

Editorial

Tectonic Uplift Variations along the Danghe Nan Shan Constrained by Fluvial Geomorphic Indices

Yanxiu Shao^{*1, 2}, Xucong Zheng¹, Wei Wang², Xiaobo Zou³

1. Institute of Surface-Earth System Science, School of Earth System Science, Tianjin University, Tianjin 300072, China

2. State Key Laboratory of Earthquake Dynamics and Forecasting, Institute of Geology, China Earthquake Administration, Beijing 100029, China

3. Gansu Earthquake Agency, Lanzhou 730000, China

0 INTRODUCTION

The Qilian Mountain Belt, at the forefront of the Tibetan Plateau's expansion, offers key insights into the plateau's tectonic deformation (Zuza et al., 2018; Zheng et al., 2010; Zhang et al., 2004; Tapponnier et al., 2001; Meyer et al., 1998). The northwest-trending mountain ranges in the Qilian Shan ("Shan" means "Mountain" in Chinese) have significantly influenced this deformation (Zheng et al., 2013). While much research has focused on the slip rates of major boundary fault systems like the Altyn Tagh, North Qilian, and Haiyuan faults, quantitative studies on internal faults within the orogenic belt, such as the Danghe Nan Shan thrust fault, Daxue Shan fault, and Changma fault, remain insufficient. Understanding the deformation characteristics of these internal faults is crucial for comprehending the region's tectonic deformation.

The Danghe Nan Shan, situated in the northwestern portion of the Qilian Shan, exhibits geomorphic features indicative of differential tectonic activity. The range is characterized by deeply incised river valleys, asymmetric drainage patterns, and active fault segments that control regional topographic evolution (Wang et al., 2019; Zuza et al., 2018). However, the degree of spatial variability in uplift and its driving mechanisms requires further investigation. Understanding these variations is essential for reconstructing the neotectonic evolution of the region and assessing associated seismic hazards.

High-resolution digital elevation models (DEMs) have become essential for extracting topographic indices that reflect fault activity (Bian et al., 2025; Wang D et al., 2024; Zhou et al., 2022; Wang Y Z et al., 2018; Kirby and Whipple, 2012). This study utilizes SRTM 30 m data (Farr and Kobrick, 2000) to analyze the standard stream steepness index (k_{sn}) and river knickpoints. The k_{sn} effectively reveals spatial variations in erosion/uplift rates (Wang and He, 2020; Gallen and Wegmann, 2017;

Wobus et al., 2006, 2003; Kirby et al., 2003; Whipple and Tucker, 2002). while river knickpoints provide insight into temporal variations (Wang et al., 2018; Kirby and Whipple, 2012; Whipple, 2004).

This study integrates knickpoint and k_{sn} analysis to illustrate the tectonic deformation of thrust faults on both sides of the Danghe Nan Shan, enhancing our understanding of the interplay between tectonic processes and surface dynamics in the northeastern Tibetan Plateau and the region's landscape evolution.

1 RELATIONSHIP AMONG k_{sn} , KNICKPOINTS AND UPLIFT RATE

The stream power model incorporates erosion rate and geomorphic parameters. Under steady-state conditions, erosion, and uplift rates are equal, establishing a relationship between k_{sn} and uplift rate (Howard, 1994; Howard and Kerby, 1983).

$$k_{sn} = \left(\frac{U}{K} \right)^{\frac{1}{n}} \quad (1)$$

$$k_{sn} = \left(\frac{S}{A^\theta} \right) \quad (2)$$

In Equation 1, k_{sn} represents the river channel steepness index, U is the uplift rate, K denotes bedrock erodibility, and n is the slope exponent (generally set to 0.45) (Wobus et al., 2006; Kirby et al., 2003; Whipple and Tucker, 2002; Snyder et al., 2000). Thus, k_{sn} reflects the relative intensity of the uplift rate. Further studies indicate k_{sn} is also valuable for assessing transient rock uplift rates in dynamic systems (Ma et al., 2021; Wang et al., 2019, 2017; Pan et al., 2015). In Equation 2, S is the slope, A is the drainage area, and θ is a constant (typically 0.4 to 0.6) representing the relationship between drainage area and erosion rate (Wobus et al., 2003); in this study, θ is 0.45.

A knickpoint represents a distinct break in the slope along a river's longitudinal profile. Once formed, it migrates upstream, altering the channel's gradient in response to various geological and geomorphic processes. In tectonically driven knickpoint migration, k_{sn} increases downstream, resulting in a higher k_{sn} value compared to

*Corresponding author: shaoyx@tju.edu.cn

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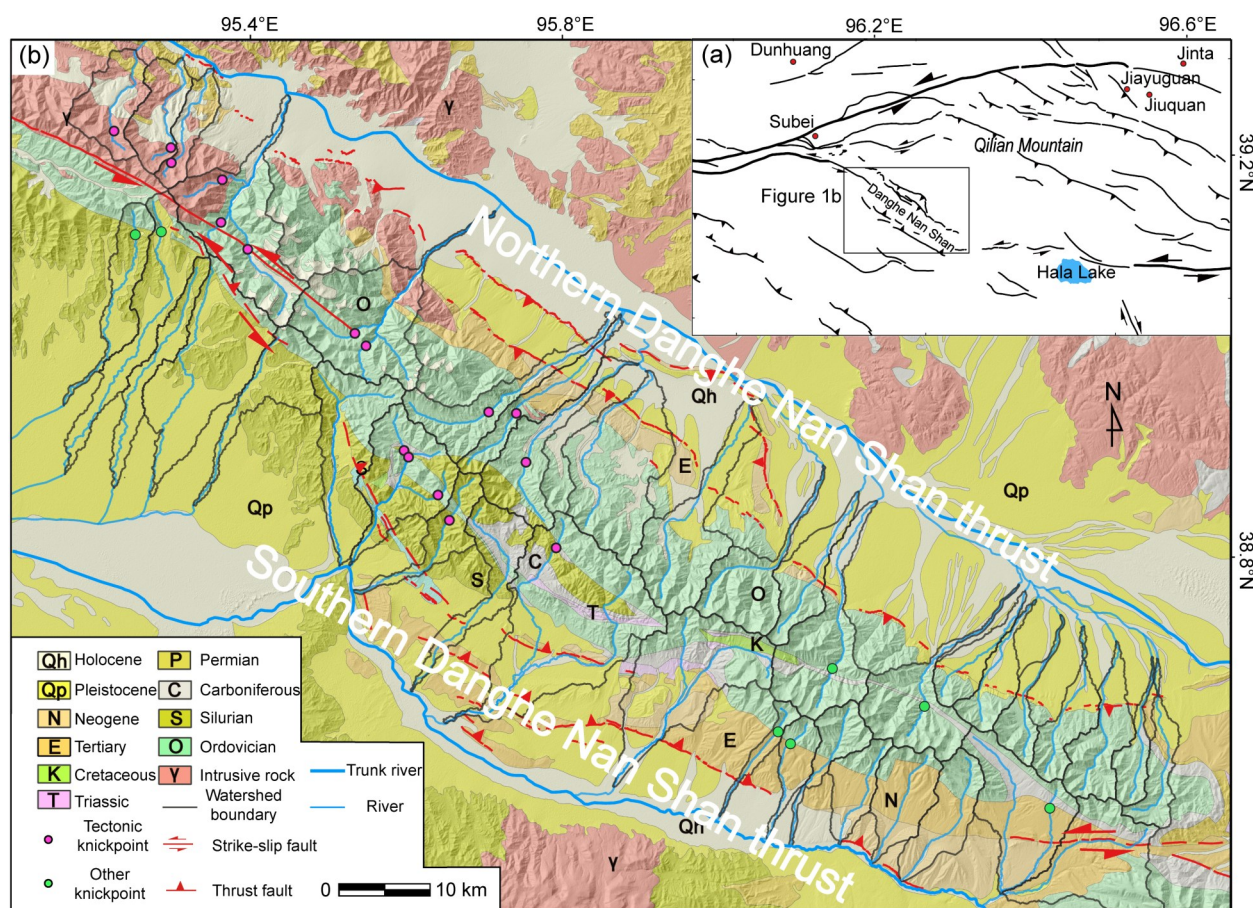


Figure 1. (a) Tectonic map of the Qilian Mountain, showing the location of the Danghe Nan Shan and surrounding fault distribution. (b) Structural map of the Danghe Nan Shan. The Danghe Nan Shan predominantly comprises Ordovician (O) metamorphic quartz sandstone. In certain areas, Silurian (S) sandstone, Carboniferous (C) sandstone and shale, Permian (P) sandstone, Triassic (T) quartz-feldspar sandstone, as well as Cretaceous (K) siltstone and mudstone are exposed. The foreland mainly comprises Paleogene (E) feldspar-quartz sandstone, Neogene (N) sandstone, Pleistocene (Qp), and Holocene (Qh) loose alluvial deposits. Thrust faults are developed on both sides of the Danghe Nan Shan, with opposing dip orientations (geological information sourced from the 2011 Gansu Province 1 : 250 000 geological survey).

the upstream segment. In contrast, non-tectonic knickpoints generally exhibit irregular k_{sn} distributions without a systematic trend (Pavano et al., 2016; Yang and Simoes, 1998). However, in the Danghe Nan Shan area, non-tectonic knickpoints display elevated k_{sn} values upstream. Consequently, the downstream k_{sn} reflects the contemporary uplift of the associated fault. Nevertheless, if the downstream section is dominated by sediment deposition, the k_{sn} value may be lower than upstream, potentially leading to an underestimation of the relative magnitude of uplift.

Based on the above illustration, this study uniformly chose 25 rivers from both the north and south sides of the Danghe Nan Shan to investigate the uplift rate in the area (Figure 2a). Rivers were chosen from basins adjacent to the watershed on both sides of the Danghe Nan Shan. The TopoToolbox package (Schwanghart and Scherler, 2014) was used to extract k_{sn} values and knickpoints, with k_{sn} calculated using Equation 2. Knickpoints were classified as tectonic (upstream k_{sn} smaller than downstream k_{sn}) or non-tectonic (upstream k_{sn} larger than downstream k_{sn}).

2 SPATIAL VARIATION IN UPLIFT RATES

Our analysis reveals that k_{sn} values on the northern flank are significantly higher than those on the southern flank (Figure 2a), indicating a greater uplift rate in the northern region. Furthermore, the k_{sn} values on both the northern and southern flanks exhibit spatial variability along the fault strike, likely influenced by differential tectonic activity and lithologic controls (Figure 2a). Notably, on the northern flank, the northwestern segment displays distinctly elevated k_{sn} values, suggesting localized regions of intensified uplift, potentially linked to variations in uplift rates and crustal deformation processes.

The elevation trend of tectonic knickpoints along the northern flank of the Danghe Nan Shan closely corresponds to that of the active fault, with an elevation difference ranging from 600 to 1 600 m (Figure 2b). Similarly, on the southern flank, the elevation trend of tectonic knickpoints aligns with the trends of three active faults, with elevation differences varying between 200 and 600 m (Figure 2c). These observations indicate that the formation of tectonic knickpoints is directly influenced by fault activity, and the downstream k_{sn} of these knickpoints

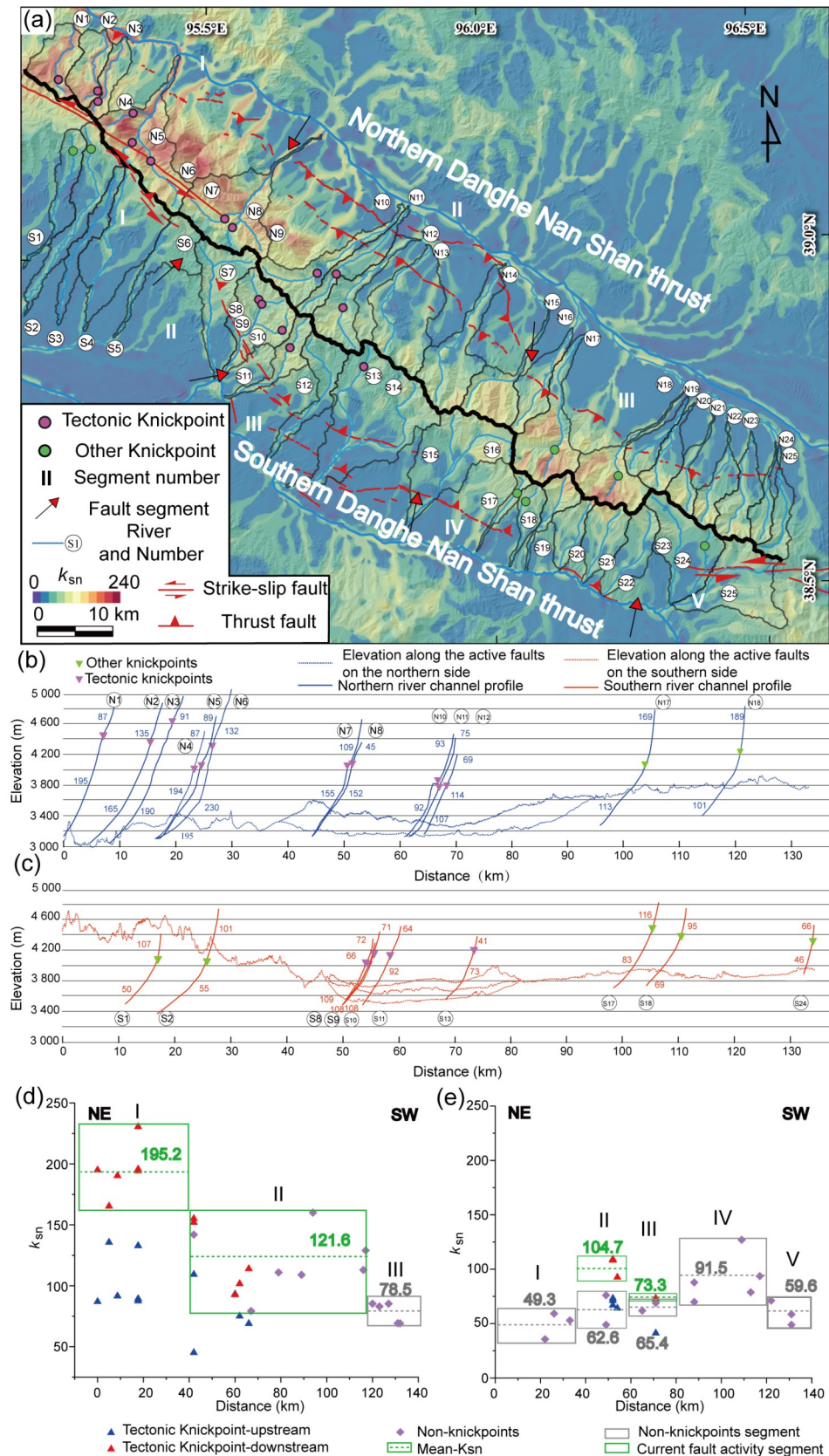


Figure 2. (a) Distribution map of k_{sn} and knickpoints in the Danghe Nan Shan region; (b) comparison of knickpoint elevation with fault elevation on the northern side, along with the k_{sn} distribution of rivers containing knickpoints; (c) comparison of knickpoint elevation with fault elevation on the southern side, accompanied by the k_{sn} distribution of rivers containing knickpoints; (d) k_{sn} distribution and segmented uplift rates for selected rivers on the northern side; (e) k_{sn} distribution and segmented uplift rates for rivers chosen on the southern side.

serves as a proxy for the current uplift rate of the associated faults. Additionally, variations in downstream k_{sn} values provide further insights into uplift heterogeneity along the fault strike, enabling segmentation of the flanks based on differential uplift characteristics.

On the northern flank, the average downstream k_{sn} values for segments I and II are $195.2 \text{ m}^{\circ.9}$ and $121.6 \text{ m}^{\circ.9}$, respectively. In contrast, no tectonic knickpoints are observed in segment III, where the average k_{sn} for river channels is $78.5 \text{ m}^{\circ.9}$ (Figure 2d). These values suggest a relative uplift rate hierarchy of $U_I > U_{II} > U_{III}$. On the southern flank, only segments II and III contain rivers with tectonic knickpoints, exhibiting average k_{sn} values of $104.7 \text{ m}^{\circ.9}$ and $73.3 \text{ m}^{\circ.9}$, respectively. The average k_{sn} values for segments I, IV, and V are $49.3 \text{ m}^{\circ.9}$, $91.5 \text{ m}^{\circ.9}$, and $59.6 \text{ m}^{\circ.9}$, respectively. Notably, although segment IV lacks tectonic knickpoints, its average k_{sn} is comparable to the downstream k_{sn} observed in segment II. This suggests the possibility that knickpoints in segment IV have migrated upstream and have disappeared at the divide. Despite this, the similar k_{sn} values between segments II and IV imply comparable uplift rates, leading to the inferred uplift rate hierarchy on the southern flank: $U_{II} = U_{IV} > U_{III} > U_I = U_V$. These results highlight the spatial variability of tectonic uplift in the Danghe Nan Shan.

Previous studies targeting the northern Danghe Nan Shan thrust system have provided localized assessments of its structural geometry and kinematic behavior

(Shao et al., 2023; Xu et al., 2021; van der Woerd et al., 2001; Meyer et al., 1998). Quantitative rate constraints exist for distinct segments: Shao et al. (2023) reported a vertical uplift rate of $1.4 \pm 0.4 \text{ mm/a}$ and a shortening rate of $0.8 \pm 0.2 \text{ mm/a}$ at the western terminus, while Xu et al. (2021) estimated rates of $0.6 \pm 0.2 \text{ mm/a}$ (uplift) and $0.8 \pm 0.2 \text{ mm/a}$ (shortening) in an eastern segment. The results indicate apparent uniformity in shortening rates but suggest a significant eastward gradient decrease in the rate of vertical uplift along the thrust. This result is consistent with the findings observed by k_{sn} (Figure 2d), which typically indicates an uplift rate on the order of 10^3 to 10^5 years (Wang et al., 2023).

A comparison of uplift rates derived from k_{sn} with fault geometry in the Danghe Nan Shan region indicates that hanging walls associated with single fault strands exhibit higher uplift rates than those associated with multiple fault strands. Specifically, along the northern flank, segment I, characterized by a single-strand thrust, is associated with a higher uplift rate compared to segment II, which comprises double-strand thrust faults and shows a lower uplift rate (Figure 3). A similar spatial pattern is evident along the southern flank, where segment IV (single-strand fault) exhibits a greater uplift rate than segment III (multiple fault strands) (Figure 3). These observed variations in uplift rate are hypothesized to be primarily attributable to differences in fault dip angles (Figures 3b, 3c, 3d). Steeper dip angles, generally associated with single

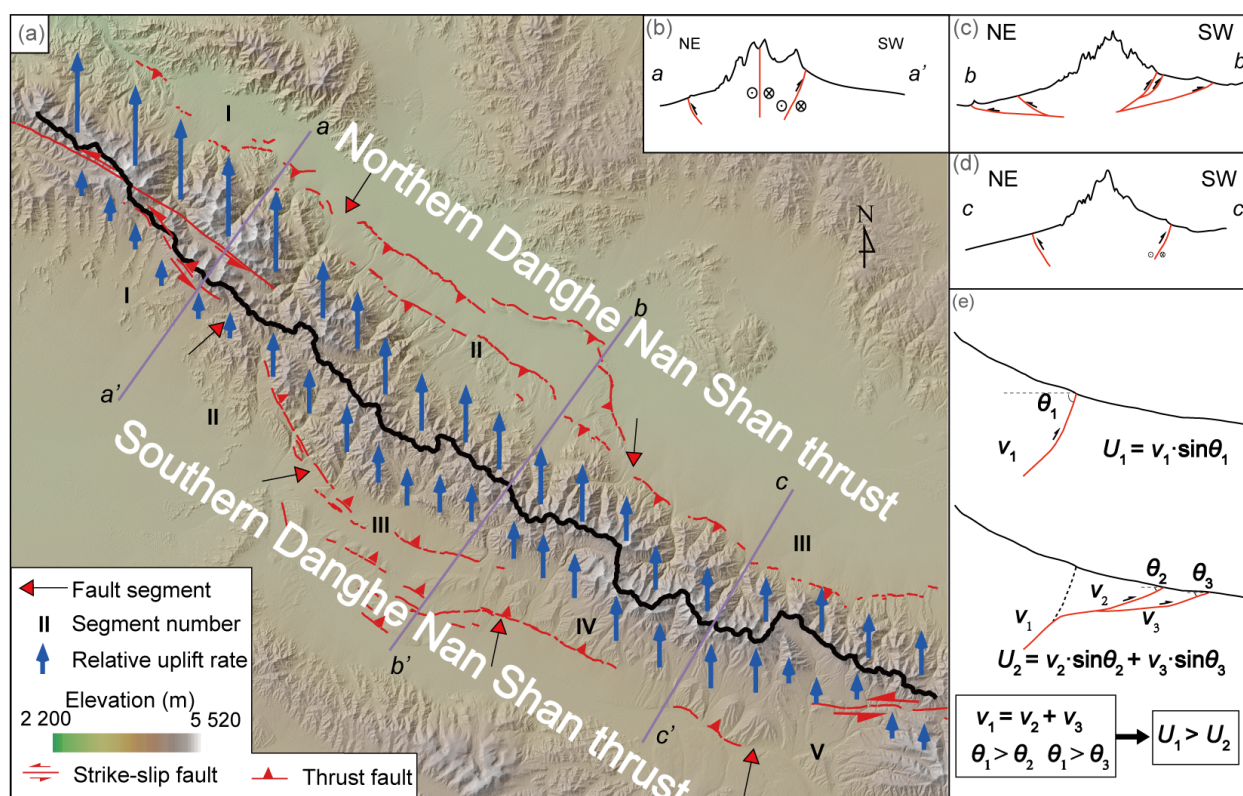


Figure 3. (a) Segmentation of relative uplift rates of the Danghe Nan Shan fault; (b) profile $a-a'$ illustrates the tectonic model of the western part; (c) profile $b-b'$ presents the tectonic model of the central part; (d) profile $c-c'$ depicts the tectonic model of the eastern part; (e) a schematic diagram showing how fault geometry influences uplift rates.

faults as depicted schematically in the kinematic model (Figure 3e), are expected to yield a larger vertical component of uplift for a given magnitude of horizontal shortening. However, additional factors likely influence local uplift rates, including probable strain partitioning onto adjacent fault systems. For instance, the reduced uplift rate observed in southern segment I may be explained by significant deformation accommodation along a strike-slip fault within that segment. Similarly, lower uplift rates in segments III and V could result from the transfer of substantial deformation to an eastern strike-slip fault system (Figure 3a; Zheng et al., 2013). Collectively, these observations suggest that geomorphic analyses based on metrics like k_{sn} can effectively delineate spatial variations in uplift rates along active thrust systems and may provide valuable indirect constraints on subsurface fault geometry and regional strain distribution.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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