Late Quaternary Kinematics and Deformation Rate of the Huoyanshan Structure Derived From Deformed River Terraces in the South Piedmont of the Eastern Chinese Tian Shan

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The deformation pattern and strain partitioning in the Eastern Chinese Tian Shan are poorly known because of the lack of quantitative study of the kinematics and deformation rate of the major structure. Here we report a late Quaternary shortening rate for the most active reverse fault-and-fold in the Eastern Chinese Tian Shan. We quantified the kinematics and late Quaternary shortening rate of the Huoyanshan structure based on detailed high-resolution remote sensing image interpretations, field investigations and geological mapping. Six generations of folded terraces along the Tuyugou valley that showed the progressive folding process by the Huoyanshan structure were identified. A kinematic model of curved thrust fault propagation and folding allowed us to describe the terrace deformation pattern and subsurface fault geometry and calculate shortening across this structure. Combined with a regional age control of terrace T4 in the Tuyugou valley, a late Quaternary shortening rate of 2.0–3.2 mm/yr of the Huoyanshan structure was obtained. This is a relatively high shortening rate in the whole Eastern Chinese Tian Shan (roughly east of 88°E). This shortening rate of the Huoyanshan structure highlights that the ongoing India and Eurasia collision has affected the entire Tian Shan but shows two strain partitions: the main strain-absorption belt is located within the Eastern Chinese Tian Shan interior, but strain also occurs at the range-front foreland in the Western Tian Shan.

Keywords: Eastern Chinese Tian Shan, Huoyanshan structure, listric fault, shortening rate, strain partitioning

INTRODUCTION

To unravel the deformation across thrust-and-fold belts, various kinematic models that draw relationships between surface deformation, subsurface geometry and cumulative fault slip after the overlying strata were deposited have been proposed (Suppe, 1983; Erslev, 1991; Suppe et al., 1992; Medwedeff and Suppe, 1997; Suppe et al., 1997; Allmendinger and Shaw, 2000; Amos et al., 2007; Charreau et al., 2008; Le Béon et al., 2014; Saint-Carlier et al., 2016; Trexler et al., 2020; Wang et al., 2020b). Although strata, such as growth strata, are usually used as markers to depict fold kinematics and growth in previous studies Suppe et al. (1992), Storti and Poblet (1997), the difficulty of dating and lack of sediments limit the reconstruction of sequential kinematic development of thrust systems (Goode et al., 2011; Goode et al., 2014; Li et al., 2015; Stockmeyer et al., 2017; Wang et al., 2020b).
Commonly, even when growth strata have been preserved in outcrops, they are always missing across the core of a fold. In contrast, well-preserved abandoned fluvial terraces may extend across the entire fold and record incremental fold deformation. When combined with deformed river terraces and suitable kinematic models of fault-related folding Lavé and Avouac (2000), Thompson et al. (2002), Scharer et al. (2006), Hubert-Ferrari et al. (2007), Hu et al. (2015), Stockmeyer et al. (2017), Charreau et al. (2018), Cardozo and Oakley (2019), the spatial and temporal patterns of deformation of thrust-and-fold belts can be characterized.

In the Tian Shan, N-S crustal shortening dominates in response to the ongoing India-Eurasia collision during the late Cenozoic Tapponnier and Molnar (1979), Zhang et al. (2004), Yang et al. (2008), Zubovich et al. (2010), which has been accommodated by a series of roughly E-W-trending thrust-and-fold belts in foreland and/or intermontane basins (Figures 1A, B; Avouac and Peltzer, 1993; Burchfiel et al., 1999; Deng et al., 2000; Thompson et al., 2002; Wu et al., 2016; Lu et al., 2019). Therefore, quantifying the geometry, kinematics and deformation rate of the thrust-and-fold belt is the key to exploring tectonic deformation and strain distribution in the Tian Shan region. Many studies e.g., Deng et al. (2000), Thompson et al. (2002), Shen et al. (2003), Hubert-Ferrari et al. (2007), Yang et al. (2008), Lu et al. (2019) have been conducted in the Western Tian Shan region to reveal the kinematics and deformation rate of fault-related folding and have shown that shortening is relatively uniformly distributed across the major intermontane basin boundaries and basin interior structures along a N-S transect of the Western Tian Shan, rather than solely at its margins. The Eastern Chinese Tian Shan is also dominated by intense tectonic deformation, which is shown by the study results of widespread active faults Deng et al. (2000), Lin et al. (2002), Wu et al. (2016), Huang et al. (2018a), Huang et al. (2018b), Ren et al. (2019), Wang et al. (2020a), paleoearthquake ruptures Feng (1997) and global positioning system (GPS) measurements (Zhang et al., 2004; Yang et al., 2008; Wang and Shen, 2020). However, in contrast to the Western Tian Shan, the deformation pattern and slip partitioning in the Eastern Chinese Tian Shan remain unclear because of the lack of quantitative study on the deformation rate and kinematics of the major structural belt.

The Huoyanshan (also known as Flame Mountain) structure, which is part of the Turpan foreland thrusting system (Figures 1C, 2A), is the most active structural belt in the Eastern Chinese Tian Shan Deng et al. (2000) and consists of the Huoyanshan Fold and the Huoyanshan Fault (Figure 2B). A previous study Deng et al. (2000) determined the fault slip rate and further reconstructed the paleoseismic sequence based on the interpretation of trenches and dating of sediments. Kinematic models and shortening rates across the entire Huoyanshan structural belt have rarely been reported. This work aims to i) reveal the geometry of the Huoyanshan structure and estimate the late Quaternary crustal shortening rate from deformed river terraces and ii) understand the kinematics of this structure as well as strain partitioning in the Eastern Chinese Tian Shan.
GEOLOGICAL SETTING

The Tian Shan orogenic belt, which is approximately 1,200 km north of the frontal Himalayan thrusts, is bounded by the Junggar Basin to the north and the Tarim Basin to the south and displays a basin-and-range topography (Tapponnier and Molnar, 1979; Burbank et al., 1999). GPS measurements and geological studies all suggest that the N-S convergence rate across the Tian Shan gradually decreases from west to east, with the shortening rate decreasing from ∼12 mm/yr at 75 E (Abdrakhmatov et al., 1996; Avouac and Peltzer, 1993; Thompson et al., 2002; Zhang et al., 2004; Yang et al., 2008) to ∼9 mm/yr at 78 E (Campbell et al., 2019), and ∼5 mm/yr of shortening occurs at 85 E (Wang and Shen, 2020). The Eastern Chinese Tian Shan is located to the east of 88 E longitude (Figure 1B,C). Although few large earthquakes have been recorded in its history, widespread active faults and present-day geodetic measurements attest to its active deformation. In the study region, the estimates of the N-S shortening rate across the Tian Shan gradually decreases from west to east, with the shortening rate decreasing from ∼12 mm/yr at 75 E (Abdrakhmatov et al., 1996; Avouac and Peltzer, 1993; Thompson et al., 2002; Zhang et al., 2004; Yang et al., 2008) to ∼9 mm/yr at 78 E (Campbell et al., 2019), and ∼5 mm/yr of shortening occurs at 85 E (Wang and Shen, 2020). The Eastern Chinese Tian Shan is located to the east of 88 E longitude (Figure 1B,C). Although few large earthquakes have been recorded in its history, widespread active faults and present-day geodetic measurements attest to its active deformation. In the study region, the estimates of the N-S shortening rate across the whole range are based on present-day GPS measurements and range from 3–5 mm/yr (Liang et al., 2013; Wang and Shen, 2020). The Eastern Chinese Tian Shan consists of the Bogda and Kuruktag ranges and several intermontane basins, such as the Turpan, Yanqi and Kumysh Basins (Figure 1B). Previous field investigations have recognized a series of active faults that bound the intermontane basins and accommodate N-S convergence (Deng et al., 2000; Lin et al., 2002; Fu et al., 2003; Wu et al., 2016; Wang et al., 2020a). The Eastern Chinese Tian Shan can be divided into two parts based on the Turpan basin (the largest intermontane basin). To the south of the Turpan Basin, the Bolokenu-Aqikekuduke Fault (BAF) and the Baoertu Fault (BETF) are strike-slip faults (Shen et al., 2003; Ren et al., 2019). Farther south, the Kuruktag range is thought to be dominated by right-lateral faulting since the late Cenozoic (Tapponnier and Molnar, 1979; Yin et al., 1998; Lin et al., 2002; Huang et al., 2018b). The right-lateral slip rate of the Kaiduhe Fault was estimated to be ∼1.0 mm/yr (Huang et al., 2018b), and the angle between these strike-slip fault trends and N-S shortening is small; hence, the crustal shortening accommodated by these faults is negligible. Moreover, a recent geological study reveals only ∼0.3 mm/yr of shortening of the intermontane basin-bounding fault (Wang et al., 2020b), further indicating that crustal shortening is not prominent in the southern Turpan Basin. In contrast, the Bogda range to the north of the Turpan Basin has intense crustal shortening, as manifested by the strongly uplifted landscape. Based on surveying of the deformed late Quaternary alluvial fan and dating of the geomorphic surface, Wu et al. (2016) estimated ∼1 mm/yr of shortening in the northern piedmont of the Bogda range. Within the Turpan Basin, the foreland thrusting system is composed of the Hongshankou, Yanshan, Kendek, Huoyanshan, and Qiketai sub-belts from west to east (Figure 1C). These folds are the surface expressions of ramp thrusts whose decollement surface appears near the base of the Lower Jurassic sequence in the seismic profile (Deng et al., 1996; Deng et al., 2000; Yao et al., 2013). A series of inland rivers that originate from glaciers transversely cut the Turpan foreland thrusting system and flow into the Turpan Basin (Figure 1C), and river terraces are well developed in the thrusting system (Deng et al., 2000).
FIGURE 3 | (A) Orthography images of the Tuyugou Valley (see Figure 2A for the location). Red stars show the locations of GPS survey ground control points, and pink symbols indicate the locations and orientations of structural measurements. (B) Digital elevation model (DEM) surveyed by an unmanned aerial vehicle. (C) Geomorphic mapping of terraces in the Tuyugou Valley. Colours and numbers indicate the six generations of terraces (T4 represents a secondary terrace of T4), black dots show the individual points on terraces and river channels that are projected onto line A-A'.

Map legend:
- River channel
- Fault scarp
- Ground control points
- Survey points
- Quaternary terrace
- Strike and dip
- Projection line
- Older
Since the late Pleistocene, the Huoyanshan sub-belt is the largest active tectonic structure in the basin and is mainly composed of Jurassic to Cretaceous strata (Figure 2A). The structural pattern Peng (1995) suggests that it is an asymmetric fold that is dominated by a deep fault structure (Figure 2B). Jurassic, Cretaceous, Paleogene, Neogene strata, and the overlying late Quaternary alluvial terraces have been deformed by the fold (Figure 2B). A previous study indicated that the thrust located south of the Huoyanshan structure has a dip angle of ∼30° (Deng et al., 2000). From west to east, several valleys cut through the Huoyanshan structure: the Taoergou, Putaogou, Futougou, Shengjingou, Tuyugou, and Ertanggou Valleys (Figure 2A). Among these valleys, the Tuyugou Valley, which cuts through the middle of the Huoyanshan structure, contains the most continuous terrace sequences.

MATERIALS AND METHODS
Classification and Age Constraints of Fluvial Geomorphology
In this study, we focused on the middle part of the Huoyanshan structure where it is crossed by the Tuyugou Valley. Terrace classification and mapping were conducted based on Google Earth image interpretation and field investigations. Terraces of the Tuyugou Valley were interpreted again with a high-resolution digital elevation model (DEM). To obtain the high-resolution DEM of the Tuyugou Valley, 4,782 photos were captured by an unmanned aerial vehicle (UAV). To improve the accuracy and precision of the DEM, 85 ground control points (Figure 3A) that cover all surveying areas were placed and measured with a real-time kinematic global positioning system (RTK-GPS). The DEM was derived using PhotoScan (version 1.26.2834) based on the classical workflow (Agisoft L.L.C., 2018): 1) loading the 4,782 photos of the Tuyugou Valley acquired by the aerial platform into PhotoScan, then inspecting the loaded images and removing unnecessary images (after the removing procedure, 4,600 photos remain); 2) aligning these photos; 3) building a dense point cloud; 4) building a mesh (3D polygonal model); 5) generating a texture; 6) building a tiled model; 7) georeferencing 85 RTK-GPS surveyed ground control points that are distributed on the terrace surfaces; 8) repeating steps 1–6; and 9) building the DEM (Figures 3B, C).

Due to coarse-grained material and the low quartz content in the sediments, it is difficult to collect appropriate samples for dating from river terraces in the Tuyugou Valley (Figures 4A, B, D, E, F). Although the exact number of terraces within each division may vary locally, several regional terraces could be correlated with regional climate change. In this study, terrace ages rely on previous studies of the neighbouring valley (Peng, 1995; Deng et al., 2000). Terraces that cross the anticline may be divided into tectonic and climatic terraces. The climatic terraces are more widely developed, are relatively continuous compared to tectonic terraces, and can be compared regionally. The Turpan Basin, which is located in the hinterland of Eurasia and lying in the northeastern part of the Tian Shan, has a semiarid climate. The Quaternary denudation and sedimentation process, in terms of erosion and deposition, was inevitably affected by the impact of glaciation (glacial and interglacial periods) and climate change. Quaternary sediments filling the basin and geomorphological units such as river terraces have been affected by climate change. The river terraces in the Turpan Basin are mainly distributed in the river valleys of the Turpan foreland thrusting system, which can be compared and correlated locally.

The Turpan foreland thrusting system (Figure 1C) contains a widely developed generation of terraces. These terraces are mainly composed of early late Pleistocene fluvial sediments with thicknesses of 5–10 m and form a relatively broad platform on the tops of the mountains in the Turpan foreland thrusting system, including the western Hongshankou mountaintop, western Kendeke mountaintop, and Huoyanshan mountaintop Deng et al. (2000), Peng (1995), which indicates
that this generation of terraces is climatic. The heights above the river of the main portions of this generation of terraces are ∼90 m on the Hongshankou mountaintop, ∼100 m on the Kendeke mountaintop, ∼100 m in Putaogou Valley in the Huoyanshan structure, and ∼100 m in Shengjingou Valley in the Huoyanshan Mountains (Figures 1C, 2A; Peng, 1995). The optically stimulated luminescence (OSL) ages of this terrace have been dated in previous studies: on the Hongshankou mountaintop, 56.9 ± 4.4 ka (Deng et al., 2000); on the Kendeke mountaintop, 73.8 ± 5.8 ka (Peng, 1995); and on the southeast mountaintop of the Shengjingou Valley, 61.2 ± 11.6 ka (Deng et al., 2000). The abandonment age of this terrace seems to be related to the climatic event of early Last Glacial during 55–75 ka, corresponding to MIS 4 (Deng et al., 2000; Wu et al., 2004).

In the Tuyugou Valley, T4 is a major terrace that is developed on the mountaintop of the Huoyanshan structure and is relatively broad and continuous (Figure 4B). The maximum height above river of T4 is ∼160 m (considering that the Tuyugou Valley is in the middle of the Huoyanshan structure, the deformation is much more intense). The terrace is composed of ∼10 m of fluvial sediments. By comparing the geomorphic characteristics of T4 in the Tuyugou Valley and the terrace described above, T4 could be compared with the widely developed terrace in the Turpan foreland thrusting system. Therefore, the age of T4 in the Tuyugou Valley was constrained by the ages that have been dated that is 56.9 ± 4.4–73.8 ± 5.8 ka. These ages were defined by OSL samples that had been taken from fine sand in the middle of fluvial deposits (Figure 1C; Peng, 1995; Deng et al., 2000).

Determination of Crustal Shortening by Morphometry

To determine the pattern and amount of deformation in the Huoyanshan structure, topographic lines were plotted at terrace surfaces and modern riverbeds (Figure 3C), and the coordinates and elevations of the topographic lines were extracted from the DEM, which was derived from UAV measurements (these procedures were conducted in ArcMap, version 10.8). Then, these raw survey measurements of the topographic lines were projected onto the N-S-trending line A–A’ (Figure 3C), parallel to the Tuyugou Valley and roughly perpendicular to the trend of the synclinal axial surface. To depict the spatial distribution geometry of terraces and riverbeds, topographic profiles along all terraces and the modern riverbed were plotted (Figure 5A). To eliminate the modern river gradient, a polynomial that fits the modern riverbed was subtracted from each fluvial terrace to eliminate the modern river gradient. The vertical exaggeration is 10. The distance is projected along line A–A’, where A’ is the direction downstream, and a fault scarp exists at the southern margin of the Tuyugou valley (see Figure 3C for the location).
To construct the kinematic model of the Huoyanshan structure, 22 bedding attitudes of bedrock at intervals of ~300–400 m (the measurement interval increased as the bedrock outcrops improved) were measured across the Tuyugou Valley (Figures 3A, 7B). By integrating the vertical uplift longitudinal profile of terraces (Figure 5B), the measured bedding attitudes and the combined fault folding model (Figure 6C), the best-fit kinematic model between the Quaternary terrace surface deformation and the inferred subsurface geometry in the Huoyanshan structure was established. Because high-resolution seismic profiles were not available across the Tuyugou Valley, the depth of the decollement (Figure 7B) was constrained and inferred from previously published nearby seismic reflection data (Figure 2B; Deng et al., 2000; Yao et al., 2013; Chang, 2016).

RESULTS

Terrace Description and Deformation

Six terraces along the Tuyugou Valley, T1–T6, that increase in height above the modern riverbed, were defined (Figure 3C). Most of these terraces are strath terraces that have been eroded into the base rock, capped and covered by several metres of fluvial gravels and subsequently buried by variable depths of eolian loess (Figures 4D, F). T4 is the most spatially extensive and best-preserved terrace, and it has a secondary terrace, namely, T4‘ (Figure 3C). Among these terraces, only T3 is capped by 50–80 m of lacustrine deposits, which are dominated by grey mudstone, green mudstone and red siltstone and are horizontally bedded (Figure 4E). The presence of lacustrine deposits indicates that there was a relatively humid environment during the T3 formation period. The width of the Tuyugou Valley is relatively narrow (Figures 3A, 4E), which could cause sediments to be dammed in the river and create a lake.

Terraces preserved in the western Tuyugou Valley are more continuous (Figure 3C). T6–T5 are not very continuous compared with other terraces and have been found only at the southern margin of the valley (~7–8 km in Figure 5A). Different
degrees of deformation exist in all terraces. Compared with the younger terraces, such as T2 and T1, the older terraces have deformed much more significantly. T6-T4 have been significantly deformed by the Huoyanshan Fault (Figure 5A). These terraces reach their peak heights at the core of the anticline and gradually extend to the wings (∼4–6 km in Figure 5A). T3 appears to be nearly horizontal in the true elevation profile in Figure 5A. We assume that T3 was deposited by the sediment dammed in the river during the formation of the lake. Regardless of the origin of the terraces in the Tuyugou Valley, the terrace surfaces could be deformed by folding. However, due to its lacustrine deposit characteristics, there is no reason to believe that T3 was graded by the river compared with other fluvial terraces; therefore, T3 was not used to restore the kinematics of folding.

The Huoyanshan Fold has a relatively short forelimb that is approximately 1.4 km long. After ∼8 km, terraces and modern riverbeds meet on undeformed alluvial fans. The length of the axial top is ∼2.5 km at T4 (the discontinuous terrace makes it difficult to confirm). The backlimb is relatively long (∼3.0 km), and the anticline has a relatively broad wavelength (∼7 km) (Figure 5B). The vertical uplifts (relative to the undeformed terrace surface) are 14.8–16.6 m for T1, 36.7–40.5 m for T2, and 122.2–127.2 m for T4 (Table 1). The tilt angles of deformed terraces increase with terrace age; they are 0.2° for T1, 0.5° for T2, and 2.2° for T4. These characteristics demonstrate that fluvial terraces in the Tuyugou Valley are syntectonic sediments deposited during the growth of the fold that recorded the folding deformation process, and the older terraces accumulated more fold deformations than the younger terraces.

**Kinematic Model and Late Quaternary Slip Along the Huoyanshan Reverse Fault-and-fold Belt**

The most important aspect of calculating the deformation rate of the Huoyanshan structure is establishing the kinematic relationship between terrace deformation and subsurface geometry. We have summarized several kinematic models to reflect different thrust fault-related folding processes (Suppe, 1983; Erslev, 1991; Suppe et al., 1992; Medwedeff and Suppe, 1997; Suppe et al., 1997; Allmendinger, 1998; Amos et al., 2007; Charreau et al., 2008; Trexler et al., 2020; Wang et al., 2020b). In the simple fault-bend folding model, the fault grows linearly, the surface deformation is uniform within each dip domain defined
by the planar fault, and the backlimb is short and relatively steep (Figure 6A). In listric fault folding model, the fault grows listrically by limb rotation, the surface deformation and dip angles of the bedrock are sequential and nonuniform, the backlimb is long and has a gentler dip, and no axial top exists (Figure 6B). In the combined fault folding model, the fault grows listrically and then connects to a linear segment and follows a constant dip angle to the surface. The surface deformation pattern is similar to the listric fault model but with an axial top (Figure 6C). In all three models, it is assumed that there was no tilt in the substrata when the surface above the fault was undeformed, and the deep fault was initially developed from a subhorizontal detachment structure.

Bedding attitude data along the Tuyugou Valley indicate forelimb dips reaching 70° and gentler backlimb dips from ~50 to 12 with a northeast dip direction. Between the forelimb and the backlimb, the dip domain is ~50 (Figure 7B). The dip angle of each fold segment and the characteristics of terrace deformation in Terrace Description and Deformation reveal that the terrace deformation pattern and subsurface structure are incompatible with other fault-related folding models except for the combined fault folding model (Figure 6C). Therefore, we interpret the Huoyanshan fault as a fault that dips 50, is a planar feature that extends from the surface to ~2 km depth and connects to a listric segment that gradually merges into the detachment and changes its dip angle to 0 at ~4.0–5.0 km depth (Figure 7B).

Total shortening was estimated from the trigonometric relationship between the vertical uplift of the terrace and the dip angle of the bedrock at the surface (Trexler et al., 2020). If folding results from total horizontal shortening that detaches from the footwall with a vertical surface uplift of $dz$ and a surface dip angle $\theta$, the relationship between these parameters is:

$$s = \frac{dz}{\sin \theta}$$

Following this approach and using the dip angle of the fault plane as 50, the different vertical uplifts of the terraces yield shortening values of 19.3–21.7 m for T1, 47.9–52.9 m for T2, and 159.5–166.1 m for T4. The shortening rate of T4 is 2.0–3.2 mm/yr after T4 was abandoned. The uncertainty in the shortening rate is mainly derived from the uncertainties in the length of shortening and the age of the terrace (Table 1). As the surface of T4 is not continuous and given the orientation of the surface, T4 would reach even higher above the river channel (Figure 5B), which indicates that the shortening estimate is a minimum (Figure 6C). The terrace age of T4 is defined by OSL, samples for which were taken from fine sand in the middle of fluvial deposits Peng (1995), Deng et al. (2000); therefore, the OSL age is a maximum estimate of the terrace abandonment age considering erosion, which may cause the actual terrace abandonment age to be younger. Based on these two factors, the estimate of the shortening rate is the minimum value.

**DISCUSSION**

**Fault Geometry**

We used the combined fault folding model (Figure 6C) to reconstruct the geometric features of terrace deformation and subsurface fault geometry and believe that it is the best-fit kinematic model of the Huoyanshan structure. In this model of the Huoyanshan structure in the Tuyugou Valley, the subsurface fault starts with a subhorizontal detachment and is connected by a listric segment to a linearly dipping fault. As mentioned above in Terrace Description and Deformation, it is difficult to confirm the existence of an anticline axial top because the T4 surface is not continuous, which makes it difficult to identify. However, if there is no axial top, the fault follows the simple listric folding model (Figure 6B), and the dip angle of the bedrock should gradually change at the surface, which is not consistent with our measurement results of the bedding attitudes across the fold. According to these measurement results, a dip domain is present after the dip angle of bedrock reaches ~50 (Figure 7B). The appearance of the dip domain indicates the existence of a linear fault segment that forms an axial top at the surface. Integration of available subsurface data lends validation to this interpretation. The subsurface fault geometry inferred in this study is consistent with the characteristics reflected in the interpreted cross-section (Figures 2B, 7B).

In addition, according to the interpretation, the fault crosses the main fault and forms a fault scarp. However, there is a good chance of the development of a secondary fault that outcrops at the surface, as intense deformation exists in front of the forelimb (Figure 7B). It is commonly a challenge to differentiate among kinematic models for specific thrust fault-related folds and match the geometry of subsurface faults with the patterns of deformed surfaces. This requires both surface deformation patterns and high-resolution seismic reflection data of the subsurface fault to determine which type of model most represents the nature of faulting and folding (Goode et al., 2011; Goode et al., 2014; Li et al., 2015; Stockmeyer et al., 2017; Wang et al., 2020b). To improve our work, a detailed study of the entire Huoyanshan structure should be carried out, such as investigating terrace deformation in other valleys of the Huoyashan area and constraining the subsurface fault geometry with a high-resolution seismic profile.

**Slip-Partitioning in the Eastern Chinese Tian Shan**

This study infers a crustal shortening rate of 2.0–3.2 mm/yr across the Huoyanshan structure since the late Quaternary, which is significantly larger than that across the other intermontane basin-bounding faults in this region. Within the Yanqi Basin in the Eastern Chinese Tian Shan, by using seismic data and the attitude of strata and faults to restore the geometry of the fold, Li et al. (2012) calculated the shortening rate in the Hejing thrust-fold belt, which has been ~0.3 mm/yr since the late Pleistocene. By studying the typical offset landforms and lineaments of scarps on the eastern segment of the north-edge fault of the Yanqi Basin, Huang et al. (2018a) constrained the shortening rate to 0.4–0.5 mm/yr on the northern margin of the basin. Based on dating the alluvial fan surfaces, measuring the heights of the fault scarps, and investigating a paleoearthquake trench wall, Wang et al. (2020a) estimated that a ~0.3 mm/yr shortening rate was accommodated by the Kunysh Fault during the late Quaternary. The shortening rate was estimated to be ~1 mm/yr since the late Quaternary at the
Bogda foreland thrust fault through geologic and geomorphologic field surveys, trench excavation and OSL dating (Wu et al., 2016). The relatively high shortening rate of the Huoyanshan structure indicates that it is the main strain-absorption belt in the Eastern Chinese Tian Shan region. In the Western Tian Shan (Figure 1B), the strain was proposed as mainly being partitioned into the foreland thrusting system Yang et al. (2008) or evenly distributed across the entire mountain (Thompson et al., 2002), rather than solely at its margins. What mechanism could explain the relatively large crustal shortening rate of the Huoyanshan structure in the Eastern Chinese Tian Shan?

The Turpan basin is underlain by a strong basement Allen et al. (1993) and extends approximately 100 km in the N-S direction. Petroleum seismic profiles and our field mapping indicate that the folds in the northern Turpan Basin mainly involved Mesozoic and Cenozoic sedimentary rocks (Deng et al., 2000). If the pre-Mesozoic basement of the Turfan Basin did not deform, the thin-skinned structure belt would have splayed from the basin-bounding fault at the margin of the basin. With the foreland-ward expansion of the range, the stress was concentrated on the thrust faults in the northern margin of the Turpan Basin. Active deformation propagated into the Huoyanshan structure belt. Therefore, high crustal shortening rate can be observed within the intermontane basin (Campbell et al., 2019). The Huoyanshan thrust fault-and-fold belt may have acted to concentrate stress onto the Turpan Basin margin fault in the north, which, in turn, may have built up the present-day high-elevation Bogda range observed today (Figure 1C). The rigid blocks in an orogenic belt are always the places where major crustal shortening and deformation occur and determine the deformation pattern.

CONCLUSION

Based on detailed high-resolution remote sensing image interpretations, field investigations and geological mapping of the Huoyanshan structure, we quantify the kinematics and late Quaternary shortening rate of the Huoyanshan structure, and we summarize the following conclusions.

By considering both the bedrock structure recorded by folded strata and the terrace deformation pattern, we propose a kinematic model of curved thrust fault propagation folding that describes the whole structural deformation of the Huoyanshan structure.

Based on the unique kinematic model, the survey of the deformed river terraces, and age correlation, we estimate a late Quaternary shortening rate of 2.0–3.2 mm/yr for the structure.

Comparisons of strain are partitioned along several structures within the Western Tian Shan, and our shortening rate of the Huoyanshan structure highlights that the main strain-absorption belt is located within the Eastern Chinese Tian Shan interior.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

ZL, CW, and XY initiated the study. CW, ZL, WW, and XY designed the manuscript, XY carried out the calculation and interpretation work and wrote the manuscript. CW, ZL, and WW provided helpful discussions and helped to improve the manuscript. Co-authors GC, LD helped to carried out filed work.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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