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

Zheng Wen-Jun¹, Zhang Hui-Ping¹, Zhang Pei-Zhen¹, Peter Molnar², Liu Xing-Wang³,⁴, and Yuan Dao-Yang³

¹State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China
²Department of Geological Sciences, and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado 80309, USA
³Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou 730000, China
⁴Key Laboratory of Western China’s Environmental Systems, Ministry of Education, Lanzhou University, Lanzhou 730000, China

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 that NNE–SSW shortening across the northwestern 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; Tappinonier 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; Tapponnier 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 NW, and therefore are almost perpendicular to the Altyn Tagh fault but oblique to the Qilian Shan (Fig. 2). Further 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)?

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 Tappinonier, 1993; Meyer et al., 1998; Molnar and Tappinonier, 1975; Tappinonier and Molnar, 1979; Tappinonier 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; Tappinonier 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; Tappinonier 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, remain 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; Tapponnier 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; Tapponnier 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 NW, and therefore are almost perpendicular to the Altyn Tagh fault but oblique to the Qilian Shan (Fig. 2). Further 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 Jintan 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 Jintan 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).

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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, 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; Métivier 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 northwest-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° southwesterly (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...
results in 0.19–0.47 mm a\(^{-1}\) of horizontal shortening, given the 65° fault dip.

The Hanxiao-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\(^{-1}\).

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.
Introduction of 10Be is largely negligible for the time as below this depth the post-depositional process which the exponential curve tends below ~2 m, with depth, 10Be concentration versus depth was provided an estimate of the production rate at the sample depth from the surface. The parameter $t$ gives an estimate of the production rate at the time since the alluvial fans deposition ended.

To quantify both a constant inheritance component and an exponential production decay with depth, $^{10}\text{Be}$ concentration versus depth was then fit with a general expression (Anderson et al., 1996; Farber et al., 2008):

$$[^{10}\text{Be}] = [^{10}\text{Be}]_{\text{inherited}} + (Pt) e^{-\lambda t}. \quad (1)$$

Here, $[^{10}\text{Be}]_{\text{inherited}}$ is the measured concentration of samples at different depths. The inheritance $[^{10}\text{Be}]_{\text{inherited}}$ is defined by the asymptote toward which the exponential curve tends below ~2 m, as below this depth the post-depositional production of $^{10}\text{Be}$ is largely negligible for the time range we consider (Burbank and Anderson, 2001). All of the amalgamated samples were used to determine the age of the surface exposure, instead of only the top-surface samples. The exponential term of the fitting function provides an estimate of the production rate at the surface ($P$) in the time since the alluvial fans were abandoned ($t$). The parameter $z$ donated the sample depth from the surface. The parameter $\lambda$ is the ratio of the attenuation length of the cosmogenic particle to the density of the material. For our present study, this factor was first chosen to be 0.0125 cm$^{-1}$, following Champagnac et al. (2010), to maximize the best fit for both profiles and to be consistent with previous studies using unconsolidated sediment (Brocard et al., 2003; Ritz et al., 2003). This corresponds to a sediment density of 2.0 g cm$^{-3}$ for an attenuation length of 160 g cm$^{-2}$ (Champagnac et al., 2010). For both sites, we also allowed this factor in the exponential term to be free, but best fits gave much different values (0.0286 cm$^{-1}$ for the Jiayuguan fault site and 0.0145 cm$^{-1}$ for the Jintanan Shan fault site). We reject the higher index (0.0268 cm$^{-1}$) because it corresponds to a density of unconsolidated sediments as large as 4.6 g cm$^{-3}$ for a characteristic length scale of 160 g cm$^{-2}$ (e.g., Brown et al., 1992). Therefore, we adopted 0.0145 cm$^{-1}$ (corresponding to a density of 2.3 g cm$^{-3}$ for 160 g cm$^{-2}$ length scale) as a second feasible index to determine ages and inheritance for both sites.

To estimate ages from the concentrations at the surface, we used a low-elevation, high-latitude production rate of 5.11 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 Jintanan 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 (Forster, 1991; Lu et al., 1995; 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 $^{85}$Sr/$^{87}$Y beta source for irradiation. All luminescence measurements were made at 125 °C with both IR and blue stimulation intensities at ~45 mW cm$^{-2}$. Luminescence emissions were detected by an EMI 9235QA photomultiplier and two 3 mm U-340 glass filters. All OSL dating results are listed in Table 2.
Jiayuguan Fault

The Jiayuguan fault strikes about 340°, almost perpendicular to the Altyn Tagh fault (Fig. 2). The fault forms scarpes 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 scarp (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 surface 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 1). 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 $^{10}$Be 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):

$$[^{10}\text{Be}](\text{g}^{-1})] = [1.37 \pm 1.95] \times 10^6 + (1.91 \pm 0.48) \times 10^4 \times e^{(0.0125 \times z_{\text{cm}})}$$

(2)

and

$$[^{10}\text{Be}](\text{g}^{-1})] = [1.81 \pm 1.44] \times 10^6 + (2.00 \pm 0.391) \times 10^4 \times e^{(0.0145 \times z_{\text{cm}})}$$

(3)

Using coefficients in the exponential term of $-0.0125 \text{ cm}^{-1}$ and $-0.0145 \text{ cm}^{-1}$, 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

$$[^{10}\text{Be}]_1 = [^{10}\text{Be}]_{\text{inherited}} + (P t_1) e^{-\lambda z}.$$  

(4)

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

$$[^{10}\text{Be}]_1 = [^{10}\text{Be}]_{\text{inherited}} + (P t_2) e^{-\lambda z}.$$  

(5)

In this layer, $z$ is negative. The present-day concentration in the lower layer Unit 2, after another elapsed time of $t_3$, becomes

$$[^{10}\text{Be}]_2 = [^{10}\text{Be}]_{\text{inherited}} + (P t_3) e^{-\lambda z} + (P t_1) e^{-\lambda h}.$$  

(6)

Collecting terms, this is

$$[^{10}\text{Be}]_2 = [^{10}\text{Be}]_{\text{inherited}} + P (t_3 + t_1) e^{-\lambda h}.$$  

(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 × 10$^6$ atoms g$^{-1}$ for the case of $\lambda$ = 0.0125 cm$^{-1}$ (and 1.81 × 10$^6$ for $\lambda$ = 0.0145 cm$^{-1}$). If we assume that the inheritance, $[^{10}\text{Be}]_{\text{inherited}}$, 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 $^{10}$Be in the surface sample (07-YH-016) and the inherited concentration of 1.37 × 10$^6$ 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.,

$$[^{10}\text{Be}]_{\text{top}} = [^{10}\text{Be}]_{\text{inherited}} + P t_1 e^{-\lambda z} + P t_2 e^{-\lambda h}.$$  

(8)

or

$$P t_1 = [^{10}\text{Be}]_{\text{top}} - [^{10}\text{Be}]_{\text{inherited}} - \frac{[^{10}\text{Be}]_{\text{top}} - [^{10}\text{Be}]_{\text{inherited}}}{P} e^{-\lambda h}.$$  

(9)

Because $P t_1 = [^{10}\text{Be}]_{\text{top}} - [^{10}\text{Be}]_{\text{inherited}}$, $t_1 = [^{10}\text{Be}]_{\text{top}} - [^{10}\text{Be}]_{\text{inherited}} - \frac{[^{10}\text{Be}]_{\text{top}} - [^{10}\text{Be}]_{\text{inherited}}}{P} e^{-\lambda h}$ / $P e^{-\lambda h}.$

(10)

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

Substituting all known quantities into Equation 10, we finally get $t_1 = 62.4 ± 2.9$ 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 $^{10}$Be 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.
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, and the footwall strata are composed of fluvial gravels and sands.
suggesting that the fault is basically a high-angle reverse fault. In addition, we can correlate several surfaces across the scarp, 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 north 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 south 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

\[
^{10}\text{Be} (\text{g}^{-1}) = [1.62 \pm 0.782] \times 10^{5} + [1.84 \pm 0.289] \times 10^{5} \times e^{-(0.025 + 0.289)t} \quad (11)
\]

and

\[
^{10}\text{Be} (\text{g}^{-1}) = [2.19 \pm 1.76] \times 10^{5} + [1.88 \pm 0.370] \times 10^{5} \times e^{-(0.045 + 0.370)t} \quad (12)
\]

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 $\sim 75$ 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 $\sim 120$ 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:

\[
\nu' = H/t. \quad (13)
\]

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 a$^{-1}$ and $0.25 \pm 0.05$ mm 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 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 a$^{-1}$ of vertical slip rate, by using $H \approx 12.1 \pm 1.5$ 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 a$^{-1}$ during the past $\sim 107$ ka for the Jiayuguan fault and $0.11 \pm 0.03$ mm 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 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...
Fault with unknown kinematics
Thrust fault
99°
98°

The interpretation of seismic reflection profiles shows that the Quaternary sedimentary rock, such as the Yumen formation (early Quaternary) and Jiuan formation (middle Quaternary), has not only been faulted, but also folded within the basin (Fig. 8). Although we cannot quantity 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 (or 1.6–22 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 Jintanan Shan fault suggests that this fault would not be the eastward continuation of the Altyn Tagh fault. The Altyn Tagh fault appears to end west of the Jiyuguan fault (Fig. 2).

The highest elevation of the Jintanan 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 Jintanan Shan fault. Thus the total vertical offset of the Tertiary red beds on the Jintanan Shan fault is 160–170 m. If the slip rate on the Jintanan Shan fault has been constant since initiation of faulting, the vertical slip rate of 0.11 ± 0.03 mm a⁻¹ on the Jiayuguan fault during the past ~107 ka., and 0.11 ± 0.03 mm a⁻¹ on the shortening rate across fault. Numbers represent the names of the faults: 1—Yumen fault; 2—Xinminpu fault; 3—Yinwashan fault.

CONCLUSIONS

Using structural investigations, air-photo imagery, topographic profiling, OSL dating, and ¹⁰Be 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 the northern side of the Hexi Corridor basin to form since ca. 2 Ma. Previous studies show that the shortening across the Qilian Shan began, or accelerated, near 10 Ma (Métivier et al., 1998; Zheng et al., 2010). The Yumu Shan, the northwestern 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 Jintanan Shan and Heli Shan appears to reflect a northeastward growth of the Qilian Shan.

Figure 7. Map showing slip rates on faults at the front of western Qilian Shan and Hexi Corridor. In addition to our results, we indicate slip-rate estimates of others (Min et al., 2002; Hetzel et al., 2002; Chen, 2003; Palumbo et al., 2009; Tapponnier et al., 1990; Zheng, 2009; Zheng et al., 2012). H—Horizontal slip rate; V—Vertical slip rate; S—Shortening rate across fault.
**TABLE 3. COMPILED 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 (mm a⁻¹)</th>
<th>Shortening 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 dating⁶</th>
<th>Age (ka)</th>
<th>Offset (m)</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>0.05</td>
<td>TL dating</td>
<td>3.20 ± 0.25</td>
<td>0.8</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>0.02–0.03</td>
<td>TL dating</td>
<td>T1: 7.29 ± 0.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td>98.42  39.57</td>
<td>0.4–1.0</td>
<td></td>
<td></td>
<td>OSL dating</td>
<td>T5: 16.32 ± 1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>99.21  39.22</td>
<td>0.45–0.50</td>
<td></td>
<td></td>
<td>OSL dating</td>
<td>T4: 8.08 ± 0.39</td>
<td></td>
</tr>
<tr>
<td>Yumen fault</td>
<td>97.67  39.85</td>
<td>0.35</td>
<td>0.09–0.42</td>
<td>0.03–0.14</td>
<td>¹⁰Be and ²⁶Al</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>110–120</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40–32</td>
<td></td>
</tr>
<tr>
<td>Jiyuguan fault</td>
<td>97.91  39.87</td>
<td>0.18</td>
<td>0.43</td>
<td>0.40</td>
<td>TL dating</td>
<td>10.64 ± 0.83</td>
<td>2</td>
</tr>
<tr>
<td>Jitian Shan fault</td>
<td>97.66  39.98</td>
<td>0.24</td>
<td>0.18–0.66</td>
<td>0.16–0.57</td>
<td>TL dating</td>
<td>5.43 ± 0.42</td>
<td>1.3</td>
</tr>
<tr>
<td>Xinminpu fault</td>
<td>98.57  39.98</td>
<td>0.11 ± 0.03</td>
<td></td>
<td></td>
<td>¹⁰Be</td>
<td>115.30 ± 21.63</td>
<td>12.1 ± 1.5</td>
</tr>
<tr>
<td></td>
<td>98.20  39.83</td>
<td>0.22 ± 0.03</td>
<td>0.26</td>
<td>0.24</td>
<td>¹⁰Be</td>
<td>107 ± 12</td>
<td>24 ± 2.3</td>
</tr>
<tr>
<td></td>
<td>98.71  40.03</td>
<td>0.20–0.35</td>
<td></td>
<td></td>
<td>OSL dating</td>
<td>27.7 ± 1.5</td>
<td>7–10</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.06–1.87</td>
<td>0.90–1.43</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).
Late Quaternary slip rates of the thrust faults in western Horizont (Northern Qilian Shan, China)

the Jintan Shan fault over the past ~115 ka. These rates are consistent with low rates determined for similar thrust faults at the front of the western Qilian Shan and in the west end of the Hexi Corridor (Hetzelt et al., 2002; Min et al., 2002; Zheng, 2009; Zheng et al., 2013).

All of these suggest that NNE-SSW shortening across the northeastern Tibetan Plateau is distributed on several active faults, each with a thrust rate of ≤1 mm a⁻¹.

GPS data and a balanced cross section across the western part of the Qilian Shan and Hexi Corridor reveal a shortening rate of ≤10 mm a⁻¹ (Metivier et al., 1998; Meyer et al., 1998; Yuan, 2003; Zhang et al., 2004; Zheng et al., 2013), which must be accommodated by slip on several active faults. We think that the decreasing slip rate on the eastern end of the Altyn Tagh fault and the low slip rates of these thrust faults are related. The total shortening rate of 0.90–1.43 mm a⁻¹ in the direction parallel to the Altyn Tagh fault in the Yumen Basin implies that the Altyn Tagh fault dies out in the Yumen Basin, and the left-lateral strike slip on it is indeed absorbed by deformation within the Yumen Basin. We infer that the Tibetan Plateau continues to grow northeasterward through the low-rate thrusting and fault deformation above thrust faults in the Hexi Corridor.

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