

Asymmetric Deformation along the Altyn Tagh Fault Zone Revealed by Geomorphic Analysis

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ABSTRACT: The Altyn Tagh fault zone (ATFZ), which defines the northern boundary of the Tibetan Plateau, is one of the most striking features related to the India/Eurasia collision. Concurrent with the strike-slip movement, vertical uplift, and topographic building have formed a ~3 000–4 000 m height difference between the Tarim Basin (TB) in the north and the Tibetan Plateau in the south. However, the spatial uplift characteristics and mechanism have not been well understood, particularly in the Late Quaternary. This research presents a comprehensive geomorphic analysis to establish the Late Quaternary tectonic uplift pattern for the entire ATFZ. We statistically excluded climatic and lithological factors that provided prominence for tectonism; combined with leveling data, river incision rate, and seismicity data, we reveal the along-strike and across-fault vertical deformation variations. The spatial distribution of the integrated geomorphic index (*I_G*) suggests significant differences between the two sides of the ATFZ. The *I_G* values decrease with slip rates in the northwestern side of the ATF, whereas wave-like in the southeastern side. The significant along-strike deformation difference between the two sides of the ATFZ may cause by differential rheology. These findings are crucial for assessing regional seismic hazards and providing new independent data to understand the Late Quaternary deformation style of the northern boundary of the Tibetan Plateau.

KEY WORDS: Altyn Tagh fault, fluvial indices, differential uplift, seismic hazards, deformation, strike-slip faults, earthquakes.

0 INTRODUCTION

The Altyn Tagh fault zone (ATFZ) is one of the largest active strike-slip fault systems in the world, and defines the northern border of the Tibetan Plateau. It has undergone deformation due to continuous collisions between the Indian and Eurasian plates (Craddock et al., 2011; Yin et al., 2008, 2007, 2002; Burchfiel et al., 1989; Molnar and Tapponnier, 1978, 1975). Understanding the tectonic activity of the ATFZ is critical to comprehending plateau growth, continental deformation models, and seismic hazards. Therefore, in the last 40 years, the strike-slip rate along the main fault of the ATFZ has been intensively studied and discussed (e.g., Yun et al., 2020; Cunningham et al., 2016; Guo et al., 2016; Wu et al., 2012; Gold et al., 2011, 2009; Mériaux et al., 2005, 2004; Cowgill, 2007; Peltzer et al., 1989). Most of these studies relate to the argument of large or low slip rates (e.g., Gold et al., 2011, 2009; Zhang et al., 2007; Wang and Burchfiel, 1997) as crucial data for distinguishing be-

tween two end-member continental deformation models (e.g., Tapponnier et al., 2001; England and Molnar, 1997; Burchfiel et al., 1989; Tapponnier and Molnar, 1977). The lithosphere extrusion model, or the crustal deformation model, proposes that the India-Eurasia collision be accommodated laterally along large-scale narrow bounding fault zones through lithosphere extrusion, which is supported by the large fault slip rate (20–30 mm/yr) of the ATF (Mériaux et al., 2012, 2005, 2004; Shen et al., 2001; Van der Woerd et al., 2001; Peltzer and Tapponnier, 1988; Avouac and Tapponnier, 1993). The model emphasizes the slip rate differences between the rigid block boundary/large strike-slip fault and the area within the block. Due to the integrity of the block, the areas within the block are relatively stable with much lower slip rates compared to the boundary of the block. In contrast, the continuum model, which emphasizes that numerous, isolated fault structures partition the Eurasian collision, is supported by the slow/evenly distributed slip rate across the ATF (e.g., Elliott A J et al., 2018; Chen et al., 2013, 2012; Gold et al., 2011, 2009; Cowgill et al., 2009; Elliott J R et al., 2008; Cowgill, 2007; Zhang et al., 2007).

However, the ATFZ also experiences differential vertical uplift with peaks and summits of the mountains within the fault zone to the elevation of ~4 700–5 550 m. In fact, the ATFZ acts as a major topographic boundary sep-

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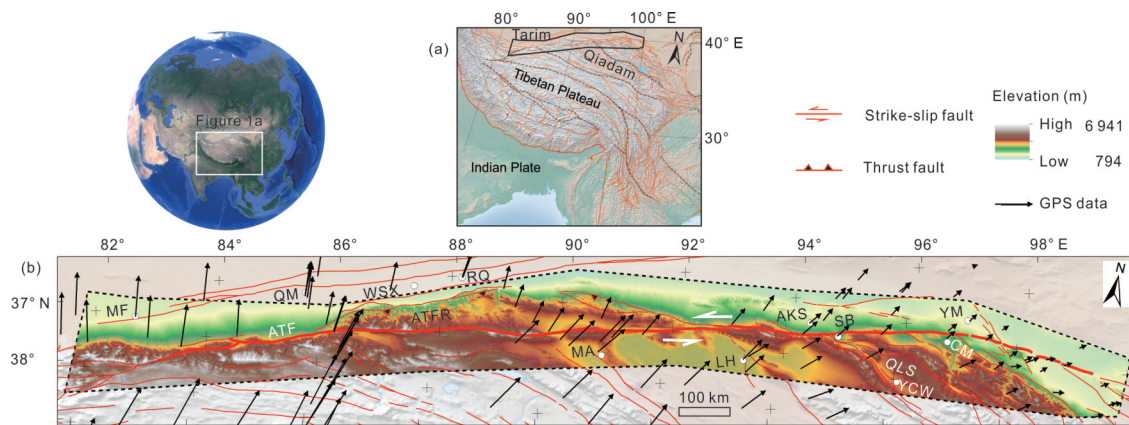


Figure 1. Topographic characteristics of Altyn Tagh and the active fault distribution. (a) The polygon outlines the study area displayed in Figure 1b; (b) topographic features of the Altyn Tagh derived from the shuttle radar topography mission (SRTM) digital elevation model. Global Positioning System (GPS) velocity field data is from Li et al. (2018). We calculated three fluvial indices in this investigation: the stream length-gradient index (SL), normalized channel steepness (K_{sn}), and hypsometric integrals (HI). MF. Minfeng; QM. Qiemo; WSX. Washixia; RQ. Ruqiang; MA. Mangai; LH. Lenghu; AKS. Aksay; SB. Subei; YC. Yanchiwan; CM. Changma; YM. Yumen; ATFR. Altyn Tagh fault range; QLS. Qilian Shan; TB. Tarim Basin; TP. Tibetan Plateau.

arating the Tarim Basin and the Tibetan Plateau with a ~3 000–4 000 m height difference. River networks are known to record horizontal offsets much more direct than vertical ones (e.g., Peltzer and Tapponnier, 1988; Meyer et al., 1996). Still with careful consideration and treatment of the climatic and lithological influences, rivers are the best recorders of vertical uplift variation. There is so far a lack of sufficient data constraint on the vertical deformation, which hinders our comprehension of how the ATFZ rises and how various faults interact within a comprehensive fault zone. Consequently, the mechanism behind the vertical growth of the ATFZ remains unclear. It is therefore essential to conduct systematic investigations on vertical motion data of the entire ATFZ to reveal the Late Quaternary uplift pattern and to understand which end member deformation model fits best.

The relief along the main strike-slip fault indicates differential vertical tectonic deformation. Previous investigations are either focused on a narrow swath of the main strike-slip fault or a small segment of a single fault within the fault zone. For example, Ye et al. (2022), using fluvial indices combined with field investigations, show that the thrust of the northern branch of the ATF was active during the Quaternary. Huang et al. (2022) analyzed topographic indices along the main strike-slip fault and found that the index values were characterized by wave-like changes from west to east. Wang et al. (2019) used K_{sn} combined with terrace archives in the eastern Altun Shan and suggested that the uplift rate rose eastward. Therefore, a systematic investigation of the entire fault zone is insufficient due to incomplete or inadequate vertical motion data. Thus far, the vertical uplift data still needs to be strengthened when referring to the rising mechanism of the mountain ranges along the ATFZ and its relationship with the activity of the main strike-slip fault, the ATF. Insufficient investigations of the vertical tectonic movement of the entire ATFZ system are also obstacles in evaluating

regional thrust fault-associated seismic hazards. Thus, in this study, we analyzed geomorphic indices on a regional scale to comprehensively reveal the Late Quaternary tectonic uplift pattern along the ATF system.

Geomorphological evidence contains information on the deformation rate, which can be used to reveal relatively fault activity and the spatial distribution of tectonic uplift anomalies (Kirby and Whipple, 2012). Subsequently, within the intermediate timescales of 10 to 300–400 ka, quantitative analyses of geomorphic indices are a reliable method for detecting landform responses to deformation processes (El Hamdouni et al., 2008; Chen et al., 2003; Keller and Pinter, 2002; Burbank and Anderson, 2001; Brookfield, 1998). In this study, we employed the hypsometric integral and river channel indices of fluvial indicators to (1) reveal the Late Quaternary differential uplift patterns on both sides of the ATFZ, (2) identify the most active thrust fault along the ATFZ, and (3) in combination with the geologic/geodetic and instrumental seismic data to determine which deformation model is most suitable for explaining the vertical deformation style along the ATFZ.

1 GEOMORPHOLOGICAL AND GEOLOGICAL SETTING

The ATF spans over 1 600 km and connects numerous blocks (i.e., the Qiangtang, Qiangtang) and the Qilian thrust system on the northern margin of the plateau. ATF separates the rigid Tarim Basin (TB) from the weak Tibetan Plateau (TP) (Neil and Houseman, 1997) (Figure 1). Previous studies suggest that the sinistral ductile shear zone along the ATF system indicated the existence of the ancient ATF, which then reactivated and became the present fault system after the collision between the Indian and Eurasian plates (e.g., Gold et al., 2009; Gehrels et al., 2003; Peltzer and Tapponnier, 1988). Measurements of total left-lateral displacement since initiation for

the central ATF range from 280 to 500 km based on an offset tectonic terrane boundary of Paleozoic Age (Gold et al., 2011, 2009; Cowgill et al., 2003), a Paleozoic plutonic belt (Gehrels et al., 2003; Peltzer and Tapponnier, 1988), a Jurassic shoreline (Ritts and Biffi, 2000), Oligocene and Miocene sediments from inferred sources (Yue et al., 2001), and reconstructions of areas with distinctive $^{40}\text{Ar}/^{39}\text{Ar}$ cooling histories (Sobel et al., 2001). Regarding the 3D magnitude of the fault, some researchers favor that the ATFZ is restricted to crustal depths (e.g., Zhao et al., 2006; Burchfiel et al., 1989), whereas others suggest that the ATFZ could reach the lower crust, and even the mantle (Bedrosian et al., 2001; Tapponnier et al., 2001; Herquel et al., 1999; Wittlinger et al., 1998).

The Late Quaternary slip rate of the main ATF has been highly debated. For example, some research groups found that the slip rates of the central and western segments were up to 17.5 ± 2 mm/yr (Tapponnier et al., 2005). The reported Quaternary slip rates in the central segment of the ATF between 83° – 94°E reaching 20–30 mm/yr by dating the alluvial fans and river terraces of the ATF (Mériaux et al., 2005, 2004). Those with high rates largely support the brittle deformation model (Tapponnier et al., 2005, 2001; Mériaux et al., 2005, 2004). However, many other research groups have suggested that the minimum Quaternary slip rate of the ATF is much slower, ~ 5 mm/yr, based on their geological investigations (Gold et al., 2011, 2009; Cowgill, 2007; Zhang et al., 2007; Wang et al., 2004, 2003; Xiang et al., 2000; Chinese State Bureau of Seismology, 1992). In addition, relatively low slip rates of ~ 10 mm/yr have been obtained based on global positioning system (GPS) and interferometric synthetic aperture radar (InSAR) measurements (Ge et al., 2022; Li et al., 2018; He et al., 2013; Zhang et al., 2007; Wallace et al., 2004; Shen et al., 2001; Bendick et al., 2000). Although the Quaternary slip rates of the ATF are still unsettled, the results of recent research with more reliable analysis, consistent with GPS and InSAR measurements, suggest that previously obtained ~ 20 – 30 mm/yr slip rate may be overestimated (Liu et al., 2020). Instead, a lower slip rate of ~ 10 mm/yr is more realistic. This rate, as the essential proof of the crust thickening model, implies that the northeastward extrusion of the ATF is limited (Liu et al., 2018; Zheng et al., 2017; Zhang et al., 2007). Regarding fault kinematics, some researchers have advocated that the ATF system is predominantly strike-slip (Zhao et al., 2006). In contrast, others suggest that the ATFZ is a transpressional system manifesting slip partitioning, with the left lateral slip focused along the main trace of the fault and thrust faulting along the North Altyn fault (NAF) (Wittlinger et al., 1998) and Qilian Shan (QLS) (e.g., Yue et al., 2004; Tapponnier et al., 2001; Bendick et al., 2000; Avouac and Tapponnier, 1993).

Concurrent with strike-slip displacement, a series of thrust faults are also active along the ATFZ. Although researchers have diligently investigated Quaternary vertical uplift rates, much of their attention has been dedicated to

dissecting the uplift processes of distinct mountain ranges, such as the Altun Shan (e.g., Jolivet et al., 2008; Yuan et al. 2006; Ge et al., 2002) and the northern Altyn fault (Ye et al., 2022). These studies, however, have only addressed the uplift history within specific periods with low resolution, due to the limited availability of chronological frameworks that were only approximate. Moreover, accessing some key field sites was challenging (e.g., Wang et al., 2019; Yuan et al., 2006). Thus, compared with the strike-slip rates, the intensity and distribution pattern of the tectonic uplift rates across the ATFZ are yet to be determined precisely.

2 DATA AND METHODS

Vertical movement constraints along the ATFZ are derived from a diverse array of sources, including geomorphic analysis-derived data, leveling data, river incision rates, seismicity data, and field validations. Shuttle Radar Topography Mission (SRTM) elevation data with a resolution of 90 m are used for geomorphic analysis. Regional geological maps at the scale of 1 : 500 000 (Figure 2) were used for lithological factor analysis, and precipitation data extracted from the Worldclim database v2.1 from 1970–2000 (<http://worldclim.org>) were used to investigate how climate affects geomorphic indices. River tool 3.0 (<http://rivix.com>), a commercial software is used to extract the drainage network. We classified the lithologies into six major groups (Table 1), and calculated three fluvial indices: stream length-gradient index (SL), normalized channel steepness (K_{sn}), and the hypsometric integrals. We first calculated the indices based on DEM, and then we selected the indices underlay with uniform lithology to exclude the influences from different rock resistance. We further statistically analyze the potential influences from differential rainfall to minimize the climatic impact factor. Finally, we integrated the indices into a normalized indice by using the fuzzy membership method. SL values were calculated following Chang (2014), and K_{sn} values were calculated following Schwanghart and Scherler (2014). We processed the hypsometric integral (HI) following the method developed by Chen et al. (2003). In addition, we statistically probed three major factors that can affect the values of the indices: (i) lithological contrasts, (ii) precipitation, and (iii) tectonic forcing, which can induce differential uplift.

Table 1 The rock strength levels and the classification of lithological groups¹

Lithological group	Description of dominant sediments/rock type
1. Quaternary sediments	Very weak unconsolidated sedimentary
2. Clastic rock	Medium-strong sedimentary
3. Limestone	Weak sedimentary (non-clastic)
4. Granite	Extremely strong
5. Metamorphic	Strong
6. Volcanic rock	Very strong

¹ Modified after Hoek and Brown (1997).

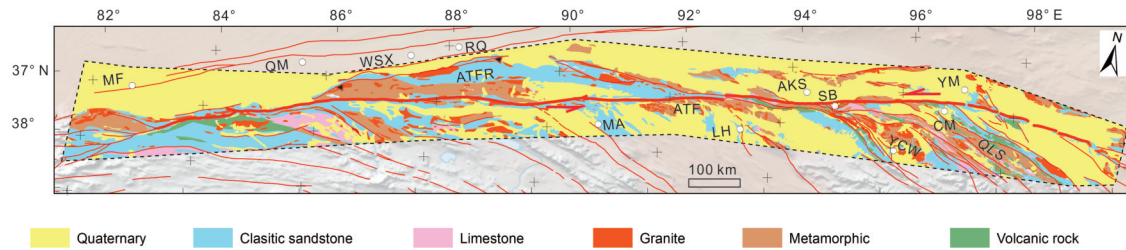


Figure 2. Map of rock types (Table 1) along ATFZ based on regional 1 : 500 000 geological map.

2.1 SL

The *SL* is a quantitative geomorphic parameter that marks river channel steepness anomalies (Hack, 1973; Strahler, 1952). As rivers and streams cross the uplifting block of an active thrust fault, *SL* values usually increase (Gao et al., 2016; Hack, 1973). By contrast, when rivers and streams flow along strike-slip faults in areas with fewer topographic changes, they typically exhibit low values (Chen et al., 2003; Burbank and Anderson, 2001). *SL* is defined as follows (Hack, 1973).

$$SL = (\Delta H / \Delta L) L \quad (1)$$

where *L* is the total length of the channel from the divide to the midpoint of the channel reach, and $\Delta H / \Delta L$ is the slope of each channel segment. We determined the *SL* values for the Strahler order from the eighth to tenth order using ArcGIS. We interpolated and re-classified the *SL* values into five groups: blue: very low (< 200 m), green: low (200–500 m), yellow: moderate (500–800 m), orange: high (800–1 000 m), and red: very high (> 1 000 m).

2.2 K_{sn}

The normalized channel steepness (K_{sn}) was developed based on information regarding the tectonic and/or climatic perturbations recorded in the stream profiles. A river channel can be represented by an empirical power-law relationship between the local channel slope *S* (m/m) and the upstream drainage area *A* (m²) in a wide range of natural settings.

$$S = k_s A^{-\theta} \quad (2)$$

where k_s is the channel steepness index as a function of the erosion coefficient (*K*) and uplift rate (*U*).

$$k_s = (U/K)^{1/n} \quad (3)$$

The concavity index θ is determined by the gradient index (*n*) and area index (*m*) as follows.

$$\theta = m/n \quad (4)$$

It is usually necessary to consider the drainage area, erosion rate, and rock uplift rate when evaluating the regional differential uplift of a large area with multiple channels (Wobus et al., 2006; Kirby and Whipple, 2001; Snyder et al., 2000). In this study, we used the normalized channel steepness index (K_{sn}) as a proxy for the uplift rate in addition to *SL* (Wobus et al., 2006; Whipple, 2004;

Kirby et al., 2003; Whipple, 2001). We used the TopoToolbox (Schwanghart and Scherler, 2014; Schwanghart and Kuhn, 2010) to calculate the K_{sn} for rivers across the ATFZ.

2.3 HI

The drainage basin hypsometry integral (*HI*) is used as a quantitative parameter for indices that could reflect anomalies in an area. The *HI* value defines the stage of a watershed (Strahler, 1952): young (hypsometric integral value close to 1), mature (values of the hypsometric integral value close to 0.5), or elderly (hypsometric integral value close to 0) (Keller and Pinter, 2002). *HI* equals the ratio of the maximum elevation to the minimum elevation. *HI* values were selected from the seventh Strahler order watershed for this study.

2.4 Statistical Tests and Calculation of the Integrated Indices

The relationships between the values of the three geomorphic indices and their potential controlling factors were analyzed using several statistical tests.

(1) Kendall's rank correlation (Figure 3) was used to measure the relationship between rainfall and the geomorphic indices (*SL*, K_{sn} , and *HI*), given that precipitation variation can potentially influence their values. The mean precipitation data for the ATFZ are available at <http://worldclim.org> and shown in Figure 4.

(2) Because the drainage basin size can also influence the geomorphic index values, for example, differences in drainage area between the 8th and 4th Strahler order are great enough to affect the geomorphic index values, and therefore, it is inappropriate to compare them directly. Thus, we selected close Strahler order of drainage basins and streams to analyze the *SL* values. We selected points mainly from the eighth Strahler order streams, and for *HI*, we calculated the values for the seventh Strahler order drainage basins. As such, we could generate sufficient data points for interpolation, and more importantly, the influence of drainage size could be minimized.

(3) To analyze the influence of different types of underlying rocks, we analyzed the possible relationships between these selected lithologies and geomorphic indices. We used the Kruskal-Wallis test (Figure 5) to check if different lithologies significantly impacted the geomorphic indices' values.

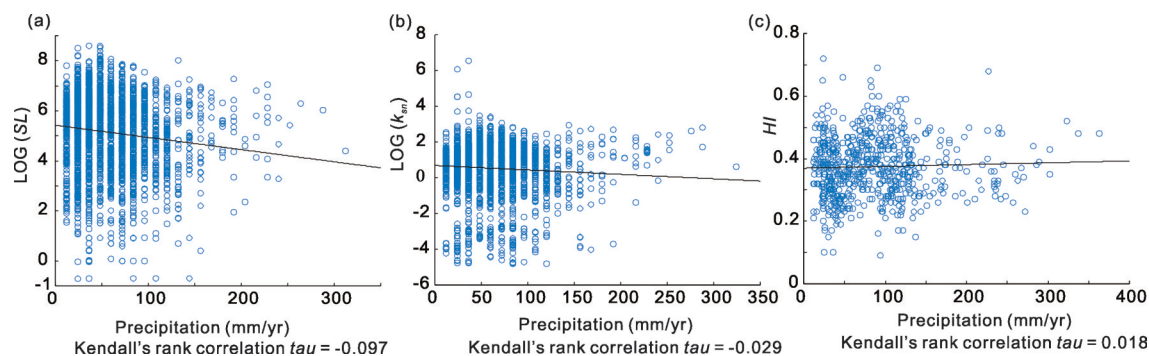


Figure 3. (a) According to Kendall’s rank correlation, precipitation lightly decreases with SL values; (b) K_{sn} decreased slightly with precipitation; (c) Kendall’s rank correlation shows that HI values slightly increase with precipitation.

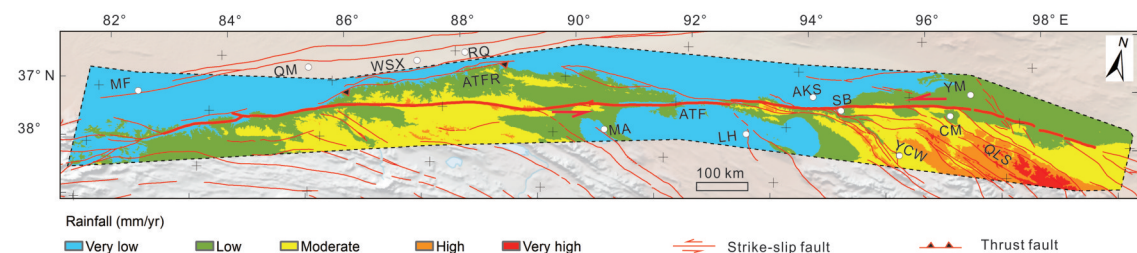


Figure 4. Mean precipitation data of the ATFZ (<http://worldclim.org>). Blue. very low (< 50 mm/yr); green. low (50–100 mm/yr); yellow. moderate (100–200 mm/yr); orange. high (200–300 mm/yr); red. very high (300–444 mm/yr). Moderate rainfall occurred mainly in the south of the ATFZ between the QM and RQ section, and the maximum rainfall occurred in the Qilian Shan (QLS) region in the north.

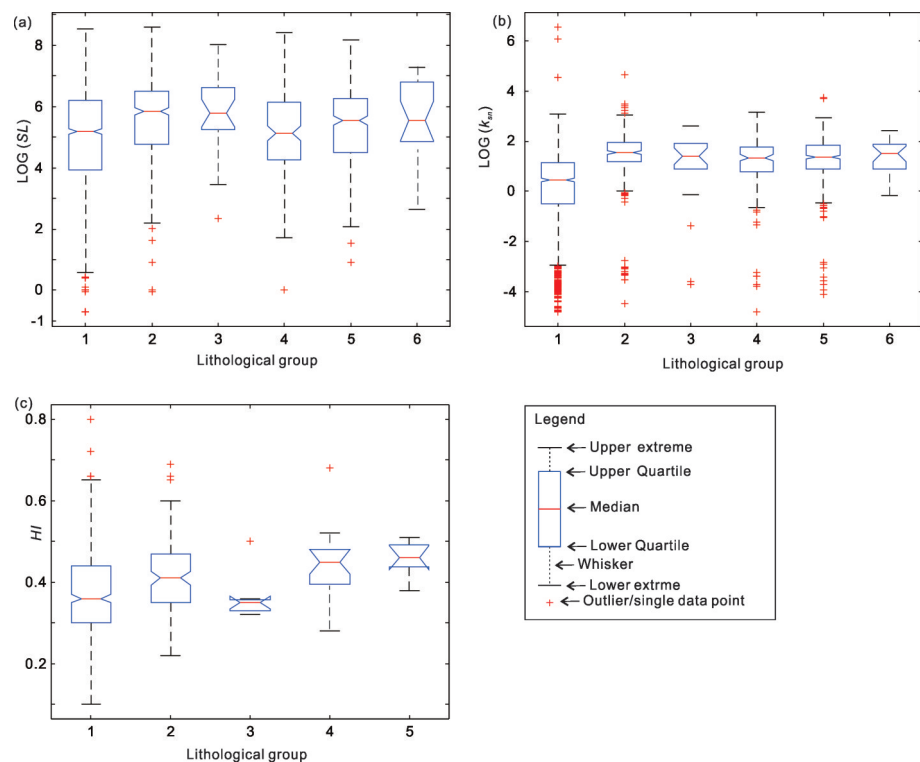


Figure 5. (a) The statistical correlation between SL values and the lithological groups that underlie them; (b) the statistical correlation between the K_{sn} values and the lithological groups that underlie them; (c) the statistical correlation between HI values and the lithological groups that underlie them. For groups of lithology, see Table 1.

Following the above-mentioned processing procedures, the potential influencing factors of climate and drainage basin size were carefully considered. Also, influencing factors from different lithology types have been excluded by selecting the indices underlaid by uniform lithology, namely clastic rocks. We used the fuzzy mem-

bership method to transform each index value into a 0–1 scale, which indicates the strength of membership in a set based on a specified fuzzification algorithm. A value of 1 indicates complete membership in the fuzzy set, while a decreasing value approaching zero indicates diminishing membership in the fuzzy set. We used the MS-Large membership type to calculate membership based on the mean and standard deviation of the input data, where large values have high membership. The results indicate that large input raster values have a high membership in the fuzzy set. We further calculated the mean values of the three rasters as integrated geomorphic indices (*IGI*) (Figure 6). We divided the ATFZ into northwestern and southeastern sides along the main trace of the strike-slip fault. Finally, we calculated the mean values for the *IGI* and compared the along-strike variations between the two sides (northwestern side and southeastern sides) of the fault.

3 RESULTS

3.1 Geomorphic Indices

3.1.1 *SL*

The ATFZ exhibited *SL* values between 1 and 4 040. Figure 7 shows that individual values were divided into five categories. Very high *SL* values were located intermittently along the southern segment of the ATFZ, from

the MF to the east of the RQ. The main strike-slip fault was located south of the ATFR until the AKS lacked apparent vertical motion. Near the SB, the *SL* values were very high in the junction area where the strike-slip fault meets the thrust faults. Further to the east, a few patches with very high values were distributed in the QLS (Figure 7). The *SL* values decreased lightly with mean precipitation data (Figure 3a).

According to the Kruskal-Wallis test results, the lowest *SL* value was associated with granite, which is highly resistant to erosion and unconsolidated Quaternary sediment. In contrast, the highest *SL* value was associated with clastic rocks (Figure 5a). A previous study suggested that lithological and/or tectonic uplift changes significantly affect the *SL* value (Pérez-Peña et al., 2009). To further test the impact of lithology, we analyzed the *SL* values of the exposed clastic rocks (Figure 8). The results show that the fault junction area near the SB and southwestern end of the ATFZ had very high *SL* values (> 1 000). The ATFZ and northern QLS showed high *SL* values (800–1 000).

3.1.2 K_{sn}

The study area had a K_{sn} value between 1 and 699. Figure 9 depicts the five value ranges used to group individual values. Very high index values were located along

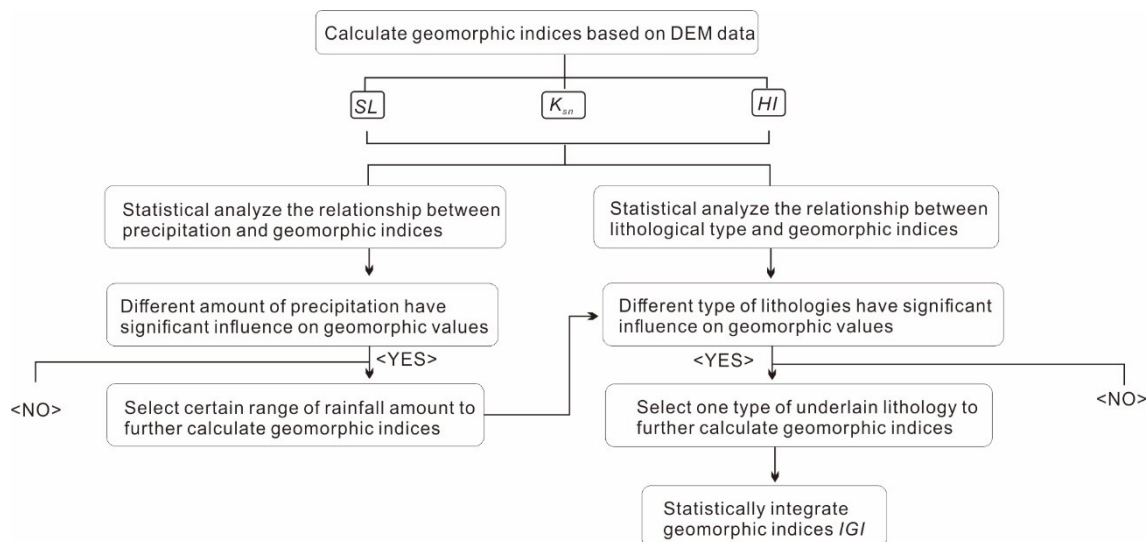


Figure 6. Workflow chart of integrated geomorphic indices (*IGI*) calculation.

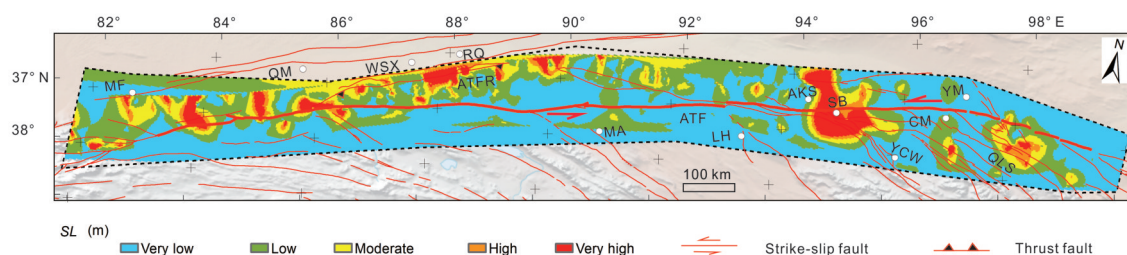


Figure 7. Values of the stream length gradient (*SL*) are interpolated for the Strahler order eighth and above streams. The colors represent the interpolated values: blue. very low (< 200 m); green. low (200–500 m); yellow. moderate (500–800 m); orange. high (800–1 000 m); red. very high (> 1 000 m).

the southern segments of the ATFZ, ATFR, SB Section, and QLS. High values were observed at the southern end of the ATFZ (Figure 9). Moderate-to-low or very low values dominate areas along the main strike-slip fault south of the ATFR. The K_{sn} values were not significantly correlated with the mean precipitation (Figure 3b). According to the Kruskal-Wallis test results, clastic rock had the highest K_{sn} value. In contrast, Quaternary loose sediments had the lowest K_{sn} value (Figure 5b). A previous study suggested that lithological and/or tectonic uplift changes could affect the K_{sn} value (Bernard et al., 2019). To further test the impact of lithology, we analyzed the K_{sn} values of the exposed clastic rock (Figure 10). The results show a similar pattern as exhibited in Figure 9.

3.1.3 HI

The majority of the drainage systems in the study area had a mean HI value of 0.37, indicating that these basins were near-mature. The ATFR accounts for most of the high values (red color) in the HI distribution, while along ATF, the main trace of the strike-slip fault, the high values are located where fault geometry has changed. Near the SB and QLS, a few drainage basins showed high to very high values (Figure 11). The very low was

distributed mainly along the section south of ATFR and the segment north of LH.

Kendall's rank correlation revealed a near-zero ordinal association between the HI and mean precipitation data (Figure 3c). According to Kruskal-Wallis test results, limestone or loose Quaternary sediments had the lowest HI values. In contrast, granite, with high resistance to erosion, had the highest HI values (Figure 5c). To further test the impact of lithology, we analyzed the HI values of the exposed clastic rock (Figure 12). The results show a similar pattern as exhibited in Figure 11.

3.1.4 Integrated geomorphic indices (IGI)

In the ATFZ, the IGI distribution revealed a spatial pattern, with most of the high values (red color) in the ATFR, while along AFT, the very high values were distributed more on the southern section of the ATF. High values were also located where the fault geometry had changed or was partitioned on the southeastern side of the ATF. For example, the area near the SB and QLS showed patches of high to very high values (Figure 13a). Very low values were distributed mainly along the ATF segment south of the ATFR and further east of the SB. Compared with the thrust faults, we found that along the main

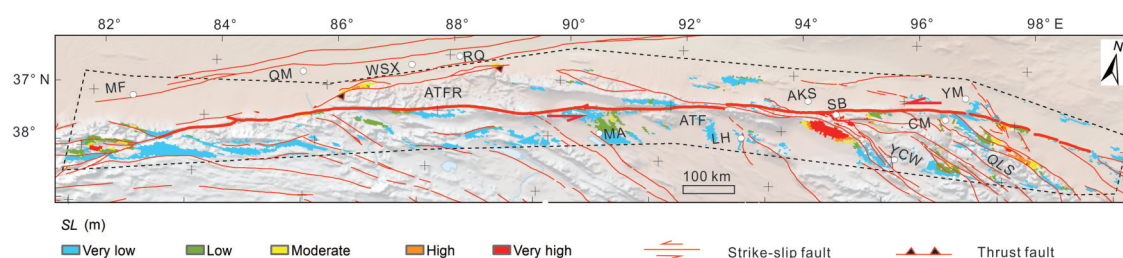


Figure 8. SL values for sandstone-covered streams.

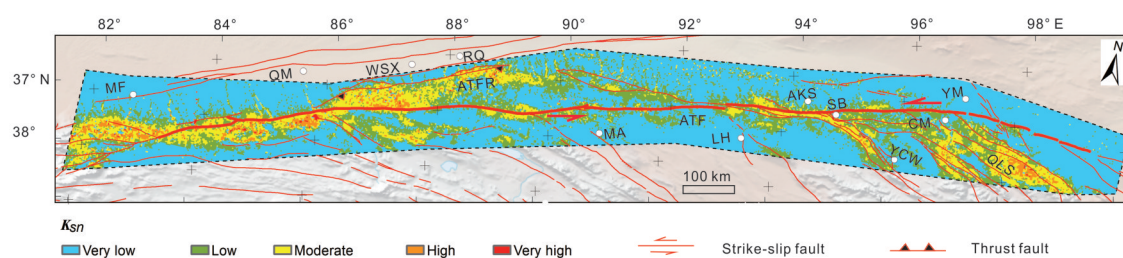


Figure 9. Normalized channel steepness index (K_{sn}) map with a reference concavity ($\theta_{ref} = 0.45$). The colors represent the following values: blue is very low (< 2.7), green is low (2.7–5), yellow is moderate (5–10), orange is high (10–20), and red is very high (> 20).

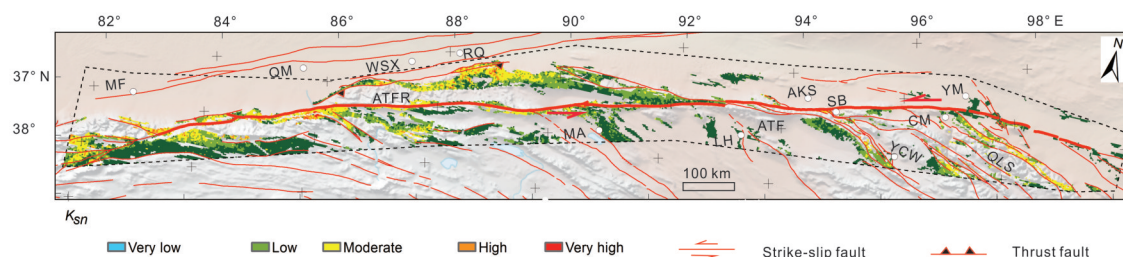


Figure 10. K_{sn} values for sandstone-covered streams.

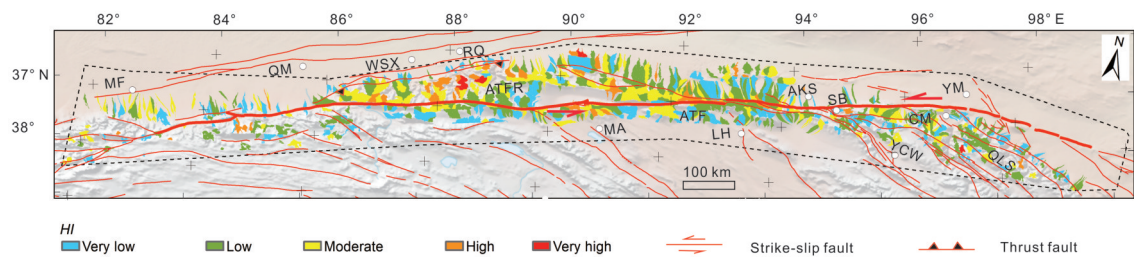


Figure 11. The hypsometric integrals (*HI*) of the seventh Strahler order drainage basins. The catchment colors represent the following values: blue. very low (< 0.3); green. low (0.3–0.4); yellow. moderate (0.4–0.5); orange. high (0.5–0.6); red. very high (> 0.6).

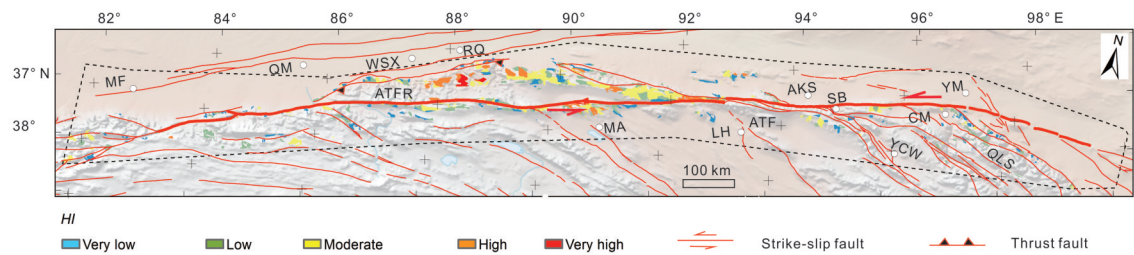


Figure 12. *HI* values for drainage basins underlain by sandstone.

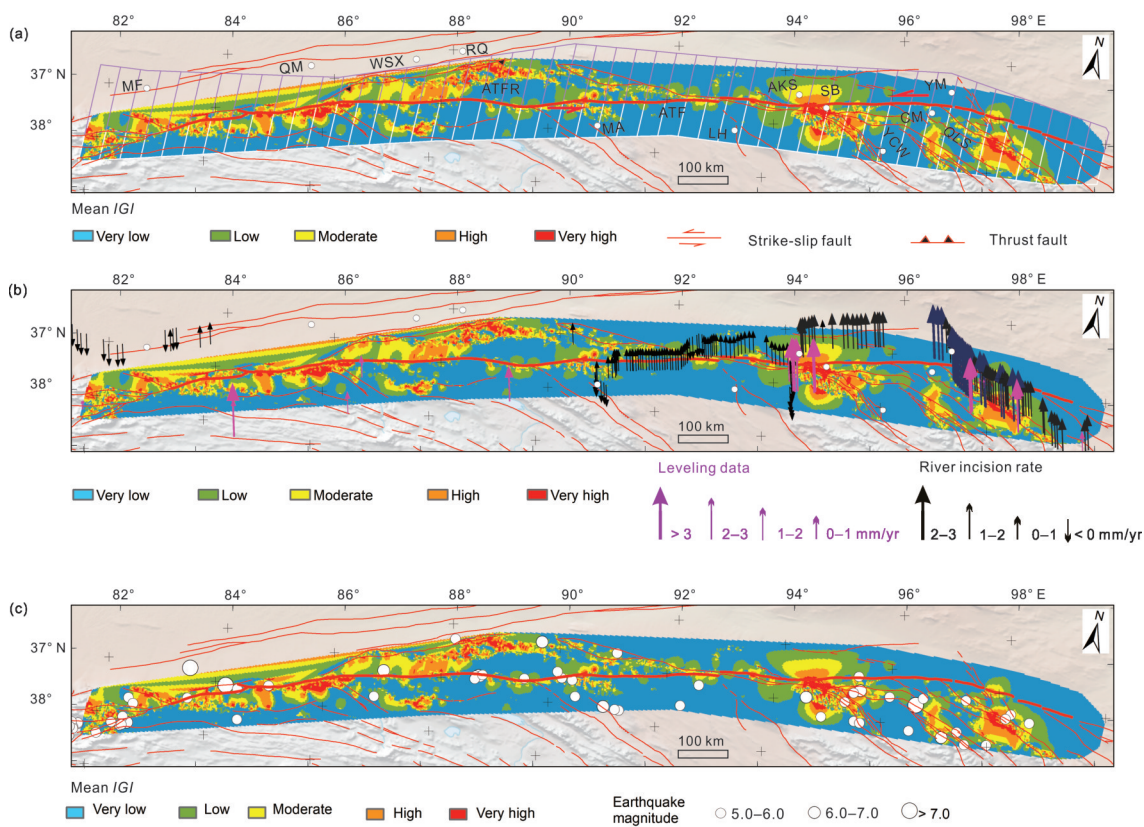


Figure 13. (a) Integrated geomorphic indices (*IGI*) values underlying clastic sediments; (b) *IGI* map and the decadal uplift rates derived from leveling data and long-term river incision rate compiled after Tao et al. (2020); (c) *IGI* map and the distribution of the earthquakes (magnitude ≥ 5). NQL. North Qilian thrust belts; HS. Hei Shan.

strike-slip fault trace, the *IGI* values were very low or moderate, except for the local branching area or geometry changing area, such as the area northwest of the MA.

3.2 Spatial Variations from Geodetic/Geological Data
3.2.1 Leveling data

Modern geodetic techniques such as GPS and leveling data can constrain the present uplift rates. We com-

piled leveling data for the study area from 1978–1988, 1990–2000, and 2012–2015 (Figure 13b). A Helmert joint adjustment method was implemented to integrate cGNSS and leveling data effectively (Wu et al., 2022). The vertical movement data points show that the central segment of the ATFZ remained at a relatively low rate of < 1 mm/yr. In the frontal thrust of the QLS, leveling data showed rates of > 3 mm/yr. The data in the southern Tarim Basin was subsiding with a low rate of 0.5–1 mm/yr.

3.2.2 Incision rates derived from river terrace dating

The formation of fluvial terraces is a response to regional tectonic deformation and climate change. Specifically, the Late Quaternary incision rates derived from fluvial terrace dating contain differential rock uplift information. We compiled 221 data points for the dated fluvial terraces in the ATFZ (Tao et al., 2020) (Figure 13b). We used the incision rate as a proxy to reflect the Late Quaternary regional uplift from 100 ka B.P., all of which was located on the southeastern side of the ATFZ. The mean incision rates showed that high or very high incision rates dominated the terraces near the SB junction and QLS region. Therefore, the regional incision rate variations were spatially associated with the integrated geomorphic values (Figure 13b).

3.2.3 Seismicity data

Instrumentally recorded seismicity data between 1903–2023 from the USGS were used for statistical analysis between the *IGI* values and the number of earthquakes/magnitudes. Figure 13c shows that the spatial distribution of earthquakes was asymmetric, with more earthquakes occurred on the southeastern side of the ATFZ. The density of the seismicity is high near the SB Section.

3.3 Field Evidence for Differential Tectonic Uplift and Fluvial Incision

We assessed whether the actual geological and geomorphic settings corresponded to the *IGI* values calculated from the field observations. We found gentle relief with very low *IGI* values north of the CM and SBC (Figures 14a, 14b). In areas with very high *IGI* values, we observed deeply incised streams along the SB (Figures 14c, 14d). In the basin west of Altun Shan (ATS) and east of Lapeiquan (LPQ), moderate relief topography had moderate *IGI* values (Figures 14e, 14f). In general, the values of the calculated geomorphic indices are in line with the observed tectonic landforms, with high values in areas with active uplift and moderate-to-low values in areas with strike-slip faulting dominance or relatively stable tectonics.

4 DISCUSSION

4.1 Influencing Factors for Geomorphic Indices

Drainage basin size may correlate with *SL*, *K_{sn}*, and *HI*. Because we had already selected drainage basins with similar Strahler orders, the influence of this factor was minimized. Similarly, using this strategy, previous

studies have shown that geomorphic values, closely ordered streams or drainage basins have a close-to-zero Kendall's rank statistical correlation.

Precipitation may also influence the *SL*, *K_{sn}*, and *HI*. This is because precipitation can alter the erosional processes by either increasing or decreasing runoff, which is the primary agent in transporting and removing eroded sediments (Weissel et al., 1994). The three geomorphic indices and precipitation data were statistically analyzed to demonstrate that the index values were not significantly associated with precipitation (Figure 3). The *SL* values slightly decreased with increasing rainfall. However, this influence can be neglected because the number of *SL* points distributed in rainfall areas greater than 200 mm/yr was only 0.7% of the total *SL* values. These findings suggest that precipitation does not primarily influence the *SL*, *K_{sn}*, and *HI* values. One of the critical reasons for this is that a dry environment with a small amount of rainfall ranges narrowly from 0–400 mm/yr.

Third, *SL*, *K_{sn}*, and *HI* were affected by the lithological contrast between granite and soft Quaternary sediments (Figure 5). This result is consistent with the significance of lithology in determining erosion processes (Nadeu et al., 2015; Pedrera et al., 2009; Harkins et al., 2005), which suggests that *SL* is insensitive to sedimentary basins and sensitive to hard outcropping rocks. Therefore, we further analyzed *SL*, *K_{sn}*, and *HI* in regions with uniform lithology, the clastic rock, to ward off the effects of various lithologies. Finally, after excluding potential factors from climate, drainage size, and lithology, we statistically integrated the three indices into *IGI* values. Thus, a direct association between the *IGI* value and relative tectonic uplift rates was established.

4.2 Implication for the Late Quaternary Deformation, Differential Rheological of Tectonic Units, and Thrust Fault-Related Seismic Hazards

The *IGI* revealed significant differences between the two sides of the ATF (Figure 15). The elevation and *IGI* were positively correlated on the northwestern side. The ATFR exhibited the highest *IGI* values. South of the ATFR, the *IGI* remained relatively high. This indicates that for a rigid block, the area experienced strong local compression. Such an area tends to exhibit high *IGI* values. The along-strike *IGI* values on the northwest side of the ATFZ generally decreased, with smaller peaks at the AKS-SB Section and Hei Shan (HS). This may suggest that the along-strike shortening or uplift in the fault zone was also decreased eastward.

In contrast, the elevation and integrated geomorphic indices were negatively correlated on the southeastern side. The high peaks are located near the SB and NQL, which are higher than the QM section in the south. The along-strike *IGI* values are opposite to the eastward dropping of the along-strike horizontal slip rate from $\sim 10 \pm 2$ to 0 ± 2 mm/yr of the ATF (Wang and Shen, 2020; Zhang et al., 2007). The pattern of eastward decrease in horizontal slip rate, the high *IGI* values in the QLS, and more

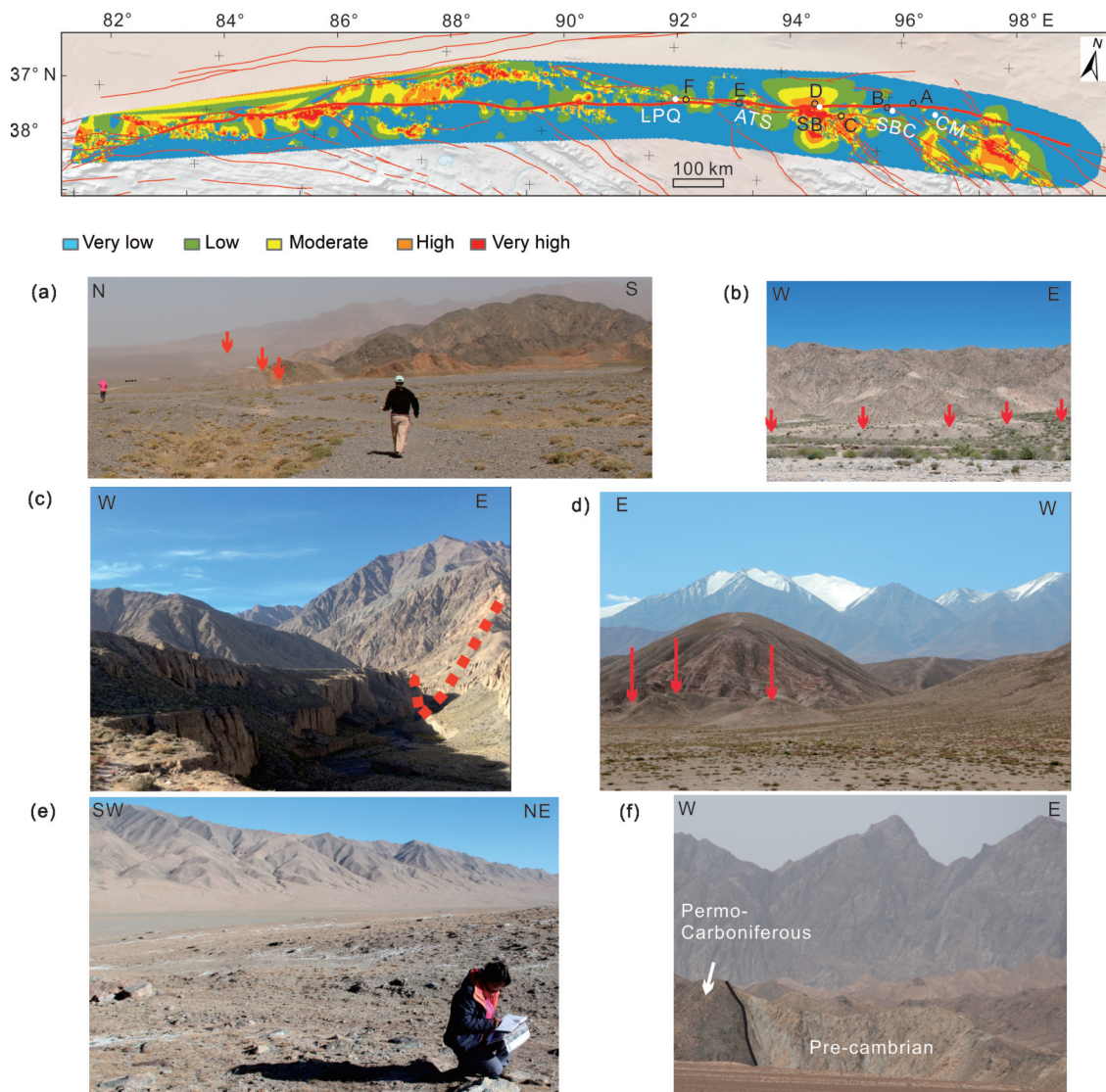


Figure 14. The top figure is the *IGI* value map with locations of field validation sites (a)–(f): The topography in field photo (a) has very low *IGI* values and low relief at the eastern end of ATF. Red arrows point to the strike-slip fault trace. (b) Low-relief topography with very low *IGI* values near the SBC section of the ATF, with red arrows pointing to the fault trace. (c) The fault sinistrally offsets the alluvial fan, and the river channel shows an incised “V” shaped valley with high *IGI* values. (d) Topography with high relief and extremely high *IGI* values. South dipping Oligocene–Miocene red layers thrust on top of the surface. (e) Moderate *IGI* values to the west of Altun Shan (ATS). (f) Local steep topography where multiple faults meet with moderate to high *IGI* values. LPQ. Lapeiquan; ATS. Altun Shan; SBC. Shibaocheng.

faulted geological units on the southeastern side of the ATF indicate that, partial deformation may be absorbed and contribute to an increase in topography in the southeastern side of the ATFZ. Still, in areas experiencing compression, such as the northwest corner of the Qiadam Basin, where the main strike-slip fault joined the QLS, the highest *IGI* peak value still manifested at the SB segment, with the second peak value within the QLS Mountain. Within the Qiadam Basin, the *IGI* values are relatively low and uniform (Figure 15c). The section near the QM and southern end of the ATFZ shows similar high values. This phenomenon indicates that crustal deformation was also involved in the topographic building. Therefore, for the southeastern side of the ATFZ, which consists of multiple collided blocks, both the “continuum model” and the

“brittle deformation model” may co-contribute the rising of the topography.

Recent GPS data obtained across the central ATFZ revealed asymmetric straining on both sides of the fault. Deformation is absorbed by straining within the southeastern side of the ATFZ, but with very little shortening in the northwest side of the ATFZ (Ge et al., 2022). The along-strike *IGI* values of both sides of the fault are consistent with this asymmetric GPS-revealed pattern (Figure 15). On the northwestern side of the ATFZ, the NAT system is the northern bounding fault of a rhomb-shaped transpressional strike-slip duplex along the ATF system that coincides with the Altyn Mountains. The transpressional deformation could be restricted to the duplex (Cowgill et al., 2000). The geomorphic anomalies revealed

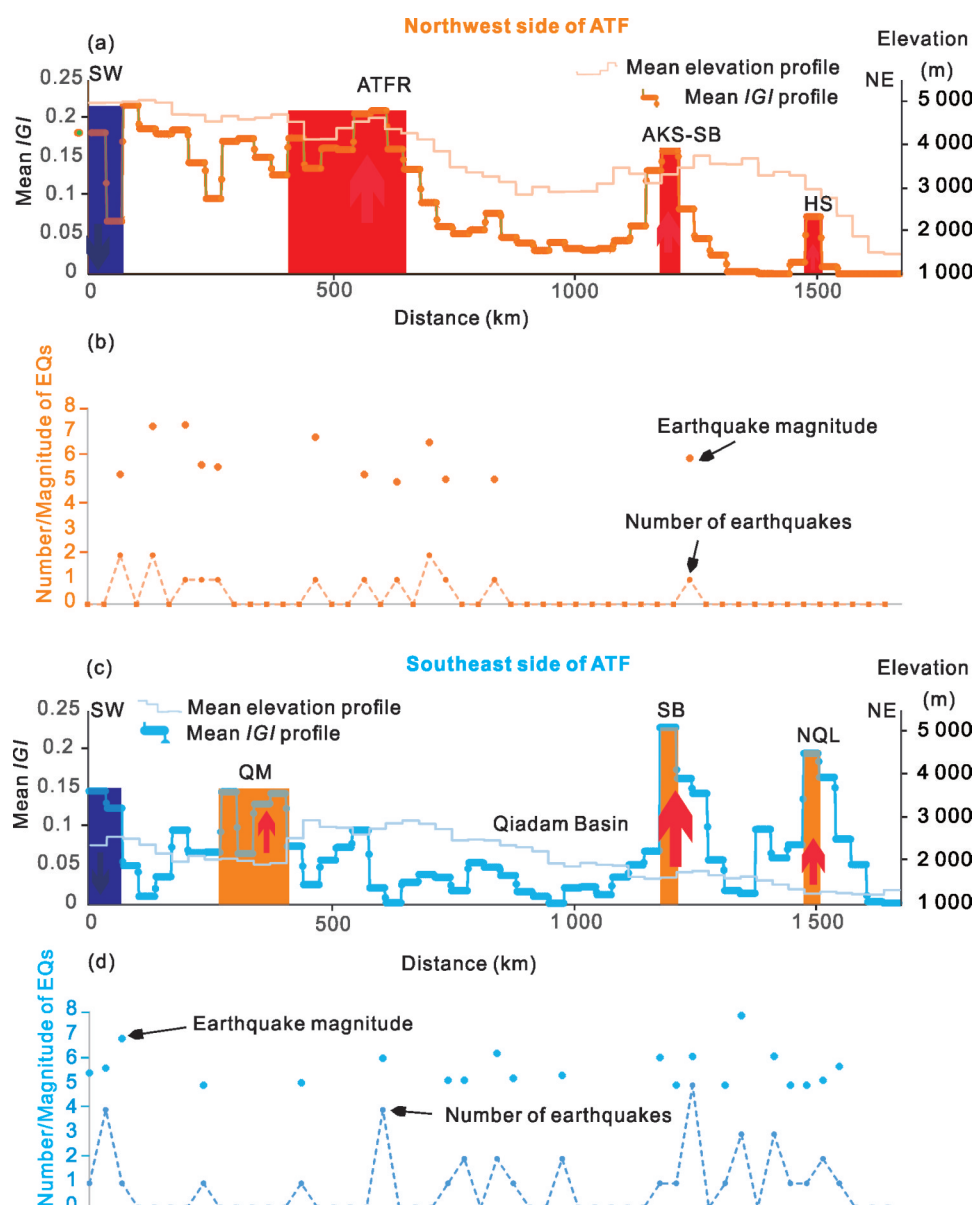


Figure 15. (a) Along-strike *I/GI* profile and elevation profile for the northwestern side of the ATF. (b) Along-strike distribution of the historic earthquakes and their magnitudes in the northwestern side of ATFZ. (c) Along-strike *I/GI* and elevation profile for the southeastern side of the ATF. (d) Along-strike distribution of the historic earthquakes and their magnitudes in the southeastern side of ATFZ. Earthquake data is from USGS (1903–2022) (<https://earthquake.usgs.gov/>). The red arrows in different sizes indicate the sections that experienced different intensities of uplift. The dark blue arrows indicate the fault sections that experienced subsiding. See Figure 13a for the location names.

that the Altyn mountains are still experiencing rapid uplift. Notably, the WSX-RQ segment experienced a relatively rapid uplift compared with the other segments. On the southeastern side of the ATF, most of the high geomorphic index values occurred at the junction areas where the thrust faults met the main trace of the ATF, such as the sections near the QM and SB.

In particular, the distribution of earthquakes and their magnitudes were associated with areas with high *I/GI* values (Figure 15). On the southeastern side, the earthquakes showed a distributed pattern with an indirect association with the *I/GI* profile. Due to tectonic influences on the topography that have continued over the last thousands of years, the *I/GI* indices' time scale is much longer

than modern seismicity, and the faults' slip rates may vary over time. However, if seismicity recurrence follows "characteristic" slip or time, which means fault slips at a relatively uniform rate within Late Quaternary, which is the case for the Haiyuan fault and Kunlun fault (i.e. Li et al., 2009; Van der Woerd et al., 2002), then the long-term relative slip rate of a fault revealed by the *I/GI* values could be analyzed and compared with seismicity parameters, such as the magnitude (*M*), which is determined by the average displacement (Biasi and Weldon, 2006). So far, there is insufficient data to show whether the seismicities along the main ATF and its sub-branches follow the "characteristic model" or not.

The Late Quaternary uplift differences exhibited on

both sides of the ATF suggest that the seismic hazards associated with active thrust faults need to be investigated in detail in areas where faults are partitioned (Figure 13c), particularly in the SB Section on the southeastern side of the ATF. On the northwestern side of the ATF, the section near WSX-RQ requires additional detailed paleoseismological work.

5 CONCLUSIONS

This study quantitatively analyzed the geomorphic characteristics of the ATFZ. The geomorphic indices revealed differential Late Quaternary uplift patterns on both sides of the ATFZ.

(1) Statistical analysis of the relationship between various impact factors and geomorphic indices indicated that lithological contrasts significantly impact SL , K_{sn} , and HI . SL , K_{sn} , and HI showed relatively low values in soft Quaternary sediments, whereas clastic sediments and sandstone exhibited the high/highest values.

(2) On the southeast side of the ATFZ, at least two major compressional areas (QM and SB sections) show that the near E-W trending thrust faults block horizontal motion and partially transfer it to vertical uplift. While on the northwestern side of the ATFZ, the ATFR is the main feature experiencing Late Quaternary rapid uplift. The IGI pattern was consistent with the GPS results in the central ATFZ. The asymmetrical pattern of the spatial distribution of the rapid uplift indicates that the different tectonic behaviors of the two sides of the ATFZ are closely associated with the differential rheology of different tectonic units, such as the relatively undeformed Tarim Basin on the northwestern side and the relatively faulted geological units on the southeastern side of the fault. Still, there are deformation variations on the southeastern side of the fault from south of QM to Qaidam and Qilian Shan. The Qaidam Basin is a smaller rigid block than the Tarim Basin, which has relatively low and uniform IGI values compared to the QM Section in the south and the Qilian Shan in the north.

(3) The southern section of the ATFR is the most tectonically active uplifted segment of the region. Hence, we suggest conducting more in-depth research to determine the seismic risks posed by thrust faults.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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