Transformation of displacement between strike-slip and crustal shortening in the northern margin of the Tibetan Plateau: Evidence from decadal GPS measurements and late Quaternary slip rates on faults

Zheng Wen-jun a,*, Zhang Pei-zhen a, He Wen-gui b, Yuan Dao-yang b, Shao Yan-xiu b, Zheng De-wen a, Ge Wei-peng a,b, Min Wei a

a State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China

b Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou 730000, China

A R T I C L E   I N F O

Article history:
Received 29 August 2011
Received in revised form 22 December 2011
Accepted 2 January 2012
Available online 12 January 2012

Keywords:
Deformation dissipation
GPS measurement
Geologic rates
Large strike-slip fault
Northern Tibetan Plateau

A B S T R A C T

Studies of Late Quaternary geological slip-rates and the GPS decadal slip-rates along the major strike-slip faults in the northern margin of the Tibetan Plateau show that slip-rates remain relatively constant along the middle sections of each fault and decrease rapidly toward the ends. Our recent studies suggest that the slip rates are low (<10 mm/yr) along the major strike-slip faults, i.e., Altyn-Tagh fault and Qilian-Haiyuan fault. West of 95°E, the slip rate on the Altyn-Tagh fault has been determined to be 8–12 mm/yr, and gradually decreases from 95°E eastward to about 1–2 mm/yr at the easternmost segment of the fault. The slip-rate of Qilian-Haiyuan fault is about 1–2 mm/yr near the Halahu Lake, near the western tip of the fault, then increases to a relatively constant value of 4–5 mm/yr in the Qilian area (101°E and eastward). Eastward, the fault merges into the NS trending Liupan Shan fault zone east of Haiyuan, and the slip rate drops to 1–3 mm/yr, or even lower. Our present observations on the variation and distribution of slip rates along the major strike slip faults indicate that slip on the Altyn-Tagh fault is mainly dissipated through internal deformation, by thrust faulting within the Qilian Shan and shortening within the adjacent Cenozoic basins. Left-lateral strike-slip on the Qilian-Haiyuan fault might be transformed into shortening and growth of the Liupan Shan to the east, and may also contribute partially to the deformation in the western Qilian Shan. In conclusion, the distribution of slip rates from both late Quaternary geological records and the current GPS observations suggest a decrease in slip rate, a redistribution of strain, and the transformation of displacement along the major strike slip faults into crustal shortening, basin formation and mountain uplift that characterize present-day deformation of the northern margin of the Tibetan Plateau.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Although slip on strike-slip faults does not affect the surface area of deforming regions, and hence the direct growth of mountain belts, these faults play important roles in continental deformation and mountain building by distributing deformation. In particular, strike-slip faults have been recognized as important structures during Cenozoic tectonic deformation of Asia including the formation and evolution of the Tibetan Plateau (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1976). One of important roles that strike-slip faults play is to accommodate relative motions among effectively rigid blocks in continental deformation (Mériaux et al., 2004, 2005; Peltzer et al., 1989; Replumaz and Tapponnier, 2003; Tapponnier et al., 1982, 2001). Because there is no or minor tectonic deformation within rigid blocks, the differential movements among rigid blocks mainly occur on their bounding strike-slip faults with large amounts of total slip and rapid slip-rates. Another potentially important role of strike-slip faults is to transfer crustal materials to redistribute crustal thickness within the same geological territory (Burchfiel et al., 1987; England and Molnar, 1997a, b; Royden et al., 1997; Zhang et al., 2007). How is slip distributed along a particular strike-slip fault? How is strike-slip displacements transformed or dissipated near its ends? How has strike-slip deformation been transformed into structures of different orientations, styles and degrees of activity? These questions are important in studies not only of continental deformation but also for behavior of strike-slip faults.

On the other hand, large-scale faults are often composed of many small faults or segments with different geometry and different degrees of activity, and are successively linked together during many episodes of fault activity (Burbank and Anderson, 2001; Cartwright et al., 1995; Corne and Machette, 1984; Dawers et al., 1993; Zhang et al., 1995; 2001). How is slip distributed along a particular strike-slip fault? How is strike-slip displacements transformed or dissipated near its ends? How has strike-slip deformation been transformed into structures of different orientations, styles and degrees of activity? These questions are important in studies not only of continental deformation but also for behavior of strike-slip faults.
et al., 1988, 1991). With regard to the slip distribution along a fault, model studies are used due to the lack of field observations. Through physical experiments, Dawers et al. (1993) show that slip increases rapidly from zero at one tip to about 1/3 of the length of the fault, increases very slowly to its maximum near the middle of the fault, then starts to decrease slowly to about 2/3 of the length of the fault, and then decreases rapidly again to zero at the other end. This arcuate-shape distribution agrees with field observations of co-seismic displacements and modeling results (Cartwright et al., 1995; Corne and Machtette, 1984; Dawers and Anders, 1995; Dawers et al., 1993; Pollard and Segall, 1987; Scholz et al., 1996). Transitions of displacements from one fault to another occur through pull-apart basin, push-ups, and en echelon, and other structures (Burbank and Anderson, 2001; Christie-Blick and Biddle, 1985; Deng et al., 1986a; Machtette et al., 1992a, 1992b; Wesson et al., 1975). At the ends of strike-slip faults, displacements either transform into contraction or extension along structures perpendicular to the fault or are dissipated through zones of broad distribution (Christie-Blick and Biddle, 1985; Deng et al., 1984, 1986a, 1986b; Keller et al., 1982; Zhang et al., 1991).

The northern margin of Tibetan Plateau is bounded by several large strike-slip faults and serves as a good example of interactions and transformations of faults with different orientations and senses of motion (Gaudemer et al., 1995; Meyer et al., 1998). The northern margin can be divided into three structural domains: the left-lateral strike-slip region dominated by the Altyn Tagh fault west of 95°E, the contraction and crustal shortening in the Qilian Shan, and again the left-lateral strike-slip region dominated by the Qilian-Haiyuan fault east of 101°E (Fig. 1). Two different models have been proposed to account for the deformation of the northern margin of the Tibetan Plateau. One of them emphasizes the extrusion of rigid blocks along the major strike-slip faults (the Altyn-Tagh and the Qilian-Haiyuan faults) with very large displacement and very high slip rates (Gaudemer et al., 1995; Lasserre et al., 1999, 2002; Mériaux et al., 2004, 2005; Meyer et al., 1998; Peltzer and Tapponnier, 1988). The other favors that internal deformation through interactions of crustal shortening, strike-slip motion, tectonic rotation, and mountain uplift accommodate the oblique outward growths of the Tibetan Plateau (Burchfiel et al., 1987, 1991; Molnar and Deng, 1984; Zhang et al., 1991, 2007). The two different views invoke different amounts, rates, and styles of deformation, and also predict different relationships between strike-slip faulting and crustal shortening (Zhang et al., 2007). Thus, the goal to understand the mechanism of continental deformation in the northern margin of the Tibetan Plateau is to understand slip distributions along the major strike-slip faults and the relations between strike-slip and crustal shortening.

Studies of active tectonics of the northern margin of Tibetan Plateau have continued for several decades with emphasis on the Altyn Tagh fault (Cowgill, 2007; Cowgill et al., 2003; Cowgill et al., 2009; Mériaux et al., 2004, 2005; Zhang et al., 2007), the Qilian-Haiyuan fault (Burchfiel et al., 1991; Lasserre et al., 1999, 2002; Li et al., 2009; Zhang et al., 1991), and the Qilian Shan (Champagnac et al., 2010; Gaudemer et al., 1995; Hetzel et al., 2002, 2004; Meyer et al., 1998; Tapponnier et al., 1990). These studies reveal wide-spread deformation including active reverse faults, strike-slip faults, active anticlines, basin subsidence, and mountain uplift. GPS measurements during the last two decades not only depict a pattern of regional deformation and slip rates along major faults, but also reveal variations of slip rates along major strike-slip faults that allow studies of slip distributions and translations between strike-slip faulting and crustal thickening (Gan et al., 2007; Wang et al., 2001; Zhang et al., 2004, 2007).

On the basis of field studies, we summarize previously published geological slip rates on the major active faults within the northern margin of the Tibetan Plateau. We also constrain the present-day slip rates along these faults through GPS measurements. Then we compare long-term geological rates with present-day geodetic rates to study the activity, behavior and slip distributions along the major active faults, and also to study structural transfers, slip interactions, and displacement accommodations among different active tectonic features with the aim of understanding mechanism of active deformation in northern margin of the Tibetan Plateau.

\[\text{Fig. 1. Map of Tibetan Plateau and adjacent region with the major active strike-slip and reverse faults. Modified after Tapponnier and Molnar (1976), 1:Qilian Shan; 2:Hexi Corridor Basin; 3:Longmen Shan.}\]
2. Slip rates of major active faults determined by GPS

The velocity field of tectonic deformation provides an important basis to understand the dynamic driving mechanism and is one of the keys to address the issues of Cenozoic deformation in Chinese mainland (England and Molnar, 1997a, 1997b; Hager et al., 1991; Molnar, 1988; Röydén et al., 1997). Measurements by the Global Positioning System (GPS) provide the high precision, great spatial coverage and near real-time quantitative data on crustal movements that reflect the current and transient activities of tectonic deformation. GPS measurements are also used to determine present-day slip rates along many active faults in the Tibetan Plateau (Gan et al., 2007; Meade, 2008; Shen et al., 2000, 2005; Thatcher, 2007; Zhang et al., 2003, 2004). In order to monitor tectonic deformation and seismic activity, many GPS stations have been set up on the both sides of the main active fault zones. Under the same reference frame, the slip rates on the fault can be determined by the velocity difference between the GPS observation stations on the both sides of the fault. We ignore the elastic deformation from the locked fault in discussion, and think that the deformation is very limited in a long period. Obviously, the slip-rate observed by GPS represents its current rate of the fault. Only when the slip-rate of the fault remains unchanged for a long time, will the current slip-rate be consistent with the long-term average slip rate of the active faults (Zhang et al., 2003). GPS data used in this paper are from Gan et al. (2007). The observational methods and data processing are described in detail by previous papers (Gan et al., 2007; Harkins et al, 2010; Niu et al., 2002; Shen et al., 2000, 2001; Wang et al., 2003a, 2003b; Zhang et al., 2004).

2.1. The Qilian-Haiyuan fault

Using early GPS data, previous studies estimated that the slip rate across the eastern segment of the Qilian Shan was 7.5 ± 1.5 mm/yr (Zhang et al., 2003, 2004) supporting the low slip rates obtained through geological methods. As more complete GPS data have become available (Gan et al., 2007), it is possible to obtain a more reliable slip-rate of the Qilian-Haiyuan fault. We constructed four profiles across the Qilian-Haiyuan fault from west to east (Profile A, B, C, D in Fig. 2). We show the shortening rates (left panels) perpendicular to the fault and the strike-slip rates (right panels) in Fig. 3.

Profiles A and B, which cross the whole Qilian Shan yield total crustal shortening rates of 7.5 ± 2.0 mm/yr and 5.6 ± 1.5 mm/yr (left chart of Fig. 3). This shortening is distributed throughout the Qilian Shan across a width of 200 to 250 km. Although velocity steps may be associated with active faults, an alternative view is that the velocity profile can better be approximated as a linear gradient across the Qilian Shan. The linear velocity gradient suggests relative homogeneous convergence across the whole mountains rather than major slip on a particular faults or structures (Left chart of Fig. 3a and b). To the east, shortening occurs mainly within a narrow zone (~40 km wide) between the Qilian-Haiyuan fault and the Zhongwei-Tongxing fault with a shortening rate of 2.3 ± 1.2 mm/yr (Left chart of Fig. 3c). Near the eastern end of the Qilian-Haiyuan fault zone, the convergence appears to be taken up entirely near the Haiyuan fault with shortening rate of about 2.6 ± 1.5 mm/yr (Left chart of Fig. 3d).

The strike-slip components of each velocity profiles are not distributed over a broad zone. Rather, slip on each profile appears to be localized along the major strike-slip fault, the Qilian-Haiyuan fault (Figs. 2 and 3). Fig. 3a (Right chart) shows that the strike-slip component on the Qilian-Haiyuan fault abruptly jumps from ~2.5 mm/yr along profile A by ~1.5 mm/yr to become ~1 mm/yr to the east, whereas rates remain negligibly small on other active faults inside the Qilian Shan. Similarly, we obtain left-lateral strike-slip rates across the Qilian-Haiyuan fault along profiles B, C, and D to be 4.0 ± 1.0, 3.6 ± 1.4, and 4.2 ± 1.5 mm/yr, respectively (Right chart of Fig. 3b, c, and d).

The overall pattern of shortening shows that rate of crustal shortening is the largest across the main part of the Qilian Shan (Profile A) which is also the widest portion of the mountain, and decreases eastward as does the width of the mountains. The distribution of shortening is also widest across the main portion of the Qilian Shan, and becomes gradually narrower eastward from more than 250 km in profile A to only a few km across the faults in profiles C and D (Fig. 3). Strike-slip components along each profile, however, are concentrated on the Qilian-Haiyuan fault regardless whether the mountain is wide or narrow (Fig. 3). It appears that the present-day deformation in northeastern margin of Tibetan Plateau is partitioned into crustal shortening distributed over the 200 km wide Qilian Shan and left-lateral strike-slip localized on the Qilian-Haiyuan fault itself (Figs. 2 and 3).

2.2. Altyn-Tagh fault

To obtain present-day velocity across the Altyn-Tagh fault, a GPS observation line was set up and occupied three times from 1994 to 2002 (Bendick et al., 2000; Wallace et al., 2004). The left lateral strike-slip rate is 9 ± 5 mm/yr. According to the GPS stations sparsely distributed over eastern and northern Tibetan Plateau, Chen et al. (2001) constrain the left lateral strike-slip rate to be 10 mm/yr, and the shortening rate is less than 5 mm/yr. Shen et al. (2001) used a GPS observation network along both sides of the eastern and central Altyn-Tagh fault to show its left lateral slip rate is about 9 mm/yr. More recently, Zhang et al. (2007) integrated all available GPS data from more than two decades in the region, and constrained the slip rate along the Altyn-Tagh fault to be 8–12 mm/yr west of 95°E, decreasing gradually eastward to 1–2 mm/yr. This updated GPS slip rate agrees with recent geological rates by various recent geological studies (Cowgill, 2007; Cowgill et al., 2009; Washburn et al., 2001; Zhang et al., 2007).

2.3. Other faults

Besides estimates based on the GPS rates along major faults, we also try to obtain slip rates along faults within and around the Qilian Shan and the Hexi Corridor. Because of the sparse distribution of the GPS stations across most of the faults, it is difficult to obtain reliable slip rates on most of the other faults. For faults within the Qilian Shan, shortening rates of ~1 mm/yr may be obtained on the faults such as the Northern Qilian Fault, the Northern Qaidam fault, and the Elashan fault, the Riyueshan fault, the Gulang fault and the Zhongwei fault. However, none of the faults shows any sign of measurable strike-slip component from GPS profiles.

3. Late Quaternary geological slip rates on faults

Slip rates and crustal shortening rates obtained from active tectonic research quantify the long-term and average rates of tectonic deformation. A fault slip-rate, especially since the late Quaternary, defines the most recent behavior of fault movement; meanwhile it also reflects the main features of the regional dynamics. In recent years, much qualitative and quantitative research have been carried out along the Altyn-Tagh fault and Qilian-Haiyuan fault, and concurrently some basic works have also been done within the Hexi corridor and the Qilian Shan (Burchfiel et al., 1991; Champagnac et al., 2010; Hetzel et al., 2002, 2004; Institute of Geology, SSB and Ningxia Seismological Bureau of China, 1990; Institute of Geology SSB and Lanzhou institute of seismology, SSB, 1993; Lasserre et al., 2002; Li et al, 2009; Meyer et al., 1996; Molnar et al., 1987; Peltzer et al., 1989; Tapponnier et al., 1990; The Group of The Altyn-Tagh Active Fault System, SSB, 1992; Van der Woerd et al., 2001; Xu et al., 2003; Zhang et al., 1988; Zheng, 2009; Zheng et al., 2012a, 2012b).
3.1. The Qilian-Haiyuan fault

The Qilian-Haiyuan fault is a major left-lateral strike-slip fault in the northern and northeastern margin of the Tibetan Plateau, and studies on this fault have been ongoing since the last century (Fig. 4) (Deng et al., 1986a, 1986b; Gaudemer et al., 1995; Lasserre et al., 1999; Li et al., 2009; Liu and Zhou, 1985; Liu-zeng et al., 2007; Ran et al., 1997; Zhang et al., 1988). The maximum horizontal displacement on the Haiyuan fault is 12–14.5 km (Burchfiel et al., 1991), and early estimates gave an average slip rate of 5–8 mm/yr (Institute of Geology, SSB and Ningxia Seismological Bureau of China, 1990). Burchfiel et al. (1991) and Zhang et al. (1988) estimated a Holocene slip rate of 8–10 mm/yr. Recently, Li et al. (2009) reevaluated slip rates along the Haiyuan fault using more advanced dating methods and more reliable displacement measurements, and obtain a refined Holocene left-lateral slip-rate of $4.5 \pm 0.5$ mm/yr. This latest result agrees with that observed by GPS and is also consistent with recent observations along other sections of the fault.

By dating the abandonment age of offset moraines, Lasserre et al. (1999) inferred that the left-lateral strike-slip rate is $19 \pm 5$ mm/yr on the Lenglongling fault and is $12 \pm 4$ mm/yr on the Laohu Shan fault. However, offset measurements and dating of river terraces suggest that the slip-rate is $4 \pm 5$ mm/yr on the Lenglongling fault and $4.4 \pm 0.4$ mm/yr on the Laohu Shan fault (He et al., 1994, 2000; Yuan et al., 1998). For the different slip rate, we reanalyzed the observation sites of Lasserre et al. (1999) and eventually found that not only the data sampling positions but also the measured displacements are disputable. Moreover, their rates are strictly upper bounds on rates, and lower rates are permitted. Hence we infer that these high slip rates are unreliable.

The Lenglongling fault is located in the middle segment of the Qilian-Haiyuan fault zone along the crest of the Qilian Shan (Fig. 5a). A stream across the Lenglongling fault has been offset left-
laterally. The stream has two levels of well developed terraces. The lower terrace T1 is about 1–2 m above the current channel bed, and the higher terrace T2 is about 2–3 m above the terrace tread of T1 (Fig. 5b). Both are strath terraces capped by more than 1 m of gravel with sandy lenses atop the bed-rock. A carbon-14 sample of organic material obtained about 1.4 m below the terrace tread T1 just above the bed rock strath, gives an age of 6955±85 years BP. (Kang et al., 1992), but other samples at shallower depths are younger (Fig. 5b). We interpret this age to date approximately the formation of lower terrace T1. In any case it postdates the formation of T2, and predates T1 by short elapsed time. The Lenglongling fault offsets terrace risers T2/T1 and T1/T0 (Fig. 5b). Total Station measurements show that the offsets of terrace riser T2/T1 and T1/T0 are about 35±3.5 m and 26±4 m, respectively (Fig. 5b). Since the formation age of lower terrace T1 postdates the abandon age of upper terrace T2, the offset of terrace T2/T1 divided by formation age of T1 gives a maximum slip rate of 5.0±0.1 mm/yr. On the other hand, the formation age of lower terrace T1 predates the abandon age of lower terrace T1, the offset of
terrace riser T1/T0 divided by formation age of T1 gives a minimum slip rate of 3.7 ± 0.1 mm/yr. Accordingly, the Holocene left-lateral slip rate of the Lenglongling fault can be constrained to 4.4 ± 0.7 mm/yr.

In the past, there have been fewer studies of the Halahu lake fault located in the western most part of the Qilian-Haiyuan fault, only that the faults that can be recognized on high-resolution satellite imagery (Gaudemer et al., 1995; Tapponnier et al., 2001; Yuan, 2003). Recent research of Yuan et al. (in review), however, shows that the slip rate of the Halahu lake fault segment is 1.6 ± 0.4 mm/yr, and the rate for Qilian segment is 4.7 ± 0.4 mm/yr. Fig. 4 shows all slip-rates estimates along the Qilian-Haiyuan fault from which we can conclude most estimates are concentrated between 4 and 6 mm/yr, except for the lower rate at the end of fault. Duvall and Clark (2010) suggest a similar change of slip rate along the Qilian-Haiyuan fault.

Many studies have discussed strike-slip rates on the Qilian-Haiyuan fault, but few have summarized vertical components of slip rates (and shortening rates). Our GPS results discussed above, however, show that the shortening rate perpendiculars to the faults are roughly equal to its horizontal strike-slip rates. This observation also explains the obvious crustal shortening on both sides of the fault.

Fig. 4. Distribution and slip rate on the Qilian-Haiyuan fault. In figure, we have indicated our result in this study and predecessor's slip rate in this study area and its adjacent region (Burchfiel et al., 1991; Gaudemer et al., 1995; He et al., 1994, 2000; Institute of Geology, SSB and Ningxia Seismic Bureau of China, 1990; Lasserre et al., 2002; Li et al., 2009; Yuan et al., in review; Zhang et al., 1988).

Fig. 5. Distribution of Lenglongling fault and faulted landforms. a. Distribution of the fault, modified from He et al. (2000). b. Total station map of the offset at the Ningchanyahuo and the TL sample profile. c. Estimates of slip rate calculations using the displacement of topography and corresponding ages.
3.2. The Altyn-Tagh fault

Dates of terraces above and below laterally offset terrace risers yield bounds on Quaternary slip rates along the Altyn-Tagh fault that range from those that agree with GPS measurements, to values as much as three times faster (Cowgill, 2007; Cowgill et al., 2009; Gold et al., 2009, 2011; Mériaux et al., 2004, 2005; Xu et al., 2003; Zhang et al., 2007). As argued by Zhang et al. (2007), the offset terrace risers that are protected by topography upstream of them are more closely dated by the age of the upper terrace than by that of the lower terrace. In some cases, valleys upstream of the fault have been incised into bedrock, and few if any terrace risers can be seen within the valleys. Such streams debouch onto alluviated floodplains or fans that become incised, presumably during climate changes, to create terrace risers. The terrace risers are then displaced so that they lie downslope from bedrock ridges on the upstream side of the fault, and thus the risers become protected from further incision. In such cases, dates of upper terraces should more closely approximate the ages of the risers than those of lower terraces. Such dates yield slip rates of ~10 mm/yr in the central segment of the fault and decreasing rates eastward (Gold et al., 2009, 2011; Zhang et al., 2007).

Although it is difficult with certainty to rule out higher slip rates along the Altyn-Tagh fault, analyses of relationships between river terrace formation and fault offset (Cowgill, 2007; Cowgill et al., 2009; Gold et al., 2009, 2011; Zhang et al., 2007) show that interpretations consistent with GPS measurements are more likely, at least along some segments of the fault.

Previous studies have paid little attention to the vertical component of slip on strike-slip faults. In fact, there are few pure strike-slip faults or pure thrust faults in nature. By inspecting the deformation of different geomorphic surfaces and dating, Van der Woerd et al. (2001) obtained the late Quaternary vertical rate on a thrust splay from the Altyn-Tagh fault of 4.1 ± 0.5 mm/yr, and concluded that about 5 mm/yr of shortening occurs nearly parallel to the Altyn-Tagh fault, so that the slip rate on it decreases rapidly to the northeast. Regardless of the reliability of their data, the development of thrust slip with a horizontal component parallel to the Altyn-Tagh fault requires a diminution in the slip rate along that fault.

How is the ~10 mm/yr convergence parallel to the fault accommodated? As noted by Meyer et al. (1996, 1998), coeval crustal shortening and strike-slip faulting occurring across almost the entire Qilian Shan testify to widespread deformation south of the Altyn-Tagh fault. The convergence parallel to the Altyn-Tagh fault manifests itself as internal deformation within the region south of the fault, the northeastern Tibetan Plateau. The total convergence rate (10.4 ± 3.2 mm/yr) across the mountain belt and parallel to the fault matches the slip rate decreasing along the fault from 90°E to 98°E. This compatibility implies that virtually all the slip along the Altyn-Tagh fault has been absorbed by convergence along the eastern segment of the Altyn-Tagh fault between longitudes 90°E and 98°E (Burchfiel et al., 1989; Tapponnier et al., 1990; Zhang et al., 2007).

3.3. Other faults

There are many active faults between the Altyn-Tagh and the Qilian-Haiyuan faults (Fig. 2). Our GPS analysis suggests that slip rates on virtually all of these faults do not exceed 1 mm/yr. Previous studies on some of these faults support the conclusion given by GPS data (Champagnac et al., 2010; Hetzel et al., 2002; 2004; Zheng, 2009). In the following, we will present a brief summary on the slip rate of these faults.

By surveying offset geomorphic surface and cosmogenic nuclide dating, Hetzel et al. (2002; 2004) determined that the vertical slip rate of the Yumen fault near the west end of the Hexi corridor is 0.35 ± 0.05 mm/yr, and that of the Zhangye fault in middle of the corridor is 0.64 ± 0.08 mm/yr. Chen (2003) determine that the average thrust rate of the Fodongmiao-Hongyazi fault in south margin of Jiuquan Basin is 0.55 mm/yr through dating of the offset terraces. Tapponnier et al. (1990) estimated that the thrust rate of the Yumu Shan fault is 0.4–1.9 mm/yr by surveying deformation of an alluvial fan. North of the central section of the Qilian-Haiyuan fault, Meyer et al. (1998) found that the thrust rate of the Huangcheng fault is 0.76 ± 0.06 mm/yr, and Zheng et al. (2004) obtained vertical slip rate of the Gulong fault is 0.16 ± 0.02 mm/yr. The highest slip rate of 2.8 ± 1.3 mm/yr was obtained by Champagnac et al. (2010) for an east–west trending fault northwest of the Gulong fault.

Few studies have been carried out on the faults within the Qilian Shan, especially in the western section of the Qilian Shan (Fig. 6). The Changma fault located in the western Qilian Shan is of sinistral strike-slip with a thrust component. Geomorphic features offset along the fault suggested a strike-slip rate of 3.3–4.3 mm/yr (Lanzhou institute of seismology, SSB, 1992). According to the latest field investigations, however, we think that the slip rate may be over-estimated because of its reliance on young geomorphic surfaces. In 2009, we carried out a topographic survey of offset stream channels on an alluvial fan (Fig. 7a and b). The Changma fault displaced alluvial fan surfaces of different ages. Two stream channels have been left-laterally beheaded by the Changma fault (Fig. 7c). Through restoration
of the beheaded stream channels, we obtain that average left-lateral displacement is 17.8 ± 0.6 m (Fig. 7d) and the height of fault scarp is about 3.5 m (Fig. 7e). The age of abandon of alluvial fan a2 has been estimated to be 12,000 to 15,000 years B.P. based on Carbon 14 dating (Lanzhou institute of seismology, SSB, 1992). The age of the abandon fan predates inceptions of the beheaded stream channels. We estimated minimum left-lateral slip rate of 1.17 ± 0.07 mm/yr and a relatively low ~0.25 mm/yr of thrust slip rate on the Changma fault.

Because of their remoteness, studies of the Danghe Nan Shan fault is limited. Van der Woerd et al., 2001 obtained the minimum thrust-slip rate of 4.1 ± 0.5 mm/yr by measuring the height of a high terrace and dating on the most western segment of Danghe Nan Shan fault, which is parallel to the Altyn-Tagh fault (Fig. 6). At another site of middle segment on the Danghe nan Shan Fault (Fig. 8), we measure the scarp height of 11.7 ± 1.5 m on Terrace T3 and 2.0 ± 0.5 m on Terrace T2 with a differential GPS. Although we have not obtained ages for this site, Wang et al. (2003a, 2003b) and Xiang et al. (2000) reported ages of ~9 kyr B.P. for T2 and ~25 kyr B.P. for T3 in this region. We use these ages to estimate the thrust-slip rate and gain 0.2–0.5 mm/yr on the middle segments of Danghe nan Shan fault (Fig. 8).

On the Yema Shan fault, we measured a left-lateral topographic map at Yangmengou (Fig. 9), and gain 13.0 ± 1.8 m and 15.1 ± 1.8 m of the offset of terrace risers T2/T1 with a differential GPS measurement. We also obtain OSL age of 3.3 ± 0.3 kyr B.P. on terrace T1 and 7.7 ± 0.9 kyr B.P. on terrace T2. So we obtained an average slip rate of 3.04 ± 0.9 mm/yr (Fig. 9). Slip on this fault accommodates part of the slip parallel to the Altyn-Tagh fault. We note that Luo (2010) gave a slip rate of ~2.8 mm/yr for the northern segment of Yema Shan fault.
East–west-trending fault zones are also present in the desert north of the Qilian Shan and the Hexi Corridor (Fig. 10). These faults trend parallel to the Altyn-Tagh fault, but are reverse faults without left-lateral strike-slip component (Zheng, 2009). Surveying and dating offset geomorphic surfaces on these faults allow us to estimate their Holocene slip-rates on different faults within this fault zone. The vertical slip rates are 0.22 ± 0.03 mm/yr for Jiayuguan fault (Zheng et al., 2012a), 0.11 ± 0.02 mm/yr for Jinta Nanshan fault (Zheng et al., 2012a) and 0.1–0.7 mm/yr for the South Helishan fault (Zheng et al., 2012b). In addition, Min et al. (2002) reported that the thrust-slip rates on the Yinwashan and Xinminpu faults in Jiuxi Basin are 0.18 mm/yr and 0.24 mm/yr, respectively. Several faults extending eastward into the Alashan block show no obvious late Quaternary activity (Fig. 10).

4. Discussion

4.1. Low slip rates along the major strike-slip faults

Slip on two major strike-slip faults, the Altyn-Tagh and Qilian-Haiyuan faults, dominates the overall pattern of deformation in the northeastern margin of the Tibetan Plateau. This is the reason why late Quaternary slip rates of these two faults are so important in testing geodynamic models of tectonic deformation of the plateau. Based on a comprehensive analysis by Zhang et al. (2007), slip rates on the western and central sections of the Altyn-Tagh fault vary within the range of 8–10 mm/yr, and then decrease rapidly near 95°E, and drop to less than about 2 mm/yr near the eastern end (Fig. 11). The slip rate on the western end of Qilian-Haiyuan fault is only 1–2 mm/yr, increases to 4.7 ± 0.4 mm/yr near Qilian (Fig. 4), maintains a rate of 4–5 mm/yr along the main section of the fault, and decreases to about 2 mm/yr at the eastern end of the fault zone (Figs. 4 and 10). The distribution of slip rates along the Qilian-Haiyuan fault illustrates well how slip on an intracratonic strike-slip fault is accommodated at its tips (Fig. 11), which is also consistent with the modeled relationship between the fault length and the slip distribution (Dawers et al., 1993). GPS slip rates along the two strike-slip faults show relationships similar to the geological slip rates (Fig. 11). The change on slip rate along strike-slip fault can be related to off-fault deformation (folding and secondary thrust faulting) and crustal shortening (formation basin and uplift mountain).

Another feature illustrated in Fig. 11 is how slip on one major strike-slip fault is transferred to another across a region of thrust faulting in the stepover between them (Fig. 11a). As mentioned above, left-lateral slip rates on the Altyn-Tagh fault decrease eastward from 95°E; this is also the place where coeval convergence and high terrain in the southern Qilian Shan become important. The majority of crustal shortening and convergence takes place across the Qilian Shan between 95°E and 100°E (Fig. 11a). This convergence ends north of the Northern of Qilian Shan fault at the eastern end of the Altyn-Tagh fault, where left-lateral slip approaches zero (Fig. 11b). A number of active reverse faults are present within the Qilian Shan, such as the northern Qaidam Basin fault (12), the Danghe Nan Shan fault (13), the Shule Nan Shan fault (14), the Changma fault (15), and...
(9), and the northern Qilian Shan fault (78) (Fig. 11b). Near their western ends, these faults contain minor left-slip components near their bifurcations from the Altyn-Tagh fault, and gradually become pure reverse fault eastward into the Qilian Shan (Meyer et al., 1998). This tectonic pattern suggests the faults within the Qilian Shan absorb and accommodate most of the strike-slip motion on the Altyn-Tagh fault. Certainly, Burchfiel et al. (1989) and Tapponnier et al. (1990) had also mentioned this tectonic pattern.

The slip distributions on the Qilian-Haiyuan fault even better illustrates how strike slip on main section of a fault is accommodated at its both ends (Fig. 11). Near the western end, with a 1–2 mm/yr left-lateral slip rate, the Qilian-Haiyuan fault seems to absorb strike-slip motion from the Altyn-Tagh fault. The main section maintains 4–5 mm/yr slip rates to its eastern end in the Liupan Shan where the left-slip is transformed into crustal shortening and contraction (Figs. 4 and 11).

Beyond the eastern end of the Altyn-Tagh fault, active faults within and in the north of the Hexi Corridor do not show evidence of left-lateral strike-slip, which, in turn, suggests that most of the left slip on the Altyn-Tagh fault has been translated to convergence within the Qilian Shan or to left slip on the Qilian-Haiyuan fault (Fig. 11). The active faults in the north of the Hexi Corridor do not define an eastward extension of the Altyn-Tagh fault. The Altyn-Tagh fault ends at the intersection with the Qilian Shan.

4.2 Slip dissipation and deformation transformation among faults in the northeastern margin of Tibetan Plateau

In order to study relative motion of various parts of the region, we first transfer our GPS data to a reference frame fixed to relative stable Gobi-Alashan block (Fig. 2), and then project the GPS components parallel to the Altyn-Tagh and Qilian-Haiyuan fault (Fig. 12). We use different symbols to denote GPS control points on different sides of the two faults (Fig. 12). Relative to the Gobi-Alashan block, velocity components parallel to the Altyn-Tagh fault in the Tarim Basin.
block vary within the velocity range from 0 to −2 mm/yr suggesting no relative motion among them within their uncertainties. North of the Qilian-Haiyuan fault in the Gobi-Alashan block, GPS velocity components parallel to the fault increase from −2 mm/yr to 2 mm/yr (Fig. 12). This large velocity gradient suggests a possible 2–4 mm/yr of extension parallel to the Qilian-Haiyuan fault within the Gobi-Alashan block. This extension might be associated with the bounding grabens on the Ordos Block, but how this extension is accommodated is unknown and remains to be studied in the future. South of the Qilian-Haiyuan fault within the Qilian Shan and northeastern margin of the Tibetan Plateau, velocity components parallel to the fault increase from about zero near western end of the fault to about 4–5 mm/yr in the middle section of the fault, and they remain this amount for the entire section, and then decrease in the eastern section to about 2 mm/yr near the eastern end of Liupan Shan (Xiang et al., 1998) (Fig. 12). This velocity pattern of present-day motion revealed by GPS data is similar to that denoted by late Quaternary slip distribution along the Qilian-Haiyuan fault (Fig. 11).

The slip dissipation and transformation along the two strike-slip faults fit the model of slip distribution along a fault (Dawers et al., 1993). In terms of strike-slip fault development, the maximum displacement and slip rate ought to occur along the central section of the fault rather than at its ends. The maximum displacement or slip rate in the central section has to be either dissipated near its ends into other forms of deformation or translated to slip onto another fault. The former would form either compressional or extensional structures at its terminations, and the later would form extensional or compressional stepovers between the two strike-slip faults. The shortening and contraction in the Liupan Shan are result from absorption of left-lateral strike slip on the Qilian-Haiyuan fault (Burchfiel et al., 1991; Zhang et al., 1991). The shortening and contraction in the Qilian Shan between 95°E and 100°E can be viewed as compressional stepovers between the Altyn-Tagh fault and the Qilian-Haiyuan fault. It is worth to notice that the scale of this compressional stepover is (more than 200 km) much larger than the thickness of the crust which is about 60 km. This implies that the primary role of strike-slip faults in the region may appear to redistribute crustal thickness within the Tibetan Plateau rather than extruding crustal blocks out of the plateau.

Moreover, the dominant characteristic of faults in Qilian Shan is thrust slip, and nearly all of the thrust-slip rates are less than ~1 mm/a, only a small number of the faults show significant sinistral strike-slip characteristics, which also supports the idea that the margin of the plateau is formed through relatively continuous deformation. The variation of GPS rates across the Qilian Shan obviously shows that the strain rate is relatively large inside the Qilian Shan and its northern margin, but it is close to zero in Hexi Corridor and Gobi-Alashan Block. The deformation occurs by localized crustal shortening and the deformation of Cenozoic basin on both sides at the narrow northern segment of Liupan Shan (Wang et al., 2011; Zheng et al., 2006). Fig. 13 further illustrates how the decrease in strike-slip rates occurs over a relatively wide area on the margin of the plateau. The width of Qilian Shan where shortening occurs is more than 200 km near the end of Altyn-Tagh fault, and similarly shortening and uplift of Longxi Basin and Liupan Shan are spread over a region about 300 km wide at the eastern end of Qilian-Haiyuan fault.

4.3. Deformation along major strike-slip fault and its implications

In the above discussions, we summarized the coincident variation of the slip-rate distribution along the two main boundary faults on the northern Tibetan Plateau. The slip rates rapidly decrease towards the end of fault. For the Altyn-Tagh fault, some previous studies had also concluded that the slip rate gradually decreases eastward (Burchfiel et al., 1989; Mériaux et al., 2005; Meyer et al., 1996, 1998; Tapponnier et al., 1990; Xu et al., 2003). Zhang et al. (2007) re-estimated the slip-rate of different locations along the Altyn-Tagh fault and re-confirmed the result of GPS observational rate. The slip rate along the Qilian-Haiyuan fault is an arc-shape distribution.
Kirby et al. (2007) obtained a similar distribution at the eastern end of the Kunlun fault; they showed that the slip rate in the middle section is ~10 mm/yr, and then decreases to <3 mm/yr to the east. These long-term geological rates are approximately coincident with the results of GPS observations over the past 10 years.

Tapponnier et al. (1990) inferred that the Altyn-Tagh fault is a boundary fault between rigid blocks, either its slip is transformed to another similar size fault, or it is dissipated by the end structure of fault. However, the distribution of GPS velocities does not support the conclusion that the Qaidam Basin to the south of the Altyn-Tagh fault behaves as a rigid block. Moreover, Meyer et al. (1996, 1998) once proposed that the crustal shortening and thrust deformation to the south of the Altyn-Tagh fault may be distributed within a relatively wide range from Qaidam Basin to the south margin of Gobi-Alashan block. In our previous summary, the slip-rate distribution along two sides of Altyn-Tagh fault and the Qilian-Haiyuan fault (Fig. 12) supports relatively static position of the Tarim Basin and the east–west tension of Gobi-Alashan block due to the stress distribution differences. The schematic drawing of Fig. 14 illustrates the characteristic of marginal strike-slip faults such that slip on the boundary faults are mainly absorbed and dissipated on the ends of the faults by means of mountain uplift, deformation or shortening of high mountains and within Cenozoic basins.

5. Conclusion

The late Quaternary geological slip-rates of the two primary boundary strike-slip faults and GPS velocities show that faults along the northern margin of Tibetan Plateau are dominated by relatively low slip rates (<10 mm/yr). The slip-rate of the Altyn-Tagh fault is steady at 8–12 mm/yr west of 95°E, but it decreases gradually eastward to 1–2 mm/yr at its easternmost segment. The Qilian-Haiyuan fault starts from Halahu Lake, where the slip-rate is 1–2 mm/yr. After increasing to a relatively steady at 4–5 mm/yr from Qilian city (101°E) to Haiyuan city, the slip-rate decreases to 1–3 mm/yr, or even lower where the fault passes Haiyuan city and merges into the Liupan Shan. The consistent distribution between the long-term (geological) slip-rate and short term (GPS observation) conform to the arc-shape slip-rate distribution finding and end dissipation mode proposed by Dawers et al. (1993). Slip is transformed and adjusted among these faults. It also indicates that differential structural deformation processes (uplift of mountains, basin shortening deformation, and development of thrust fault) near the end of faults dissipate and transform the major slip on strike-slip faults.

The GPS shortening velocity profiles across the West Qilian Shan show that the uplift (shortening) of the Qilian Shan may dissipates most of the slip of the Altyn-Tagh fault, and spatially, the Altyn-Tagh fault does not extend further northeastward beyond the Qilian Shan. The low slip rate of the Qilian-Haiyuan fault and the slip distribution along the fault also indicate that deformation of the Longxi basin and uplift of the Liupan Shan near the end of the fault are major units responsible for slip dissipation mode of 4–5 mm/yr sinistral strike-slip rate on the Qilian-Haiyuan fault. The faults are dominated by thrust slip in the northern Qilian Shan, within the Qilian Shan and in the northern Hexi Corridor. This finding further supports the view that crustal deformation is dispersed and absorbed by thrust faulting, crustal thickening, and locally high marginal mountains. The slow slip rate and the decrease in slip rate suggest toward the fault ends the boundary fault does not transfer a significant portion of the convergence between India and Asia out of India’s path into Eurasia, but merely redistributes crustal thickening.

Acknowledgments

We thank all the Global Positioning System field crews for collecting the high-quality data used in this paper. We would like to thank predecessors for a large amount of work on the structural characteristics and deformation. The research was supported jointly by the Fundamental Research Funds in Institute of Geology, CEA (IGCEA1014), the National Science Foundation of China (41172194,41030317) and the State Key Laboratory of Earthquake Dynamics (LED2008A01). We thank two reviewers (Peter Molnar and Jeff Freymueller) and editor (Liu Mian) for constructive comments that improved a previous version of the manuscript.

References


Fig. 13. GPS shortening rate across the western of the Qilian Shan and the northern of the Liupan Shan. The station in light blue rectangle would be used for estimating shortening-rate. Yellow limits are shortening and uplift area.

Fig. 14. Cartoon showing dissipation of slip along a strike-slip fault. Modified after Zhang et al. (2007).