence for Neogene uplift in the eastern Kunlun Mountains, northern Qinghai-Tibet Plateau: Journal of Asian Earth Sciences, v. 27, p. 847–856, doi: 10.1016/j.jseaes.2005.09.002.

Zhang, Y.C., 1997, Prototype of analysis of Petroliferous basins in China: Nanjing, Nanjing University Press, 434 p.

Zhao, J.M., Mooney, W.D., Zhang, X.K., Li, Z.C., Jin, Z.J., and Okaya, N., 2006, Crustal structure across the Altyn Tagh Range at the northern margin of the Tibetan plateau and tectonic implications: Earth and Planetary Science Letters, v. 241, p. 804–814, doi: 10.1016/j.epsl.2005.11.003.

Zhong, J.H., Wen, Z.F., Guo, Z.Q., Wang, H.Q., and Gao, J.B., 2004, Paleogene and early Neogene lacustrine reefs in the western Qaidam Basin, China: Acta Geologica Sinica—English Edition, v. 78, p. 736–743.

Zhou, J.X., Xu, F.Y., Wang, T.C., Cao, A.F., and Yin, C.M., 2006, Cenozoic deformation history of the Qaidam Basin, NW China: Results from cross section restoration and implications for Qinghai-Tibet Plateau tectonics: Earth and Planetary Science Letters, v. 243, p. 195–210, doi: 10.1016/j.epsl.2005.11.033.

Zhu, L.P., and Helmberger, D.V., 1998, Moho offset across the northern margin of the Tibetan Plateau: Science, v. 281, p. 1170–1172, doi: 10.1126/science.281.5380.1170.

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