Late Quaternary slip rates of the thrust faults in western Hexi Corridor (Northern Qilian Shan, China) and their implications for northeastward growth of the Tibetan Plateau

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ABSTRACT

We determined vertical components of slip rates of 0.22 ± 0.03 mm a⁻¹ for the Jiayuguan fault and 0.11 ± 0.03 mm a⁻¹ for the Jintanan Shan fault, which lie along the northeastern edge of the Tibetan Plateau and in the western Hexi Corridor (Northern Qilian Shan, China). We used structural investigations, air-photo imagery analysis, topographic profiling, optically stimulated luminescence (OSL) dating, and ¹⁰Be exposure dating. To quantify the slip rates along the faults, we identified and surveyed the well-preserved fault scarps, and we sampled quartz-rich pebbles and cobbles on fan surfaces and within ~2-m-deep pits to determine surface exposure ages and pre-depositional inheritance. Our slip rates pertain to the past ~115 ka. They are consistent with previous geological and GPS constraints that suggest ~115 ka. They are consistent with previous geological and GPS constraints that suggest ~115 ka. They are consistent with previous geological and GPS constraints that suggest ~115 ka. They are consistent with previous geological and GPS constraints that suggest ~115 ka. They are consistent with previous geological and GPS constraints that suggest ~115 ka. They are consistent with previous geological and GPS constraints that suggest ~115 ka. They are consistent with previous geological and GPS constraints that suggest ~115 ka. They are consistent with previous geological and GPS constraints that suggest ~115 ka.

INTRODUCTION

The collision between India and Eurasia has caused widespread late Cenozoic deformation in central Asia that is characterized by interactions among major strike-slip faults, numerous thrust or reverse faults, and active folds in the Tibetan Plateau and central Asia (e.g., Avouac and Tapponneur, 1993; Meyer et al., 1998; Molnar and Tapponneur, 1975; Tapponneur and Molnar, 1979; Tapponneur et al., 1990; Xu et al., 2010, Yin et al., 2007; Zhang et al., 2007). Some view the more than 1500-km-long Altyn Tagh fault (China) on the northern margin of the Tibetan Plateau, one of the most important strike-slip faults in Asia, as transferring a significant portion of the convergence between India and Asia into northeastward or eastward “extrusion” of Asian crust (e.g., Meyer et al., 1998; Tapponneur et al., 2001). Another view, however, regards the Altyn Tagh fault as terminating in the Qilian Shan and surroundings, where crustal thickening occurs (Burchfiel et al., 1987; Tapponneur et al., 1990; Zhang et al., 2007). How the Altyn Tagh fault ends, if it does, and therefore whether it participates in eastward transfer of material east of Tibet, remains controversial issues in regard to not only deformation along the northern margin of the Tibetan Plateau, but also large-scale continental deformation in general.

Along the northeastern margin of the Tibetan Plateau, the ESE-WNW-trending Hexi Corridor has developed between a series of thrust faults and folds (Fig. 1). Therefore, it can be viewed as either a foreland basin of the plateau (Chen and Lu, 2001; Hetzel et al., 2002, 2004a, 2004b; Min et al., 2002; Song et al., 2001; Yuan, 2003; Zheng, 2009; Zheng et al., 2013) or one of the Cenozoic sedimentary basins related to an eastward propagation of the Altyn Tagh fault (Métivier et al., 1998; Meyer et al., 1998; Tapponneur et al., 2001). The Hexi Corridor, 800 km long and 100–200 km wide, is also seismically active and has undergone convergence during the Neogene and Quaternary (Champagnac et al., 2010; Chen, 2003; Hetzel et al., 2002, 2004a, 2004b; Meyer et al., 1996, 1998; Tapponneur et al., 1990, 2001; Xu et al., 2010; Zheng, 2009; Zheng et al., 2013). The western end of the Hexi Corridor includes the Yumen and Jiuquan Basins, which are separated by the NNW-trending Jiayuguan fault (Figs. 1 and 2). The Yumen Basin is bounded on its northern side by the Altyn Tagh fault and the Hei Shan fault, on its southwestern side by the Northern Qilian Shan fault, and on its northeastern side by the Jiayuguan fault (Fig. 2). The Yumen Basin itself is subject to active deformation by slip on a series of southwest-dipping thrust or reverse faults that trend NNW, and therefore are almost perpendicular to the Altyn Tagh fault but oblique to the Qilian Shan (Fig. 2). Farther east, the Jiuquan Basin is bounded by the Northern Qilian Shan fault on the south and the easterly trending Jintanan Shan fault to the north. Unlike the Yumen Basin, however, the interior of this basin has not been deformed by active thrust or reverse faults (Figs. 1 and 2). What is the relationship between the shortening associated with the thrust faults in the Yumen Basin and the strike-slip movement along the Altyn Tagh fault? Does the Altyn Tagh fault terminate at the western end of the Hexi Corridor (in the Yumen Basin more specifically)?

If slip on the Altyn Tagh fault participates in extrusion of continental crust to the east, the rate of shortening near its eastern end should be less than the strike-slip rate. Accordingly, the...
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quantification of these rates provides a test of the hypothesized roles played by the Altyn Tagh fault (Fig. 1).

Several approximately E-W–trending faults are present east of the Altyn Tagh fault and extend for several hundred kilometers along a similar trend (Fig. 1). The Jintanan Shan fault is a prominent example, as it lies immediately east of the eastern end of the Altyn Tagh and Hei Shan faults. If left-lateral slip occurs on the E-W–trending Jintanan Shan fault, it may be viewed as the eastward continuation of the Altyn Tagh fault, which would imply that the Altyn Tagh fault may indeed be a continent-extruding strike-slip fault. Reverse or thrust slip on these E-W–trending faults, however, would suggest that they are probably related to north-northeastward growth of the Tibetan Plateau (Qilian Shan).

Figure 1. Active tectonics of the northeastern margin of the Tibetan Plateau. (A) Index map including a shaded digital elevation model (DEM) of the Tibetan Plateau and its adjacent regions. The blue dashed frame shows the region in B. (B) DEM shaded relief map of the northeastern margin of the Tibetan Plateau, including the western Qilian Shan, the west end of the Hexi Corridor, and adjacent regions. Locations of faults (Yuan, 2003; Zheng, 2009), as well as locations of previous neotectonic and active tectonic studies (Chen, 2003; Meyer et al., 1998; Hetzel et al., 2002, 2004b; Min et al., 2002; Tapponnier et al., 1990; Palumbo et al., 2009; Van der Woerd et al., 2001; Zheng, 2009; Zheng et al., 2013), are also indicated. White dashed rectangle shows the location of Figure 2. White line shows the location of Figure 8.

Figure 2. Geological map of the study area and its adjacent region (geological data simplified from GBGMR, 1989, and CIGMRCGS, 2004).
At the west end of the corridor, studies on active tectonics of the northern margin of Tibetan Plateau have continued for several decades with emphasis on the Altyn Tagh fault (Burchfiel et al., 1989; Cowgill, 2007; Cowgill et al., 2003, 2009; Gold et al., 2009, 2011; Mériaux et al. 2004, 2005; Seong et al., 2010; Tapponnier et al., 1990; Van der Woerd et al., 2001; Xu et al., 2005; Zhang et al., 2007) and the Qilian Shan (Champagnac et al., 2010; Chen, 2003; Gaudemer et al., 1995; Meyer et al., 1998; Hetzel et al., 2002, 2004a; Palumbo et al., 2009; Peltzer et al., 1988; Tapponnier et al., 1990; Zheng et al., 2004; Zheng, 2009). In this paper, we focus on thrust faults along the boundary of and within the Yumen Basin and along the northern boundary of the Jiuquan Basin (Figs. 1 and 2) to examine the spatial and temporal pattern of deformation near the easternmost terminus of the Altyn Tagh fault. We determine slip rates over a millennial time scale by combining fault-scarp measurements and cosmogenic exposure age dating in the westernmost Hexi Corridor. The approach that we took is similar to that of Hetzel et al. (2002, 2004a) and Champagnac et al. (2010).

GEOLOGICAL SETTING AND TECTONIC DEFORMATION OF THE JIUQUAN BASIN AND THE YUMEN BASIN

The Qilian Shan is located at the northeastern margin of the Tibetan Plateau and consists of several WNW-trending linear ranges that have been interpreted as crustal-scale ramp anticlines bounded by reverse faults (Burchfiel et al., 1989; Meyer et al., 1998; Taylor and Yin, 2009; Yin et al., 2007). As the Tibetan Plateau continues to grow northeastward, the ranges become younger toward the foreland of Hexi Corridor and its northern mountains (Bovet et al., 2009; Métiérier et al., 1998; Meyer et al., 1998; Palumbo et al., 2010; Zheng, 2009; Zheng et al., 2013). The Hexi Corridor consists of a series of northwesterly trending Cenozoic basins between the Qilian Shan and the Gobi-Alashan block (Fig. 1). Our study sites are located in the Yumen and Jiuquan Basins in the westernmost Hexi Corridor (Figs. 1 and 3), where a series of low mountain ranges, including the Kuantan Shan, Hei Shan, Jintanan Shan, and the Heli Shan, trend sub-parallel to the Qilian Shan (Fig. 1). The Jintanan Shan and Heli Shan are the outermost of these ranges and trend almost E–W. Along the northern margins of these two mountain ranges, reverse faults bound the cores of the ranges (Fig. 2). The Hei Shan and Jintanan Shan faults are dominated by slip with a reverse component, which was seldom mentioned in previous studies. Some studies, instead, regard these faults as northeastern extensions of the Altyn Tagh fault (Darby et al., 2005; Chen, 2003; Deng et al., 2003). Others conclude that the Altyn Tagh fault does not extend beyond the Kuantan Shan (Fig. 1) (Zhang et al., 2007; Zheng et al., 2013).

A number of authors have noted an eastward decrease in the left-lateral slip rate along the Altyn Tagh fault (e.g., Burchfiel et al., 1989; Mériaux et al., 2005; Meyer et al., 1996, 1998; Tapponnier et al., 1990; Xu et al., 2005; Zhang et al., 2007). The slip rate is 10 ± 2 mm a⁻¹ west of 95°E, decreasing to 1.4 ± 0.4 mm a⁻¹ near the east end of the fault (Zhang et al., 2007). Thus, the slip rate along the section of the Altyn Tagh fault that bounds the Yumen Basin on the northwestern side, 1.4 ± 0.4 mm a⁻¹ should either be accommodated by crustal shortening within the Yumen Basin or pass eastward as strike slip.

The Yumen Basin has been deformed internally. Seismic profiles across the Yumen Basin from petroleum exploration show a synclinal structure with the Qilian Shan thrust northward into the basin (GBGMR, 1989; Yang et al., 2007). The basin itself is also cut by several active faults that trend nearly perpendicular to the Altyn Tagh fault and oblique to the Qilian Shan and Hexi Corridor (Fig. 2).

Thrust slip on the Northern Qilian Shan fault, the range-front fault of the Qilian Shan, places the pre-Cenozoic rock exposed in the mountains on the Quaternary sedimentary rock of the Jiuquan Basin (Fig. 2). At the surface, the fault dips 65° southwestward (Zheng, 2009). No sign of strike-slip motion has been found along the entire strand of the fault. Zheng (2009) obtained a vertical slip rate of 0.4–1.0 mm a⁻¹, which

Figure 3. Geomorphic map of the Jiayuguan fault. (A) Digital elevation model (DEM) shaded relief map. Black square marks location of B. (B) High-resolution Thematic Mapper (TM) image along the middle segment of the Jiayuguan fault, coupled with geomorphological mapping from fieldwork in the studied area. The black lines across the scarp indicate two survey profiles with ~1 km length. The sample locations are shown (⁎ for the ¹⁰Be sample; □ for the optically stimulated luminescence [OSL] sample), as well as the modern floodplain and the orientations of photos in C and D. (C and D) Field photographs of the studied alluvial surfaces and the thrust fault scarp. (C) View of the main fault scarp and the offset alluvial surface. (D) View of the secondary fault scarp on the hanging wall.
results in 0.19–0.47 mm a\(^{-1}\) of horizontal shortening, given the 65° fault dip.

The Hanxia-Dahuanggou fault lies 15–20 km from the range front within the Yumen Basin (Fig. 2). The fault offsets alluvial fans to form a fault scarp ~1 m high. Trench exposures reveal a 30° dip to the southwest. Stream channels across the fault have not been offset laterally, suggesting negligible strike slip. Measurements of the displacement and \(^{14}\)C dating gave a vertical slip rate of ~0.25 mm a\(^{-1}\) (Min et al., 2002) that yields a horizontal shortening rate of ~0.43 mm a\(^{-1}\) for a 30° dip.

Hetzel et al. (2002) showed that the Yumen fault within the Yumen Basin (Fig. 2) has displaced a series of alluvial terraces. By measuring the offsets and dating the terraces with cosmogenic nuclides, they obtained a vertical slip rate of 0.35 ± 0.03 mm a\(^{-1}\). The fault dips 30°–60° to the southwest (Hetzel et al., 2002). We thus estimate a horizontal shortening rate of 0.18–0.66 mm a\(^{-1}\).

The Xinminpu fault, near the northern boundary of the Yumen Basin, trends northwest (315°–330°) (Fig. 2) and shows thrust slip. The fault offsets several alluvial terraces vertically with different amounts of displacement. Min et al. (2002) reported the vertical slip rate to be ~0.24 mm a\(^{-1}\) based on optically stimulated luminescence (OSL) dating of the displaced terraces. Given an ~30° dip of the fault, we estimate horizontal shortening at a rate of ~0.58 mm a\(^{-1}\).

The Yinwa Shan fault, another reverse fault, trends northwest (315°–330°) (Fig. 2) and dips southward at ~55°. Min et al. (2002) found that the fault offsets alluvial fans to form continuous scarps 2 m high. OSL dating of the displaced alluvial fans results in a vertical slip rate of 0.18 mm a\(^{-1}\) (Min et al., 2002). With a dip of 55°, the horizontal shortening rate is ~0.13 mm a\(^{-1}\).

The Hei Shan fault forms part of the northern boundary of the Yumen Basin. It strikes almost parallel to the Altyn Tagh fault (Fig. 2). Zheng (2009) found the fault to be a high-angle reverse fault that dips southward at ~70°. The fault displaces alluvial fans with 2–3-m-high fault scarps. Streams and alluvial ridges across the fault have not been deflected horizontally, suggesting that active left-lateral strike slip along the Altyn Tagh fault does not continue to the Hei Shan fault. Measurements of the heights of fault scarps and dating of the offset alluvial fans yield vertical slip rates of 0.2–0.3 mm a\(^{-1}\) (Zheng, 2009). For a 70° dip, the horizontal shortening rate would be 0.07–0.11 mm a\(^{-1}\).

Two major faults in the Yumen and Jiuquan Basins have not been studied. One, the Jiauyuguan fault, separates the Yumen Basin from the Jiuquan Basin (Fig. 2). The other, the Jintanan Shan fault, marks the eastern section of the northern boundary fault of the Jiuquan Basin. In the following we present detailed studies of Holocene slip rates along these faults and then discuss implications for active deformation associated with outward growth of the Tibetan Plateau.

**TOPOGRAPHIC SURVEYS AND SURFACE EXPOSURE AGES**

Along the front of the Qilian Shan in the Yumen and Jiuquan Basins, thrust faults are commonly covered by alluvial-fan and gravel deposits, but their positions can be inferred from topographic breaks in the landscape (e.g., Champagnac et al., 2010; Hetzel et al., 2002, 2004a; Taponnier et al., 1990). During field investigations, we identified coalesced alluvial fan systems along the front of the Qilian Shan and on both sides of the Hei Corridor. Massive sand and gravel deposits have been transported into the Hei Corridor, and therefore alluvial fans with different dimensions have been formed along the front of the Qilian Shan. After continued fault slip, sedimentation on hanging walls terminates, and rivers crossing the faults cut down into the fans to leave terraces along them. So, residual fan surfaces become ideal places to study fault slip rates.

We investigated two sites corresponding to abandoned alluvial fans that are offset by slip on thrust faults along the Beida He in the Jiuquan Basin (Fig. 1). These fan surfaces show little erosion as they have not been deeply incised by stream channels. We mapped faulted alluvial surfaces using various image data and field surveys, and we measured the fault displacements from topographic profiles using differential GPS surveys.

To constrain the ages of abandonment of alluvial surfaces, we used cosmogenic nuclide ages and the amalgamation method of Anderson et al. (1996). For each site, we took a large number (n > 50) of centimeter-size, quartz-rich pebbles at different depths in vertical profiles. Two profiles were sampled along with paleoseismic trenching sites. Quartz-rich pebbles were sampled on the surface and within ~2-m-deep pits or trenches. For each sample, pebbles were collected within a narrow depth range (5–10 cm; Table 1). Quartz extraction, usually after amalgamating more than 40 pebbles, was performed in the University of Colorado at Boulder facility (Crushing, Sieving, and Chemical Laboratory), following standard chemical cleaning and etching procedures, as well as liquid separation. Pure quartz samples were analyzed by inductively coupled plasma–optical emission spectrometry.

| Table 1. Location, Depth, and \(^{9}Be, ^{10}Be\) Concentration of Samples Used in This Study |
|---------|--------|---------|--------|---------|---------|--------|---------|
| Sample ID | Depth (cm) | Weight (g) | Weight SiO\(_2\) (mg) | Weight Be (atoms) | Be Error (10\(^{-6}\)) | Be Error (10\(^{-6}\)) | Be Error (10\(^{-6}\)) |
| 07-YH-001 | 0 | 17.35 | 0.2046 | 3.96E+07 | 6.65E+05 | 2.28E+06 | 4.38E+04 |
| 07-YH-003 | 45–55 | 25.91 | 0.2043 | 2.42E+07 | 4.98E+05 | 1.02E+06 | 2.04E+04 |
| 07-YH-004 | 75–85 | 34.82 | 0.2031 | 2.30E+07 | 6.09E+05 | 1.76E+06 | 3.53E+04 |
| 07-YH-005 | 110–120 | 44.73 | 0.2024 | 3.20E+07 | 1.09E+06 | 9.19E+05 | 1.84E+04 |
| 07-YH-007 | 195–205 | 69.72 | 0.2032 | 2.10E+07 | 3.18E+06 | 7.41E+05 | 1.48E+04 |
| 07-YH-016 | 0 | 15.57 | 0.2040 | 3.38E+07 | 7.64E+05 | 2.17E+06 | 4.35E+04 |

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To estimate ages from the concentrations at the surface, we used a low-elevation, high-latitude production rate of 51.1 atoms per year per gram of SiO$_2$ (atoms a$^{-1}$ g$^{-1}$ SiO$_2$) (Vermeesch, 2007). This rate was adjusted for elevation and latitude, following Stone’s (2000) formulation. The actual production rates are 18.97 and 14.59 atoms a$^{-1}$ g$^{-1}$ SiO$_2$ for Jiayuguan and the Jintan Shan, respectively. All of the calculations were performed using the Microsoft Excel calculator CosmoCalc (Vermeesch, 2007). Because the exposure ages are much less than the half-life of radioactive decay, the influence of that decay was ignored. We also included an uncertainty of 10% in the production rate during the calculation. Although the fans in the Hexi Corridor have developed over tens of thousands to perhaps millions of years, the gravel and sand layers on the tops of fans in the Jiayuan Basin were deposited by flowing water in a relatively short time, and subsequently the fans were incised and that deposition ended.

To obtain ages of the incised fan surfaces, we also dug pits into the alluvium and took OSL samples from the different fans that have been offset by thrust faults. We sampled at least two medium- to fine-grained sand samples from different layers within the range of 1–2 m depth in pits beneath the alluvial surfaces. The samples were processed in the OSL dating laboratory of the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences. Following the laboratory procedures for Chinese loess (Forman, 1991; Lu et al., 1988; Wang, 2006), the samples were extracted under subdued red light, and pretreated with 30% HCl and 30% H$_2$O$_2$ to remove the carbonates and organic material, respectively. The samples were then refined to a fine silt (4–11 μm) fraction, using sedimentation procedures based on Stokes’ Law. This poly-mineral size fraction was then immersed in H$_2$SiF$_6$ (30%) for 3 days in an ultrasonic bath to obtain the quartz component. The purity of the isolated quartz was checked by infrared (IR) stimulation. All measurements were performed using a Daybreak 2200 automated OSL reader equipped with a combined blue (470 ± 5 nm) and IR (880 ± 80 nm) LED unit, and a $^{88}$Sr/$^{86}$Y beta source for irradiation. All luminescence measurements were made at 125 °C with both beta source for irradiation. All luminescence ages are much less than the half-life of radioactive decay, the influence of that decay was ignored. We also included an uncertainty of 10% in the production rate during the calculation.
Jiayuguan Fault

The Jiayuguan fault strikes about 340°, almost perpendicular to the Altyn Tagh fault (Fig. 2). The fault forms scarps more than 20 m high and can be seen clearly on satellite images (Fig. 3). Field investigation revealed that the fault is a high-angle reverse fault and dips southwest. For example, in the trench excavation the fault dips ~80° to the southwest (Fig. 4A). The nearly vertical dip of the fault has been observed in many natural outcrops along the fault. Stream channels of different scales, from less than 1 m to more than 10 m wide, do not manifest any sign of strike-slip deflection across the fault, suggesting a negligible strike-slip component.

Our section of the fault lies near the Jiayuguan Pass, ~2 km to the west Jiayuguan city (Gansu Province), on the alluvial fan along the Beidahe River (Fig. 3A). Yang et al. (1998) identified and dated four terraces near this study area and 12 terraces in a region further upstream, with ages ranging from ca. 30 ka to ca. 150 ka. We chose this area because of the well-exposed alluvial surface cut by the Jiayuguan fault and the well-preserved fault scarps (Fig. 3). Quartz-rich pebbles were sampled on the surface and within an ~2-m-deep pit (Fig. 4B).

To determine the offset, we carried out a topographic survey of the alluvial surfaces with a differential GPS survey. We made two 1-km-long topographic profiles on the alluvial surface across the Jiayuguan fault (Figs. 3B and 4C). The actual offsets of the surfaces were calculated by projecting elevations onto a profile perpendicular to the fault. We distinguish another secondary fault scarp, presumably caused by a prehistoric earthquake, on the hanging wall (Fig. 3D). We obtained an age of 11.6 ± 0.5 ka based on OSL dating of sandy soil at the bottom of a wedge of collapsed material on the footwall of the fault (Fig. 4A; Table 2). Along different profiles, we obtained vertical displacements of 20.6 ± 1.5 m and 21.6 ± 2.0 m, with a mean of 21.1 ± 1.8 m for the main fault scarp (Fig. 4C). We also obtained vertical offsets of 2.9 ± 0.3 m, and 2.8 ± 0.2 m, with a mean of 2.85 ± 0.4 m on the secondary scarp above the hanging wall. So, we can determine that the hanging-wall surface is vertically separated by 24.0 ± 2.3 m from the footwall surface (Fig. 4C).

At this site, the distribution of 10Be with depth in a pit in the hanging wall suggests the superposition of two depositional sequences (Fig. 4B). This is consistent with the stratigraphy observed in the pit, which shows a ~50-cm-thick layer (Unit 1) mainly characterized by alluvial pebble deposits covering another layer (Unit 2) made of smaller alluvial pebbles. In the field, we also can distinguish two units because of the different colors and the different degrees of induration. Moreover, the interface between the units is marked by a thin layer of brown-yellow silt.

To obtain a slip rate on the Jiayuguan fault, we need to determine the age of the top surface of Unit 1. Because Unit 1 was deposited after abandonment of Unit 2, we first determine the best-fit equations of the concentration related to depth within Unit 2 to estimate the inheritance (Fig. 4D, Table 1):

\[
[\text{^{10}Be}(\text{g}^{-1})] = [1.37 \pm 1.95] \times 10^5 + (1.91 \pm 0.48) \times 10^6 \times e^{(0.0125 \times \text{cm})} \tag{2}
\]

and

\[
[\text{^{10}Be}(\text{g}^{-1})] = [1.81 \pm 1.44] \times 10^5 + (2.00 \pm 0.391) \times 10^6 \times e^{(0.0145 \times \text{cm})} \tag{3}
\]

using coefficients in the exponential term of −0.0125 cm⁻¹ and −0.0145 cm⁻¹, respectively. Here, z is the depth beneath the unconformity separating the two layers.

Let us assume that the upper layer Unit 1 was deposited instantaneously, at a time in the past, \(t_1\), prior to its deposition, the concentration in Unit 2, after an elapsed time, \(t_2\), with production rate at the surface, \(P\), and decay factor, \(\lambda\) ( = 0.0125 cm⁻¹ or 0.0145 cm⁻¹), would be

\[
[\text{^{10}Be}]_1 = [\text{^{10}Be}]_{\text{inherited}} + (P_1) e^{\lambda z} \tag{4}
\]

Then at time \(t_2\), the top layer, Unit 1, with thickness \(h\) was deposited on Unit 2. At present, the concentration of 10Be in Unit 1 would be given by

\[
[\text{^{10}Be}]_1 = [\text{^{10}Be}]_{\text{inherited}} + (P_2) e^{\lambda h + \lambda z} \tag{5}
\]

In this layer, \(z\) is negative. The present-day concentration in the lower layer Unit 2, after another elapsed time of \(t_2\), becomes

\[
[\text{^{10}Be}]_2 = [\text{^{10}Be}]_{\text{inherited}} + (P_2) e^{\lambda h + \lambda z} \tag{6}
\]

Collecting terms, this is

\[
[\text{^{10}Be}]_2 = [\text{^{10}Be}]_{\text{inherited}} + P(t_1 + t_2) e^{\lambda z} \tag{7}
\]

From the exponential fit of the bottom 4 samples, i.e., those in the lower layer (Fig. 4B), we infer an inherited concentration of 1.37 × 10⁶ atoms g⁻¹ for the case of \(\lambda = 0.0125\) cm⁻¹ (and 1.81 × 10⁶ for \(\lambda = 0.0145\) cm⁻¹). If we assume that the inheritance, [^{10}Be]_{\text{inherited}}, is the same for both layers, then the top of Unit 1 should have been abandoned at 107.3 ± 12 ka (or 105.0 ± 8.7 ka for \(\lambda = 0.0145\) cm⁻¹), calculated by using the concentration of 10Be in the surface sample (07-YH-016) and the inherited concentration of 1.37 × 10⁶ atoms g⁻¹.

Within Unit 2, the concentration of the topmost sample (07-YH-018) would be the sum of inheritance, production before deposition of Unit 1 (\(z = 10\) cm), and the consequent production after deposition of Unit 1 (at present depth of 60 cm), i.e.,

\[
[\text{^{10}Be}]_{\text{top}} = [\text{^{10}Be}]_{\text{inherited}} + P(t_2) e^{\lambda h + \lambda z} \tag{8}
\]

or

\[
P_1 = \frac{[\text{^{10}Be}]_{\text{top}} - [\text{^{10}Be}]_{\text{inherited}}}{P \cdot e^{\lambda h + \lambda z}} \tag{9}
\]

Because \(P_1 = [\text{^{10}Be}]_{\text{top}} - [\text{^{10}Be}]_{\text{inherited}} - (\text{^{10}Be}]_{\text{inherited}} e^{\lambda h + \lambda z}) / (P e^{\lambda h + \lambda z}) \tag{10}
\]

Here [^{10}Be]_{\text{top}} and [^{10}Be]_{\text{inherited}} are the concentrations for samples 07-YH-016 and 07-YH-018, respectively.

Substituting all known quantities into Equation 10, we finally get \(t_2 = 62.4 ± 2.9\) ka for \(\lambda = 0.0125\) cm⁻¹ (or 68.7 ± 3.0 ka for \(\lambda = 0.0145\) cm⁻¹). Therefore, Unit 2 was abandoned at 169.7 ± 12.3 ka (or 173.7 ± 10.2 ka).

Because there is only one sample in Unit 1, another possibility is that the upper 60 cm are sufficiently mixed to homogenize the sediment, and therefore 10Be concentrations. Alternatively, if the discontinuity in the deposits marked a very short pause during the sedimentation, and if we discarded sample 07-YH-018, the fit of the other concentration versus depth would suggest that the top of Unit 1 was abandoned at 92.9 ± 9.9 ka (for \(\lambda = 0.0125\) cm⁻¹) (Fig. 4D), -13% younger than our preferred two-layer calculations. Careful inspection in the field, however, indicated a separation of the two units at ~50 cm depth, and no clear evidence for mixing. Thus, we prefer our two-layer calculations because of the distinction of the two layers seen clearly in the field (Fig. 4C).

The sediment deposited on top of the abandoned alluvial fans should have a depositional age younger than the exposure age of Unit 2. To confirm the exposure age of Unit 2, we obtained an OSL dating age of 54.4 ± 3.5 ka in the old ground surface covered by the collapse wedge (Fig. 4A). The younger OSL age indicates that sandy soil above the old ground surface formed after the alluvial surface was abandoned.

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Jintanan Shan Fault

The Jintanan Shan fault follows the northern boundary of the Jiuquan Basin and trends ~100° along the northern range front of the Jintanan Shan (Fig. 2). This area offers well-preserved fault scarps (Figs. 5A and 5B) and quartz-rich pebble sites for cosmogenic dating (Figs. 5C, 5D, and 6D). The fault dips southward at ~68° in a trench exposure. The hanging wall consists of the Tertiary red beds that have been thrust atop the surface of the Gobi Desert to the north, and the footwall strata are composed of fluvial gravels and sands. In the field, we found two clear linear scarps with total heights of ~10 m on the alluvial fan (Figs. 5 and 6A). Stream channels across the fault scarps show no evidence of strike-slip motion,
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**Figure 5. Geomorphic and field map of the Jintanan Shan fault.**

(A) Enhanced Thematic Mapper (ETM) image displaying fault scarps and local structures at the middle segment of the fault. Black dashed square locates B. (B) High-resolution Thematic Mapper (TM) image at the studied area of the Jintanan Shan fault. Shown are four ~1-km-long scarp profiles (purple lines), as well as the sample locations (* for the \(^{10}\)Be sample; ¤ for the optically stimulated luminescence [OSL] sample), and orientations of photos in C and D. (C and D) Field photographs of the alluvial surfaces and the thrust scarp. (C) View of the northern fault scarp and the offset alluvial surface. (D) View of the southern fault scarp on the hanging wall. Note the importance of a flat remnant of the alluvial surface between the scarps, allowing a precise topographic survey.

suggesting that the fault is basically a high-angle reverse fault. In addition, we can correlate several surfaces across the scarps, allowing us to accurately determine vertical offsets (Figs. 5B and 6A).

We measured four 1.5-km-long topographic profiles of the alluvial surfaces across the Jintanan Shan fault with differential GPS surveys (Figs. 5B and 6A). On each profile, from east to west, we obtained vertical displacements on the northern scarp of 4.1 \(\pm\) 0.5 m, 3.3 \(\pm\) 0.4 m, 3.1 \(\pm\) 0.3 m, and 3.2 \(\pm\) 0.3 m, respectively, with a mean of 3.4 \(\pm\) 0.8 m (Fig. 6A). Vertical offsets on the southern scarp are 6.5 \(\pm\) 0.8 m, 8.5 \(\pm\) 0.8 m, 10.0 \(\pm\) 1.2 m, and 10.5 \(\pm\) 1.5 m, respectively, with a mean of 8.9 \(\pm\) 2.2 m (Fig. 6A). To minimize the uncertainty of total offset, we estimate the total values by extrapolating the surface north of the northern scarp to that south of the southern scarp, and obtained total vertical displacements of 10.5 \(\pm\) 0.7 m, 11.6 \(\pm\) 0.6 m, 13.0 \(\pm\) 0.8 m, and 13.4 \(\pm\) 0.9 m, respectively, with a mean of 12.1 \(\pm\) 1.5 m, which we use for the cumulated vertical offset (Fig. 6A).

The best-fit equations of the Be concentration as a function of depth (Fig. 6E; Table 1) for the Jintanan Shan site are

\[
^{10}\text{Be}(\text{g}^{-1}) = [1.62 \pm 0.782] \times 10^5 + (1.84 \pm 0.289) \times 10^5 \times e^{-(0.0125 \times \text{z}(\text{cm}))} \quad (11)
\]

and

\[
^{10}\text{Be}(\text{g}^{-1}) = [2.19 \pm 1.76] \times 10^5 + (1.88 \pm 0.370) \times 10^5 \times e^{-(0.0145 \times \text{z}(\text{cm}))} \quad (12)
\]

using coefficients in the exponential term of 0.0125 cm\(^{-1}\) and 0.0145 cm\(^{-1}\), respectively. This yields exposure ages of 126.4 \(\pm\) 21.2 ka and 128.5 \(\pm\) 26.5 ka, with corresponding apparent inheritance ages of 11.1 \(\pm\) 5.4 ka and 15.0 \(\pm\) 12.1 ka, respectively. Therefore, the corrected ages for the Jintanan Shan site are 115.3 \(\pm\) 21.6 ka and 113.5 \(\pm\) 28.8 ka. We also obtained an OSL age of 104.1 \(\pm\) 7.6 ka in the sand layer (corresponding to an old ground surface) at a depth of \(-75\) cm below the top alluvial surface (Fig. 6B and Table 2) and 57.4 \(\pm\) 3.2 ka in a fault collapse wedge at a depth of \(-120\) cm (Fig. 6C and Table 2). The age of the sand layer accords with the \(^{10}\)Be age of alluvial fan.

**SLIP RATES AND THEIR IMPLICATIONS FOR OUTWARD GROWTH OF THE NORTHEASTERN MARGIN OF THE TIBETAN PLATEAU**

**Slip Rate Determinations**

We use the vertical offset \((H)\) of an alluvial surface and its age of abandonment \((t)\) to determine the vertical component of a slip rate:

\[
\nu = \frac{H}{t} \quad (13)
\]

For the Jiayuguan fault, we use two groups of data to determine the slip rate, including a total displacement of 24 \(\pm\) 2.3 m with abandonment age of 107 \(\pm\) 12 ka on the alluvial surface and the offset of 2.9 \(\pm\) 0.4 m on the secondary scarp with the age of 11.6 \(\pm\) 0.5 ka on the fault collapse wedge. They yield 0.22 \(\pm\) 0.03 mm \(\text{a}^{-1}\) and 0.25 \(\pm\) 0.05 mm \(\text{a}^{-1}\), respectively. These two values agree with each other, within errors, but because of the greater uncertainty of the smaller offset, we use the value of 0.22 \(\pm\) 0.03 mm \(\text{a}^{-1}\) for the vertical component of the slip rate of the Jiayuguan fault. For the Jintanan Shan fault, we obtain 0.11 \(\pm\) 0.03 mm \(\text{a}^{-1}\) of vertical slip rate, by using \(H = 12.1 \pm 1.5\) m and \(t = 115.3 \pm 21.6\) ka (maximum age).

The Jiayuguan fault and Jintanan Shan fault have developed as part of the growth of the Tibetan Plateau. During this process, many thrust faults formed in the foreland of the Hexi Corridor and adjacent to the mountains on its northern margin. Our vertical slip rates of 0.22 \(\pm\) 0.03 mm \(\text{a}^{-1}\) during the past \(\sim 107\) ka for the Jiayuguan fault and 0.11 \(\pm\) 0.03 mm \(\text{a}^{-1}\) over the past \(\sim 115\) ka for the Jintanan Shan fault are consistent with geological and GPS constraints (Wang et al., 2001; Zhang et al., 2004; Zheng, 2009), suggesting that NNE-SSW shortening across the northeastern Tibetan Plateau is distributed on several active faults, each with a low slip rate of \(\leq 1\) mm \(\text{a}^{-1}\) (Chen, 2003; Hetzel et al., 2002, 2004a; Min et al., 2002; Palumbo et al., 2009; Tapponnier et al., 1990; Zheng, 2009; Zheng et al., 2013) (Fig. 7 and Table 3).
With these vertical components of slip rate and dip angles of 80° and 68° for the Jiayuguan and Jintanan Shan faults, we calculate horizontal shortening rates perpendicular to the faults to be 0.03–0.04 mm a⁻¹ and 0.04–0.05 mm a⁻¹, respectively. With these rates, we obtain estimates of shortening rates for all active faults in the Yumen and Jiuquan Basins (Fig. 7 and Table 3). (Note also that if dips at depth were 45°, horizontal and vertical components of slip would be the same.)

The Altyn Tagh fault strikes almost east-west along the northern margin of the Yumen Basin. The left-lateral strike-slip rate has been measured to be 1.4 ± 0.4 mm a⁻¹ (Xu et al., 2005; Zhang et al., 2007; Fig. 7). If the Altyn Tagh fault ends at the Yumen Basin, this amount of left slip must be absorbed by crustal shortening in the direction parallel to the fault (Fig. 7). We have mapped the strike of each active fault in the basin and determined its shortening rate. We can thus calculate the component of horizontal shortening parallel to the Altyn Tagh fault, 0.90–1.43 mm a⁻¹ (Fig. 7; Table 3), which agrees with the left-lateral strike-slip rate in the easternmost section of the fault. Moreover, if we assumed that at depth all faults dipped at 45°, that component...
The interpretation of seismic reflection profiles shows that the Quaternary sedimentary rock, such as the Yumen formation (early Quaternary) and Jiuquan formation (middle Quaternary), has not only been faulted, but also folded within the basin (Fig. 8). Although we cannot quantify easily the additional shortening associated with folding, it demonstrates that the shortening rate parallel to the Altyn Tagh fault of 0.90–1.43 mm a\(^{-1}\) is an underestimate. This observation, plus the additional component of shortening perpendicular to the Altyn Tagh fault, suggests that the deformation in the Yumen Basin results from a combination of the accommodation of strike slip on the Altyn Tagh fault and crustal shortening due to the northward growth of the Qilian Shan (Fig. 8).

**Implications for Outward Growth of the Tibetan Plateau**

High-angle reverse faulting without a left-lateral strike-slip component on the Jintan Shan fault suggests that this fault would not be the eastward continuation of the Altyn Tagh fault. The Altyn Tagh fault appears to extend west of the Jiyuguan fault (Fig. 2).

The highest elevation of the Jintan Shan is 130 m above the surface of the adjacent basin to the north (Fig. 2). The low range consists of Tertiary red beds. An unpublished near-surface shallow seismic reflection survey indicates that the Tertiary red beds lie ~30–40 m beneath the surface of the basin on the footwall north of the Jintan Shan fault. Thus the total vertical offset of the Tertiary red beds on the Jintan Shan fault is 160–170 m. If the slip rate on the Jintan Shan fault has been constant since initiation of faulting, the vertical slip rate of 0.11 ± 0.03 mm a\(^{-1}\) suggests an onset of Jintan Shan faulting at 1.5–1.6 Ma. Zheng (2009) suggested that the Heli Shan, a similar low range east of the Jintan Shan fault. Thus the total vertical offset of the Jintan Shan fault is 160–170 m. If the slip rate on the Jintan Shan fault has been constant since initiation of faulting, the vertical slip rate of 0.11 ± 0.03 mm a\(^{-1}\) suggests an onset of Jintan Shan faulting at 1.5–1.6 Ma. Zheng (2009) suggested that the Heli Shan, a similar low range east of the Jintan Shan fault, also initiated ca. 2 Ma (Fig. 1). It seems that the low ranges bounding the northern side of the Hexi Corridor basin started to form since ca. 2 Ma. Previous studies show that the shortening across the Qilian Shan began, or accelerated, near 10 Ma (Métiéry et al., 1998; Zheng et al., 2010). The Yumu Shan, the northernmost spur of the Qilian Shan, began to rise at 3.7 ± 0.9 Ma (Palumbo et al., 2009). The northward younging of crustal shortening suggests that the Tibetan Plateau has grown northward into the Gobi Alashan since ca. 2 Ma. To summarize, deformation in the Yumen Basin accommodates strike slip at the eastern end of the Altyn Tagh fault, and northward thrust slip of the Qilian Shan onto the basin also contributes to the shortening. The rise of the Jintan Shan and Heli Shan appears to reflect a northeastward growth of the Qilian Shan.

**CONCLUSIONS**

Using structural investigations, air-photo imagery, topographic profiling, OSL dating, and \(^{10}\)Be exposure dating, we estimate the vertical components of slip rates to be 0.22 ± 0.03 mm a\(^{-1}\) on the Jiyuguan fault during the past ~107 ka., and 0.11 ± 0.03 mm a\(^{-1}\) on...
TABLE 3. COMPILATION OF SLIP RATE DETERMINATIONS FOR THRUST FAULTS IN THE WESTERN HEXI CORRIDOR BASIN (JIUQUAN BASIN AND YUMEN BASIN) AND ITS ADJACENT REGIONS

<table>
<thead>
<tr>
<th>Fault</th>
<th>Location*</th>
<th>Slip rate perpendicular to the Altyn Tagh fault (mm a⁻¹)</th>
<th>Shortening rate parallel to the Altyn Tagh fault (mm a⁻¹)</th>
<th>Method of dating†</th>
<th>Age (ka)</th>
<th>Offset (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hanxia-Dahuangou fault</td>
<td>97.96 39.68</td>
<td>0.25</td>
<td>0.07</td>
<td>TL dating</td>
<td>3.20 ± 0.25</td>
<td>0.8</td>
<td>Min et al., 2002</td>
</tr>
<tr>
<td>North Qilianshan fault</td>
<td>98.47 39.51</td>
<td>0.55</td>
<td>0.03–0.04</td>
<td>TL dating</td>
<td>1.79 ± 0.58</td>
<td>T5: 14–17</td>
<td>Chen, 2003</td>
</tr>
<tr>
<td></td>
<td>98.02 39.75</td>
<td>0.35</td>
<td>0.20–0.35</td>
<td>OSL dating</td>
<td>3.59 ± 0.42</td>
<td>T6: 18–20</td>
<td>2 Min et al., 2002</td>
</tr>
<tr>
<td>Xinminpu fault</td>
<td>97.67 39.85</td>
<td>0.35</td>
<td>0.09–0.42</td>
<td>OSL dating</td>
<td>5.30 ± 0.58</td>
<td>T6: 18–20</td>
<td>3 Min et al., 2002</td>
</tr>
<tr>
<td>Jitanan Shan fault</td>
<td>97.88 39.98</td>
<td>0.11 ± 0.03</td>
<td>0.18–0.66</td>
<td>TL dating</td>
<td>10.64 ± 0.83</td>
<td>2 Min et al., 2002</td>
<td></td>
</tr>
<tr>
<td>Jiyuguan fault</td>
<td>97.67 39.85</td>
<td>0.22 ± 0.03</td>
<td>0.16–0.57</td>
<td>TL dating</td>
<td>5.43 ± 0.42</td>
<td>T4: 18</td>
<td>Min et al., 2002</td>
</tr>
<tr>
<td>Hei Shan fault</td>
<td>97.71 40.03</td>
<td>0.20–0.35</td>
<td>0.20–0.35</td>
<td>OSL dating</td>
<td>27.7 ± 1.5</td>
<td>T3: 16–21</td>
<td>Min et al., 2002</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.06–1.87</td>
<td>0.90–1.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Approximate location of each study site is given based on references. †These data are estimated from references and this study. §TL—thermoluminescence; OSL—optically stimulated luminescence. #T—terrace in the age and offset columns. The number of the lower right T is the order of terrace.

Figure 8. Tectonic section across the Qilian Shan, Yumen Basin, and Kuantan Shan. Geological and fault data from EPGY (1989), GBGMR (1989), Yang et al. (2007), and Gao et al. (1995).
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Zheng et al.