Research Article

Nonrigid Bookshelf Kinematics of Northeastern Tibet: Constrains from Fault Slip Rates around the Qinghai Lake and Chaka-Gonghe Basins

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The Elashan fault (ELSF) and Qinghainanshan fault (QHNF), two major faults developed around the Qinghai Lake and Chaka-Gonghe basins, are of great importance for investigating the deformation model of the internal northeastern Tibetan Plateau. However, their late Pleistocene slip rates remain poorly constrained. In this study, we combine high-resolution topography acquired from unmanned aerial vehicles (UAV) and geomorphological dating to calculate the slip rates of the two faults. We visited the central ELSF and western QHNF and measured displaced terraces and stream channels. We collected 10Be samples on the surface of terraces to constrain the abandonment ages. The dextral slip rate of the central segment of the Elashan fault is estimated to be $2.6 \pm 1.2$ mm/yr. The uplift rates since the late Pleistocene of the Elashan and Qinghainanshan faults are $0.4 \pm 0.04$ mm/yr and $0.2 \pm 0.03$ mm/yr, respectively. Comparing the geological rates with the newly published global positioning system (GPS) rates, we find that the slip rates of the major strike-slip faults around the Qinghai Lake and Chaka-Gonghe basins are approximately consistent from the late Pleistocene to the present day. The overall NE shortening rates by summing up the geological slip rates on major faults between the East Kunlun and Haiyuan faults are $\sim3.4$ mm/yr, smaller than the geodetic shortening rates ($\sim4.9$ to 6.4 mm/yr), indicating that distributed deformation plays an important role in accommodating the regional deformation. By analyzing the geometrical and kinematic characteristics of the major faults surrounding the basins, we suggest that the kinematic deformation of the internal northeastern Tibet is a nonrigid bookshelf model that consists of counterclockwise rotation ($\sim0.8°$ Myr$^{-1}$) and distributed thrusting.

1. Introduction

The northeastern Tibetan Plateau experienced intensive deformation during the late Cenozoic in response to the northward motion of the Indian plate with respect to Eurasia [1–7]. Two different end-member kinematic models have been proposed to explain the regional deformation: the model of lateral crustal extrusion and left-lateral simple shear. Lateral crustal extrusion, deduced from high slip rates (10-30 mm/yr) on the major left-lateral faults including the Altyn Tagh fault (ATF), Haiyuan fault (HYF), and East Kunlun fault (EKLF), states that northeastern Tibet moves eastward as a rigid block with no internal deformation and rotation [8–14]. The left-lateral simple shear model suggests that the kinematics of northeastern Tibet can be explained by a combination of rotation and shortening within the blocks with little crust materials moving eastward [15–25]. England and Molnar [21] suggest that the crustal blocks within the large left-lateral faults are a manifestation of north-striking right-lateral simple shear zone and may rotate.
clockwise at 1-2 deg/Myr. Based on England and Molnar [21], Zuza and Yin [24] proposed nonrigid bookshelf rotation to explain how the major left-slip faults and thrust belts accommodate the deformation in northeastern Tibet. Similar bookshelf rotation has also been applied to explain the deformation kinematics of Iran [26]. However, the style and magnitude of the deformation in northeastern Tibet vary considerably along major strike-slip faults. A simple, uniform nonrigid bookshelf model cannot adequately explain them all. The secondary tectonic structures between the major strike-slip faults are key to understand the kinematic model of the internal northeastern Tibet.

The Qinghai Lake and Chaka-Gonghe basins are small blocks developed between the HYF and the EKLF. The Elashan fault (ELSF), Riyueshan fault (RYSF), Qinghannanshan fault (QHNF), and Gonghenanshan fault (GHNF) around the basins are secondary tectonic structures developed under NE compression and dextral shear [22, 27]. If the nonrigid bookshelf model is correct, we would expect counterclockwise rotation and consistent right-lateral strike slip along the major strike-slip faults. There are two common ways to quantify tectonic rotation, paleomagnetism and global positioning system (GPS). Due to the difficulty of collecting paleomagnetic samples and the short-time GPS observations relative to the presumably low rotation rate, the rotation rate has not been determined [28–35]. Obtaining the slip rates of the major strike-slip faults can be used as an indirect method to constrain the rate of rotation. Displaced alluvial landforms show right-lateral slip of the ELSF and RYSF, and the rates were constrained to be ~1.2 mm/yr since the late Pleistocene [25, 36]. However, the geological slip rates are inconsistent with the predicted rates of ~2-5 mm/yr from block modeling [33, 35, 37]. Based on the nonrigid block model, the material does not move eastward, but it must go somewhere within the basins. The shortening rates of the Qinghannanshan fault (QHNF) and Gonghenanshan fault (GHNF), the major thrust faults within the basins, provide additional information about how the region deforms [38, 39]. Therefore, investigating the rates and distribution of the major active faults is vital for understanding the kinematics of regional deformation. However, due to a lack of accurate geomorphic dating results and high-resolution topographic data, the rates of the active faults around the Qinghai Lake and Chaka-Gonghe basins remain some poorly constrained.

Reliable estimates of fault slip rates depend on accurate determination of offset geomorphic features including their displacements and ages. Advancement in remote sensing and geomorphological dating techniques in the past decade enables us to better quantify fault slip rates [40–43]. High-resolution digital elevation models (DEMs), derived from Structure-from-Motion (SfM), have improved our ability of identifying offset piercing lines significantly [44–46]. In northeastern Tibet, in situ cosmogenic nuclide 10Be dating has been demonstrated as an effective method for determining the abandonment age of alluvial fan and terraces [47–51]. In this study, we obtain high-resolution DEMs from unmanned aerial vehicles (UAV), based on which we measure the horizontal and vertical offsets recorded on the faults using two self-developed MATLAB-based graphical user interfaces (GUIs)—“PointFit” and “FaultRecovery” tools. Combined with cosmogenic nuclide 10Be dating results, we recalculated the lateral and vertical slip rates of the ELSF, and the vertical slip rates of the QHNF. Based on previous studies of fault slip rates and newly published GPS velocities around the basins, we further discuss the kinematic deformation of the internal northeastern Tibet.

2. Active Tectonics around the Qinghai Lake and Chaka-Gonghe Basin

The Qinghai Lake and Chaka-Gonghe basins are located in the center of northeastern Tibet. They are bounded by a series of faults (Figure 1), many of which are seismically active during the late Pleistocene to the Holocene [52]. The region is characterized by simple shear as a result of left-lateral motion on the Haiyuan and East Kunlun faults [21, 22, 27]. The HYF, the northern boundary of the Qinghai Lake basin, striking towards 100° to 105°, is ~1000 km long. The late Pleistocene slip rates of the central segment of the HYF is 5-8 mm/yr [49, 50, 53–55] (Figures 1 and 2), and the rates gradually decrease to 1-2 mm/yr towards the NW, where the fault ends in the east of the Hala Lake [56]. The southern boundary of Chaka-Gonghe basin is the East Kunlun fault (EKLF), nearly parallel to the HYF, with a total length of ~1200 km. Since the late Quaternary, the EKLF has also been characterized by strong sinistral motion, and the rates decreased from ≥10 mm/yr to <2 mm/yr at the tip of its eastern segment [57–61] (Figures 1 and 2).

The western boundary, the Elashan fault (ELSF), separating the Qaidam, Qinghai Lake, and Chaka-Gonghe basins, is a 200+ km long dextral strike-slip fault with thrust motion. It consists of several subparallel fault strands in right- or left-stepping en echelon arrangements [36] (Figure 2). Some small pull-apart basins developed between the right-stepping segments. Yuan et al. [36] suggested that the fault ends in zones of thrust faulting at both ends that are under NE compression. Nonetheless, Cheng et al. [25] suggested that the northern end is characterized by horse-tail splay, indicating an extensional environment. In the central part of the ELSF, geomorphic features such as stream valleys and alluvial terrace risers are well preserved and show evident dextral and vertical motion. The horizontal and vertical slip rates were constrained to be ~1.1 mm/yr and ~0.15 mm/yr, respectively, since the late Quaternary [36].

The Riyueshan fault (RYSF) forms the eastern boundary of the Qinghai Lake and Chaka-Gonghe basins. It has a similar geometry to the ELSF (Figure 2). The fault can be divided into the southern and northern segments at ~36N. Limited by the extreme weather and traffic conditions, the southern segment (south of the Guide basin) is poorly studied. The lateral slip rate of the northern segment was estimated to be ~1.2 mm/yr [25, 36], and the vertical slip rate is ~0.24 mm/yr [27]. Developed at the southern end of the northern segment of the RYSF, the Laji Shan and West
Qinling faults were also considered to remain active since the late Pleistocene [62–64] (Figure 2). There are also a group of thrust faults developed around the Qinghai Lake and Chaka-Gonghe basins. The Qinghaian Shan fault (QHNF) and Gonghe Nan Shan fault (GHNF) are the major components. Both faults, trending approximately NWW, terminated at the ELSF (west) and RYSF (east) [39]. A series of fault scarps have been found on the late Quaternary alluvium fans and terraces along the western segment of the QHNF [65]. Combined with cosmogenic nuclide 10Be abandonment ages of a displaced alluvial fan, the shortening rate of the QHNF was calculated to be ~0.1 mm/yr since the late Pleistocene [39]. The vertical slip rate of the GHNF during the late Pleistocene is unknown. Restoration of shortening along balanced cross-sections and growth strata suggests that the late Cenozoic shortening rates of the QHNF and GHNF are ~0.2 mm/yr and 0.7 mm/yr, respectively [39]. The similar rates during different periods indicate that the Chaka-Gonghe basin has gone through stable NE shortening since the late Cenozoic. The low slip rates of the QHNF and GHNF are also supported by their low seismicity. Historical earthquake catalogue shows that there are no earthquakes with M ≥ 7, and only 6 earthquakes with M ≥ 6 around the region in the past 100 years (Figure 1).

3. Geomorphic Analysis Based on High-Resolution Topographic Data

3.1. Acquisition of High-Resolution DEMs Using UAV. High-resolution topographic data are important for geomorphic analysis, such as identification of alluvial landforms and measurements of offset features [66]. To obtain high-quality DEMs, we used a quadcopter Motaor-Sky MS670 unmanned aerial vehicle (UAV) at three field sites, ELS1, ELS2, and QHNS (see Figure 2 for locations). The UAV is equipped with a SONY ILCE-QX1 lens camera (20 MPix) with a focal length of 16 mm. Previous research has suggested that the overlap of adjacent images should be no less than 60% [67]. The forward overlap should be 60%–80%, and the side overlap should be within 15%–60% [68]. In our study, the viewing angle is approximately normal to the ground, with a flying height of ~100 m. The forward and side overlaps are 80% and 60%, respectively. The pixel size of the CCD is 4.4 μm, corresponding to a spatial resolution of ~2.7 cm for the UAV photographs (Figure 3(a)). Although many UAV systems are equipped with GPS, the measurements are subject to shifting and tilting due to weather conditions, e.g., strong wind. To accurately obtain for the orientation parameters, i.e., the location and rotation of the camera, we collected ground control points (GCPs)
using a Trimble R8 differential global positioning system (dGPS). Each GCP is a red checkerboard with a side length of 50 cm, which can be identified easily in the photographs (example in Figure 3(a)). The nominal accuracy of the dGPS measurements is 1-5 cm [69]. We process the aerial photographs using the Structure-from-Motion (SfM) technique built in Agisoft PhotoScan Professional Edition (version 1.2.4). The procedure includes sparse reconstruction, dense matching, and orthorectification (see [70, 71] for a detailed description of the processing steps). The resulting DEM and Digital Orthophoto Map (DOM) are used in our geomorphic analysis.

3.2. Characterizing Alluvial Landforms. At site ELS1 (36°37′38.27″N, 98°54′47.74″E), southeast of Xianquan, the displaced terrace riser and vertical fault scarp can be clearly observed in the field (Figures 3(a) and 3(b)). We acquired 517 UAV photographs and 19 GCPs for topographic mapping. The derived DOM and DEM are shown in Figures 3(c) and 3(e). From the high-resolution DEM and DOM, we identify a linear fault trace and three terraces, i.e., T1 (lowest stratigraphic position and youngest) to T3 (highest position and oldest) (Figure 3(f)). T2 can be subdivided into two secondary terrace surfaces: T2a and T2b (Figure 3(f)). The fault, striking ~330°, is characterized by evident dextral offset. The risers of T1 to T3 and small channels (marked as L1-L6) developed on the surface of T2b and T3 were all displaced by the fault (Figure 3(f)). We also observed fault scarps on T2b and T3 with clear vertical displacements, and but not on T1.

At site ELF2 (36°40′8.82″N, 98°53′11.26″E), the dextral displacement is well preserved on small channel, but the vertical displacement is less clear (Figures 4(a) and 4(b)). We surveyed the topography with 151 UVA photographs and 12 GCPs (Figure 4(c)). The high-resolution DEM and DOM reveal four alluvial terraces, T1 to T4.
**Figure 3:** Geomorphic features at site ESL1. (a) Aerial photograph, acquired from UAV, shows the GCP, fault trace, and displaced terrace riser. (b) Photograph of fault scarp preserved on terrace T2 (location shown in Figure 3(c)). (c) Orthophoto of site ESL1. The locations of 19 GCPs are marked. (d) Image positions and overlaps at site ESL1. (e) High-resolution DEM of site ESL1. Dotted black boxes show the area of extracted vertical topography profiles. (f) Interpretation of the DEM. Displaced channels and terrace risers are marked by blue and red dotted line. The red star marks the $^{10}$Be sample position.
Figure 4: Geomorphic features at site ESL2. (a) Field photo shows a displaced channel on the surface of T3. (b) Photograph shows that the fault scarp is less clear at site ELS2. (c) Orthophoto of ELS2. (d) Image positions and overlaps at site ELS2. (e) High-resolution DEM of site ELS2. (f) Interpretation of DEM.
from young to old (Figures 4(e) and 4(f)). The Elashan fault, striking ~332°, has displaced the terrace risers and several small channels developed on the surface of T3 dextrally (Figure 4(f)).

At site QHNS (36°41'1"N, 99°21'6"E), vertical fault scarps are clearly preserved on different terraces and the fault dip can be observed as 45° (Figures 5(a) and 5(c)). The high-resolution DEM shows vertical fault scarps evidently (Figure 5(e)). Based on the contour, slope, aspect maps, and surface roughness, Ai et al. [69] analyzed surface geomorphology in detail and identified six displaced terraces at this location (Figure 5(f)). We found that the geomorphic surfaces of T4 and T5 below the fault scarp are not preserved but are buried beneath T3. Therefore, the vertical offsets of T4 and T5 represent the minimum displacement. Due to sustained erosion by active streams, fault scarps developed on the surface of T1 and T2 are not well preserved (Figure 5(e)).

**Figure 5:** Geomorphic features at site QHNS. (a) North looking field photo of fault scarps at site QHNS. (b) Fault dip of the QHNF shown by displaced conglomerate strata. (c) Orthophoto of site QHNS. The locations of 33 GCPs are marked. (d) Image positions and overlaps at site QHNS. (e) High-resolution DEM of site QHNS. Dotted white boxes show the area of extracted vertical topography profiles. (f) Interpretation of the DEM showed terrace staircases and fault trace. The red stars mark the 10Be sample positions.
3.3. Measuring Horizontal Displacements. Since we obtained high-resolution topography, we can interpret the fault trace, terrace staircases, and lateral displacements preserved on different landforms in great detail. To simplify the measuring process of previous studies [72–74], we provide a MATLAB-based graphical user interface (GUI), FaultRecovery, a tool for horizontal displacement calculation from point clouds in XYZ format. FaultRecovery has two modules: “Recovery by Feature” and “Recovery by Distance.”

“Recovery by Feature” measures displacements by restoring offset surface features such as terrace edge, channel, and mountain ranges. We take a channel in Figure 6 for example to illustrate how the “Recovery by Feature” module works. Assume the channel has been displaced by fault motion (left-lateral strike slip in the example). The length of the vector P7P8 is the amount of fault offset (Figure 6(a)). Users need to manually select two key points (P1 and P2) on the topography to locate the fault trace, and 4 key points to locate the channel (P3-P6, two on either side of the channel) (Figure 6(a)). From the coordinates of the six key points, the software automatically calculates the offset and restores the point cloud to the pre-earthquake condition. We suggest repeating the measurements three times based on the left, central, and right margins of the channel, respectively, to reveal the uncertainties [75] (Figure 6(b)).

The “Recovery by Distance” module allows users to define the offset manually in order to verify the restoration. Only two key points (P1 and P2) are needed to constrain the fault trace (Figure 6(a)). Users need to input the offset (in meters), and the recovered point cloud can be obtained.

At site ELS1, L3 was chosen as an example to show the process of horizontal displacement measurement and recovery. Two red key points are located to constrain the position of the fault (Figure 6(c)). Three groups of colored key points were taken to determine the left, central, and right margins, labeled as L3-1, 2, and 3 (Figure 6(c)). Based on “FaultRecovery,” we estimated the displacements of L3-1, L3-2, and L3-3 to be 19.6 m, 21.3 m, and 22.9 m, respectively, resulting in an average displacement of 21.3 ± 1.6 m. Figures 6(d)–6(f) show the recovered topography provided by “Recovery by Feature,” and Figure 6(g) shows the recovered topography by “Recovery by Distance” based on the average displacement of L3. The two modules yielded self-consistent restoration results.

To improve the efficiency of measuring horizontal offsets made by “FaultRecovery,” we cropped the DEM into small segments. The high-resolution topographic data of site ELS1 was cropped into three small segments (Figures 7(a)–7(c)). We measured the offsets of six channels, and three terrace risers at site ELS1. Figure 7(d) shows some of the measurements. The horizontal displacements are 1.9 ± 1.03 m for terrace T1/T0, 17.5 ± 0.3 m for T2a/T1, 20.8 ± 0.5 m for T2b/T2a, 20.5 ± 1.2 m for L1, 18.4 ± 0.3 m for L2, 21.3 ± 1.1 m for L3, 20.9 ± 0.5 m for L4, 19.4 ± 0.8 m for L5, and 37.3 ± 0.1 m for L6 (Table 1).

At site ELS2, the DEM was also cut into three segments (Figures 8(a)–8(c)). Some of the offset measurements are shown in Figure 8(d). The average offsets were calculated to be 14.5 ± 1.6 m for T2/T1, 39.8 ± 0.6 m for T3/T2, 21.0 ± 0.6 m for L1, 37.2 ± 0.8 m for L2, 20.9 ± 0.4 m for L3, 20.2 ± 0.4 m for L4, 20.5 ± 2.5 m for L5, 21.6 ± 1.0 m for L6, and 20.2 ± 1.2 m for L7 (Table 1).

3.4. Measuring Vertical Displacements. In order to measure the height of the fault scarps and the associated error, we fit lines to the upper and lower terrace surfaces separated by the ramp of fault scarps [45, 76, 77]. Topographic profiles across fault scarps were extracted from the high-resolution DEMs (Figure 9(a)). We developed MATLAB-based graphical user interfaces (GUIs)—PointFit—to semiautomatically calculate fault vertical displacements based on the selected topographic profiles. As shown in Figure 9(b), users can select part of the lines for fitting. Considering the actual topographic variation, we add the line fitting error of L1 and L2 into the calculation. The tool can also calculate the gradient of the elevation across the scarp, which is helpful for the determination of the upper and lower turning points of the fault scarp.

At site ELS1, we extracted 10 topographic profiles perpendicular to fault scarps on the surface of T2 and T3 from the DEM (marked in Figure 3(c)). Figures 9(c) and 9(d) show two examples of the measurements. Using the GAUSSIAN-PEAK model, we obtained a vertical displacement of 1.7 ± 0.3 m for T2b and 7.9 ± 0.5 m for T3. At ELS2, as we mentioned previously, we did not find evident vertical displacements along the fault.

At site QHNS, fault scarps on the surface of T1 and T2 have been severely eroded by active streams, so we did not measure them. For each of T3, T4, and T5, we extracted 10 topographic profiles perpendicular to the fault trace (marked in Figure 5(c)). Figures 9(e)–9(g) show three examples of the measurements. Similarly, using the GAUSSIAN-PEAK model, the vertical displacements are estimated to be 3.8 ± 0.4 m for T3, 4.5 ± 0.3 m for T4, and 7.3 ± 0.7 m for T5, respectively (Table 1). As shown in Figure 5(e), most of the topographic data of the northern part of T6 were missing. We speculate that the high elevation of T6 surface had made the camera lens too close to the ground. The close distance would reduce image overlaps, creating difficulties in image processing. We use the acquired topographic data to extrapolate the T6 scarp profile. Assuming that the slope of the T6 surface is similar to T5, we extracted the coordinates of three points on the preserved T6 surface (marked in Figure 5(c)) above the fault scarp to simulate the topographic profile of T6. Combining the upper and lower segments of the scarp profile on T6, the minimum vertical displacement of T6 is estimated to be 16.5 ± 0.2 m (Figure 9(h)).

4. Dating Alluvial Landforms

To constrain the ages of the alluvial terraces developed at the ELSF and QHNF, we collected quartz-rich pebbles for in situ cosmogenic nuclide 10Be dating. The 10Be dating method hypotheses that quartz-rich pebbles on terrace surfaces are exposed to cosmic rays and continue accumulating nuclide concentration since the terraces have been abandoned [78]. If we know the inherited nuclide concentration preserved in the pebbles before terrace abandonment, we can subtract...
Figure 6: Schematic diagram of the horizontal offset measurement. (a) Fault sinistral motion displaced the channel shown in a 3D model. Fault traces are marked as blue line. (b) Morphology of channel profiles (black line, positions are shown in Figure 3(a)) and displacement measurements (yellow, green, and purple line). Three groups of key points represent the measuring processes are repeated for three times. (c) One segment of the DEM around channel L3 at site ELS1 (position shown in Figure 3(d)) (up). Fault trace and three groups of key points are identified (bottom). (d–f) Back-slipped topography of channel L3 for three times. (g) Oblique view of the back-slipped topography based on the average displacement.
Figure 7: Horizontal offset at site ELS1. (a–c) Three cropped topography data at site ELS1 (marked in Figure 3(f)). (d) Some of the back-slipped topography of channels and terrace risers at site ELS1. The solid red line indicates the fault trace. The red and blue dotted lines represent the trace of channels and terrace risers. The amount of fault offsets is marked on the right.
it from the total nuclide concentration to derive the exposure ages. Generally, there are two ways to obtain the inherited nuclide concentration [78]. One is to assume that the nuclide concentration in pebbles in the modern riverbed represents the predepositional exposure nuclide concentration. The other way is to consider that the nuclide concentration in samples decreases with depths beneath terrace surfaces. The second method needs to collect 5 or more samples along a 2 to 3 m depth profile which means the thickness of gravel deposition must be larger than 3 m. Thus, the method is suitable for relatively long-term stable deposition in samples. As the height difference of the alluvial terraces developed along the ELsf and QHNF in our study are mostly lower than three meters, we use the first method to correct the inherited nuclide concentration.

At site ELS1, there are many pebbles, with diameters of ~1-10 cm, sedimented on terrace surfaces (Figure 10(a)). The pebbles, composed of Silurian and Ordovician grey-white gneiss and quartzite, were transported from the Elashan at the end of the period of terrace deposition. The gravels have been stable in place since the terraces have been abandoned, which are, therefore, suitable for cosmogenic nuclide \(^{10}\text{Be}\) dating. At QHNS, many quartz-rich and subround gravel clasts are deposited on the surface of each alluvial terrace (Figure 5(a)). These pebbles, with diameters of ~1-4 cm, are also suitable for cosmogenic nuclide \(^{10}\text{Be}\) dating to constrain the abandonment ages of the terraces. We collected two superficial \(^{10}\text{Be}\) samples at site ESL1, one from the surface of T3 (Figure 10(a)) and the other from the modern riverbed. At site QHNS, a total of five \(^{10}\text{Be}\) samples were collected, one from the riverbed and four from each tread of terraces T3 to T6 (Figures 10(b)–10(f)). All samples contained at least 100 gravels of ~2-3 cm in diameter.

We preprocess the samples at the Key Laboratory of the Institute of Crustal Dynamics, China Earthquake Administration [79]. The CEREGE (Le Centre Européen de Recherche et d’Enseignement des Géosciences de l’Environnement, Laboratoire de Tectonique) tested the \(^{10}\text{Be}\)/\(^{9}\text{Be}\) ratio using accelerator mass spectrometry. After subtracting the inherited nuclide concentration from the riverbed, we used the CRONUS-Earth online calculator (http://hess.ess.washington.edu) and the time-independent scaling model of Lal [80] and Stone [81] to calculate the abandonment age of each terrace.

At site ELS1, Yuan et al. [36] determined the age of terrace T2a as 8.7 ± 0.7 ka via OSL dating. In our study, the abandonment age of terrace T3 is determined to be 13.3 ± 1.2 ka after eliminating the inherited \(^{10}\text{Be}\) concentration of the riverbed. At site QHNS, the abandonment ages of T3, T4, T5, and T6 are 12.8 ± 1.2 ka, 21.3 ± 1.9 ka, 54.2 ± 4.6 ka, and 109.2 ± 9.5 ka, respectively. The dating results are summarized in Table 2.

5. Discussion

5.1. Determining the Late Pleistocene Slip Rates of the ELsf and QHNF. With accurate measurements of the displacement and ages of terraces, we can calculate the slip rates of the ELsf and QHNF. In many cases, the displaced terrace risers may be eroded by rivers, leading to underestimation of fault displacements and hence the slip rates [20]. As river flows can incise the terrace surfaces, forming small channels within the terrace risers which may be less eroded, they can be used as additional constraints on fault displacements. To obtain more reliable and reasonable displacement, we combine the displacements of terrace risers and channels in the analysis.

5.1.1. The Elashan Fault. At site ELS1, the measured horizontal displacement, 17.5 ± 0.3 m, represents the minimum offset after T2a was formed. The upstream riser of T2a/T1 was staggered into the path of the stream. It was eroded by active river flow, and an evident curved groove was observed (Figure 7(a)). On the contrary, the downstream riser is preserved and complete due to the protection of the upstream riser (Figure 7(c)). For T1, because of the arbitrary swing of the modern river flow, a displacement of about two meters from a single earthquake is difficult to be preserved, so we believe that the measurement induced by terrace T1/T0 riser may be unreliable. At site ELS2 (Figure 8), the measurements, 39.8 ± 0.6 m (T3/T2) and 14.5 ± 1.6 m

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**Table 1: Fault displacements at different sites.**

<table>
<thead>
<tr>
<th>Label</th>
<th>ELS1 Horizontal offset</th>
<th>ELS2 Horizontal offset</th>
<th>ELS1 Vertical offset</th>
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<td>T1</td>
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<td>T2</td>
<td>14.5 ± 1.6</td>
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<tr>
<td>T2a</td>
<td>17.5 ± 0.3</td>
<td>T3</td>
<td>39.8 ± 0.6</td>
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<tr>
<td>T2b</td>
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<tr>
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<tr>
<td>L6</td>
<td>37.3 ± 0.1</td>
<td>L7</td>
<td>20.2 ± 1.2</td>
</tr>
</tbody>
</table>

**Notes:**
- T1/T0 riser may be unreliable at site ELS1.
- ELS1, ESL2, ELSF, and QHNF.
- T1/T0 riser may be unreliable at site ELS1.
- ELS1, ESL2, ELSF, and QHNF.
- T1/T0 riser may be unreliable at site ELS1.
- ELS1, ESL2, ELSF, and QHNF.

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**Tables and Figures:**
- **Table 1:** Fault displacements at different sites.
- **Figure 10(a):** Terraces T3 to T6.
- **Figure 5(a):** Terraces T3 to T6.
- **Figure 7(a):** Terraces T3 to T6.
- **Figure 7(c):** Terraces T3 to T6.
- **Figure 8:** Terraces T3 to T6.
(T2/T1), also represent the minimum lateral offset since their abandonment. Similar to ELS1, it is clear that the upstream risers of terraces T3/T2 and T2/T1 have been seriously eroded. Thirty-three offset measurements at sites ELS1 and ELS2 are clustered in two groups. Gaussian probability density function (PDF) of the offset measurements

![Diagram of offset measurements at site ELS2.](LR.png)
Figure 9: Schematic diagram of vertical fault scarp measurement. (a) Fault vertical displacement shown in a 3D model. Orange line shows the location of the extracted fault scarp profile. Red line indicates the fault trace. (b) Schematic graph showing the method used to define the vertical scarp displacement, modified from Yu et al., 2013. (c–h) Examples of vertical fault scarp measurement results at sites ELS1 and QHNS.
shows that the mean values of the two offset clusters are 20.8 ± 3.2 m and 37.5 ± 3.0 m (95% confidence level), respectively (Figure 11(a)).

Cosmogenic nuclide $^{10}$Be dating gives the abandonment age of river terraces, which is the lower bound of the occurrence time of earthquakes. At site ELS1, using the abandonment age of T2a, 8.7 ± 0.7 ka [36], we obtained an upper bound on the horizontal slip rate of 2.39 ± 0.42 mm/yr given a displacement of 20.8 ± 3.2 m. Likewise, using the abandonment age of T3, 13.3 ± 1.2 ka, we calculated a horizontal slip rate of 2.82 ± 0.34 mm/yr given a displacement of 37.5 ± 3.0 m. These two values are consistent, indicating that the average strike-slip rate of the ELSF is approximately 2.6 ± 1.2 mm/yr since ~13.3 ka (Figure 11(a)). Similarly, the vertical slip rates are calculated to be 0.2 ± 0.04 mm/yr from T2 and 0.59 ± 0.07 mm/yr from T3, yielding an average
## Table 2: Determination of the $^{10}$Be exposure ages.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Terrace</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elev (m)</th>
<th>Depth (m)</th>
<th>Dissolved mass (g)</th>
<th>Carrier mass (mg)</th>
<th>Corrected $^{10}$Be/$^{9}$Be</th>
<th>$^{10}$Be concentration (atoms g⁻¹)</th>
<th>Error (atoms g⁻¹)</th>
<th>Inheritance $^{10}$Be concentration (atoms g⁻¹)</th>
<th>Age (ka)</th>
<th>Error (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELF1-21</td>
<td>T3</td>
<td>36.627008</td>
<td>98.913312</td>
<td>3338</td>
<td>0</td>
<td>30.6763</td>
<td>0.23</td>
<td>1.6746E−12</td>
<td>8.36E+05</td>
<td>2.28E+04</td>
<td>3.27E+05</td>
<td>13.3</td>
<td>1.2</td>
</tr>
<tr>
<td>ELF1-22</td>
<td>Riverbed</td>
<td>36.630617</td>
<td>98.911454</td>
<td>1442</td>
<td>0</td>
<td>23.49</td>
<td>0.21</td>
<td>5.5364E−13</td>
<td>3.27E+05</td>
<td>1.10E+04</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>QHNF-01</td>
<td>T6</td>
<td>36.683479</td>
<td>99.351619</td>
<td>3222</td>
<td>0</td>
<td>7.8728</td>
<td>0.2200</td>
<td>2.3537E−12</td>
<td>3.83E+06</td>
<td>1.12E+05</td>
<td>109.2</td>
<td>9.5</td>
<td>4.6</td>
</tr>
<tr>
<td>QHNF-02</td>
<td>T5</td>
<td>36.681331</td>
<td>99.352411</td>
<td>3169</td>
<td>0</td>
<td>30.8159</td>
<td>0.4324</td>
<td>2.5977E−12</td>
<td>1.87E+06</td>
<td>4.78E+04</td>
<td>54.2</td>
<td>4.6</td>
<td>1.9</td>
</tr>
<tr>
<td>QHNF-03</td>
<td>T4</td>
<td>36.680492</td>
<td>99.352422</td>
<td>3162</td>
<td>0</td>
<td>30.9057</td>
<td>0.2103</td>
<td>2.8677E−12</td>
<td>7.36E+05</td>
<td>3.05E+04</td>
<td>5.68E+05</td>
<td>21.3</td>
<td>1.9</td>
</tr>
<tr>
<td>QHNF-04</td>
<td>T3</td>
<td>36.678894</td>
<td>99.352736</td>
<td>3158</td>
<td>0</td>
<td>30.4684</td>
<td>0.2662</td>
<td>1.7307E−12</td>
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<td>2.36E+04</td>
<td>12.8</td>
<td>1.2</td>
<td>1.2</td>
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<tr>
<td>QHNF-05</td>
<td>Riverbed</td>
<td>36.675289</td>
<td>99.352747</td>
<td>3142</td>
<td>0</td>
<td>30.848</td>
<td>0.2084</td>
<td>1.2587E−12</td>
<td>5.68E+05</td>
<td>1.56E+04</td>
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<td>NA</td>
</tr>
</tbody>
</table>
Figure 11: Estimates of the late Pleistocene fault slip rates. (a) Lateral slip rate of the ELSF; (b) vertical slip rate of the ELSF; (c) vertical slip rate of the QHNF. The displacement value modeled by the Gaussian probability density function (PDF) is marked in the corner of each graph.
vertical slip rate of 0.4 ± 0.04 mm/yr since the late Pleistocene (Figure 11(b)).

5.1.2. The Qinghainanshan Fault. At site QHNS, the vertical displacement of 16.5 ± 0.2 m on T6 indicates the cumulative displacement since the abandonment of T6. Using the age of T6 (109.2 ± 9.5 ka) as the upper bound, the minimum vertical slip rate is calculated to be 0.15 ± 0.01 mm/yr. Similarly, measurements of vertical displacements and abandonment ages on T5, T4, and T3 yield a vertical slip rate of 0.13 ± 0.02 mm/yr, 0.21 ± 0.02 mm/yr, and 0.3 ± 0.04 mm/yr, respectively. Therefore, the vertical slip rate of the QHNS fault since the late Pleistocene is constrained to be 0.2 ± 0.03 mm/yr (Figure 11(c)). Based on the average slip rate, we speculate that the abandonment age of T2 is approximately 7.0 ± 1.5 ka.

5.2. Comparing Geological and Geodetic Rates. Wang and Shen [34] published a new set of GPS data collected during 1991 and 2016 from continental China. In this study, we also use this newly published GPS data to investigate fault motion around the Qinghai Lake and Chaka-Gonghe basins, in order to make a comparison between the long-term geological and short-term geodetic rates. We drew three swath motion around the Qinghai Lake and Chaka-Gonghe basins, use this newly published GPS data to investigate fault abandonment ages on T5, T4, and T3 yield a vertical slip rate, we speculate that the abandonment age of T2 is 0

5.3. Kinematic Model of Internal Deformation in the Qinghai Lake and Chaka-Gonghe Basin. In this study, we reanalyze the nonrigid bookshelf model using new constraints on the slip rates of the major faults around the Qinghai Lake and Chaka-Gonghe basins. The GPS velocity profiles AA' and BB', perpendicular to the EKLF and HYF, show that the overall shortening rate ranges from ~6.4 to ~4.9 mm/yr across a zone of ~300 km wide (Figures 12(h) and 12(i)). In the eastern segment of the area, profile CC' shows a lower shortening rate of 2.5 ± 0.7 mm/yr, which is mainly concentrated between the LJSF and HYF (Figure 12(j)). The eastward decrease of shortening rates may indicate counterclockwise rotation across the EKLF and HYF. Given a dip angle of 45°, the shortening rate of the QHNS can be constrained to be ~0.2 mm/yr. The shortening rate of the GHNF has been estimated to be ~0.7 mm/yr [39]. The central ELSF with a right-lateral slip rate of ~2.6 mm/yr will compensate for ~1.7 mm/yr shortening to the 24°-directed shortening, and the RYSF with an average slip rate of ~1.2 mm/yr will absorb ~0.8 mm/a shortening. The sum of shortening compensated by the four major faults is ~3.4 mm/a since the late Pleistocene. In addition, profiles DD' and EE' yield a 66°-directed shortening rate of ~2.0 to ~2.3 mm/yr between the ELSF and RYSF (Figures 12(k) and 12(l)). The shortening rate increases sharply to ~5.3 mm/yr after entering the interior of the Qilian Shan (Figure 12(m)). As the ELSF and RYSF are primarily strike-slip faults, we assume that the dip is higher than 70°, so the shortening absorbed on them is less than 0.3 mm/yr (Figure 13). In brief summary, the sum of the geological shortening rates on the major faults is lower than the overall geodetic convergence rate across the Qinghai Lake and Gonghe basins. We suggest some of the deformations may be distributed in HYF, EKLF, and active folds developed in the Qinghai Lake and Chaka-Gonghe basins (Figure 13).

Based on the slip rates and geometry of the major faults mentioned above, we argue that the Qinghai Lake and Chaka-Gonghe basins may not rotate as a whole block. In the north, the overall left-lateral shear from GPS is equivalent to the strike-slip motion of the ELSF and RYSF, on the order of ~1 mm/yr, so this region could rotate as a block. The rotation would promote the crust material moving southwards to form thrust faults and folds in the SW direction of the basin [38, 39, 65]. The normal faults developed in the Qinghai Lake [84] may also be related to the block rotation. Assuming the center of the block as the rotation center, we calculated the counterclockwise rotation rate of the Qinghai Lake basin to be ~0.8 deg/Myr, using a strike-slip rate of ~1.2 mm/yr and a radius of ~85 km.

In the south, there is a wide distribution of thrust faults, so the southern region is unlikely to behave as a block. Interestingly, the latest GPS block modeling [35] reveals that the Qinghai Lake basin shows consistent counterclockwise rotation regardless of the number of divided subblocks whereas the Chaka-Gonghe basin may rotate clockwise or counterclockwise depending on the division of subblocks. This suggests that the Qinghai Lake and Chaka-Gonghe basins behave in a different way. Given the fact that many thrust faults formed within the Chaka-Gonghe basin and block modeling show inconsistent rotation directions, we suggest...
Figure 12: (a) Map of active faults and GPS velocities. Red lines show major active faults within the research area. Blue arrows show GPS velocities for motion relative to Eurasia. Rectangles show the locations of velocity profiles discussed in Section 5.2. Active faults are modified from "Map of active faults in China" and "Map of active faults in northern Tibet" by [47]. Black arrows denote the shortening direction. (b), (c), and (d) show strike-slip rates of the EKLF and HYF along profiles AA′, BB′, and CC′. (e), (f), and (g) show strike-slip rates of the ELSF and RYSF along profiles DD′, EE′, and FF′. (h), (i), and (j) show shortening rates between the EKLF and HYF along profiles AA′, BB′, and CC′. (k), (l), and (m) show shortening rates between the ELSF and RYSF along profiles DD′, EE′, and FF′.
that the basin may be mainly characterized by distributed thrusting (Figure 13).

**6. Conclusions**

In this study, we investigated the kinematic deformation of the Qinghai Lake and Chaka-Gonghe basins based on the high-resolution DEMs, geomorphic chronology dating, and GPS. We draw the following conclusions:

1. The late Pleistocene right-lateral strike-slip rate of the Elashan fault is $2.6 \pm 1.2$ mm/yr and the vertical slip rate is $0.4 \pm 0.04$ mm/yr. The vertical slip rate of the Qinghainanshan fault is $0.2 \pm 0.03$ mm/yr since the late Pleistocene.

2. The consistency between the long-term geological slip rates and short-term geodetic rates indicates that the present-day regional deformation may be inherited from the late Pleistocene.

3. The nonrigid bookshelf kinematic model of the northeastern Tibetan Plateau involves a combination of rotation and distributed thrusting. The Qinghai Lake basin is characterized by counterclockwise rotation with a rate of $-0.8$ deg/Myr in response to the left-lateral shear of the Haiyuan and East Kunlun faults. The Chaka-Gonghe basin is mainly characterized by distributed thrusting.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

We wish to confirm that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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