

1 **Normal Faults and Tectonic Model of the Bamei-Kangding Segment within the**
2 **Southern Xianshuihe Fault Zone in Eastern Tibet**

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22 **Key Points:**

- 23 ● The Mugecuo fault comprises two branches with cumulative sinistral slip of 2.3 ± 0.2
24 mm/yr and variable vertical slip (0.1~0.8 mm/yr).
25 ● The NW segment of the Zheduotang fault inherits primary deformation from the Selaha
26 fault with sinistral slip of 6.7 ± 1.4 mm/yr.
27 ● Releasing stepover accommodates right-stepping Yalahe, Selaha, Mugecuo, and
28 Zheduotang faults and explains normal faulting.

1. Abstract

The left-lateral strike-slip Xianshuihe fault (XSHF) located in the eastern Tibetan Plateau is considered one of the most tectonically active intra-continental faults in China. Despite extensive research on the XSHF, the detailed late Quaternary slip rates of secondary faults and mechanisms for significant normal faulting observed within the Bamei-Kangding segment remain poorly understood. Through integrated analysis of satellite imagery, field surveys, and small Unmanned Aerial Vehicle (sUAV) photogrammetry-derived Digital Elevation Models (DEMs), coupled with multiple dating methods (^{10}Be Terrestrial Cosmogenic Nuclide and Optically Stimulated Luminescence) to date moraines offset by the faults, we reveal a unique tectonic setting where the left-stepping NW Xianshuihe fault and Moxi fault create a releasing stepover that accommodates right-stepping secondary faults and explains normal faulting. The 24-km-long Mugecuo fault is characterized by two primary branches (southern and northern), with sinistral slip rates of 1.2 ± 0.1 mm/yr and 1.1 ± 0.1 mm/yr, and vertical slip rates of 0.1 mm/yr and 0.8 ± 0.1 mm/yr, respectively. The Zheduotang fault exhibits distinct segmentation with its northwestern segment showing a higher sinistral slip rate of 6.7 ± 1.4 mm/yr compared to its southeastern segment. These newly constrained slip rates indicate a strike-slip-dominated system with subordinate normal faulting and progressive strain migration toward a more geometrically smooth configuration. The secondary faults vertically connect to form a negative flower structure, elevating cascading rupture potential. Fresh scarps along the Mugecuo fault may be related to the 1725 M 7.0 Kangding earthquake, highlighting significant seismic hazard implications for this region.

Keywords: Xianshuihe Fault, Slip Rate, Normal Faulting, Cosmogenic Nuclide Dating, Releasing Stepover, Tibetan Plateau

2. Introduction

Active fault systems frequently exhibit complex strain partitioning through geometric irregularities such as bends and stepovers, which can significantly influence regional deformation patterns and seismic hazards (Wesnousky, 1988; Mann, 2007; Duan & Oglesby, 2006; Liu et al., 2024). The Xianshuihe fault (XSHF), a major left-lateral strike-slip boundary between the Bayan Har and Sichuan-Yunnan blocks in the eastern Tibetan Plateau (Wang et al., 2012; Bai et al., 2018), provides an exceptional example of such complexity through its Bamei-Kangding segment (Figure 1). Recent identification of significant normal faulting within this bending segment, particularly along the Zheduotang fault (Ma et al., 2020; Yan et al., 2020; Bai et al., 2021) and the newly identified Mugecuo fault (originally termed 'Mugecuo South fault' in Pan et al., 2020; Bai et al., 2021) (Figure 2), challenges conventional understanding of fault behavior and highlights the need for detailed investigation of fault interactions at regional scales.

The ~300-km-long XSHF, extending from Ganzi County to Moxi Town, has been actively accommodating eastward extrusion of the Tibetan Plateau since the late Cenozoic (Figure 1; Tapponnier et al., 1982). Within the Bamei-Kangding segment, the fault system has traditionally been recognized as splitting into three en-echelon faults: the Yalahe (F2), Selaha

(F3), and Zheduotang (F4) (Figure 2; Wen et al., 1989; Allen et al., 1991). The segment's structural complexity is highlighted by two recently identified structures: the Mugecuo fault system (F5) (Pan et al., 2020; Bai et al., 2021), which is further subdivided into southern (F5-1) and northern (F5-2) branches, and the northwestern extension of the Zheduotang fault (Figure 2; Ma et al., 2020). Previous studies have extensively documented strike-slip motion within the Bamei-Kangding segment, with associated transtensional deformation (Allen et al., 1991; Zhou et al., 2001; Chen et al., 2008, 2016; Zhang et al., 2016; Bai et al., 2018, 2021). However, the geometry, kinematics, and rupture mechanisms of recently identified active faults remain poorly understood, particularly the mechanisms driving significant normal faulting within this predominantly sinistral strike-slip system and the variable late Quaternary slip rates along the Zheduotang fault (Pan et al., 2020; Ma et al., 2020; Bai et al., 2021).

This study employs an integrated approach combining Google Earth imagery analysis, field surveys, high-precision DEMs derived from sUAV photogrammetry (Bemis et al., 2014; Johnson et al., 2014), ^{10}Be Terrestrial Cosmogenic Nuclide (TCN) and Optically Stimulated Luminescence (OSL) dating, alongside specialized quantitative analytical tools including the Lateral Displacement Calculator (LaDiCaoz_v2.1) (Zielke & Arrowsmith, 2012) and Probabilistic Cosmogenic Nuclide Age Analysis Tool (P-CAAT) (Dortch et al., 2022). By synthesizing these new data with published regional ^{10}Be TCN ages (Strasky et al., 2009; Bai et al., 2018, 2021; Yang et al., 2023), global paleoclimate proxies (Alley, 2004; Thompson et al., 1997; Dutt et al., 2015; Dykoski et al., 2005; Berger & Loutre, 1991), late Quaternary slip rates (Bai et al., 2018, 2021), GNSS measurements (Zheng et al., 2017), InSAR observations (Huang et al., 2023; Qiao & Zhou, 2021), experimental clay models (Mitra & Paul, 2011), and high-resolution S-wave velocity models (Zhao et al., 2023), we aim to: (1) characterize the geometry of the Bamei-Kangding segment; (2) reveal the kinematics of the Mugecuo and northwestern Zheduotang faults; and (3) investigate the rupture mechanisms and cascading rupture potential within the bending Bamei-Kangding segment. The results provide new insights into complex fault system evolution (Sylvester, 1988; Cunningham & Mann, 2007) and have important implications for seismic hazard assessment in this rapidly developing region (Wang & Shen, 2020; Jiang et al., 2015).

3. Geologic Background

The XSHF represents a major left-lateral strike-slip boundary between the Bayan Har and Sichuan-Yunnan blocks in the eastern Tibetan Plateau, accommodating eastward extrusion resulting from the India-Eurasia collision (Tapponnier et al., 1982). Together with the Ganzi-Yushu and Xiaojiang faults, the XSHF forms a curved fault system following a Euler rotation pole near the eastern Himalayan syntaxis (Figure 1a; Bai et al., 2018: 25.1°N, 93.6°E; Cook et al., 2018: 25.65°N, 94.31°E). Having undergone multiple phases of activity since the Miocene, the ~300-km-long XSHF extends southeastward from Ganzi County through Kangding to Moxi Town, playing a crucial role in regional crustal deformation and block migration (Figure 1b; Wang et al., 1997; Wang et al., 1998; Wang et al., 2008; Zhang et al., 2017). The XSHF displaces diverse geological and geomorphological markers, including granitic bedrock, fluvial networks, and glacial deposits (Allen et al., 1991), providing constraints on deformation rates across multiple temporal scales. Long-term geological slip

rates derived from ~60 km sinistral offset of the Xianshuihe River and Gongga batholith, range from 3.5-30 mm/yr (Wang et al., 1998; Zhang et al., 2017), reflecting uncertainties in the timing of fault initiation and batholith emplacement. Late Quaternary investigations utilizing offset fluvial terraces, alluvial fans, and moraines document slip rates of 8-13 mm/yr with spatial variations along distinct fault segments (Allen et al., 1991; Zhou et al., 2001; Chen et al., 2008, 2016; Zhang et al., 2016; Bai et al., 2018, 2021). Contemporary crustal deformation measured through space-geodetic techniques (GNSS and InSAR) reveals a systematic southeastward-increasing gradient in sinistral motion along the fault system, with rates increasing from ~8-9 mm/yr in the northwest to ~11-18 mm/yr in the southeast (Wang & Shen, 2020; Huang et al., 2023; Qiao & Zhou, 2021; Zheng et al., 2017), similar to the pattern observed from Late Quaternary rates (Bai et al., 2018).

The XSHF displays distinct structural patterns along strike, characterized by notable segmentation. Its northwestern segment features a simple geometry with left-stepping en-echelon arrangement of linear N45°W-trending secondary faults (Luhuo, Daofu, and Bamei), forming releasing stepovers and pull-apart basins that extend for approximately 180 km (Figure 1b; Allen et al., 1991). In contrast, the Bamei-Kangding segment between Huiyuansi Basin and Kangding City exhibits complex structural characteristics with multiple sub-parallel secondary faults (Figure 2). The western Yalahe fault has a ~7 km trace near Huiyuansi Basin that becomes indistinct southeast of Yala Mountain (Bai et al., 2021; Ma et al., 2022). The centrally located Selaha fault, with its distinctive S-shaped geometry that strikes N36°W through TG and SLH sites before deflecting to N64°W across Mugecuo Lake and finally N26°W through YJG site (Bai et al., 2018, 2021). The N32°W-trending Zheduotang fault displays recently identified active faulting north of Kangding Airport, extending the active zone beyond the well-studied southeastern segment (Ma et al., 2020). The Zheduotang fault originates south of Duoriagamo village and extends southeastward, initially displaying relatively subdued geomorphic features before exhibiting clear scarps along the SW-facing slopes of the Zheduoshan Range. After passing through the Zheduoshan Pass, the fault becomes difficult to follow in the valley due to the Kangding-Lhasa highway but becomes clear again once it reaches the steep NE-facing mountain slopes west of Kangding city (Zhou et al., 2001; Yan et al., 2019; Bai et al., 2021). Finally, the newly identified Holocene-active Mugecuo fault system comprises two distinct branches with multiple N30°-60°W-trending secondary rupture strands distributed across a 3-km-wide deformation zone (Pan et al., 2020; Bai et al., 2021). These secondary faults converge south of Kangding into the linear N20°W-trending Moxi segment, which extends ~50 km from Kangding to Moxi city and cuts through the eastern slopes of the Daxue Range (where Gongga mountain lies) (Figure 2; Bai et al., 2021). The Moxi fault shows evidence of recent faulting with numerous offset moraines, gullies, and alluvial fans, and exhibits a slight normal component creating sag ponds in places (Bai et al., 2021). Geophysical evidence reveals a transformation from a single subsurface structure in the northwest to a complex negative flower structure within the Bamei-Kangding segment (Li, 2021; Li, 2020; Yi et al., 2015).

Between Huiyuansi Basin and Kangding City, a significant ~25° clockwise deflection in

fault strike forms a northeast-protruding bend centered on the Zheduo Mountain region (Figure 2; Allen et al., 1991; Wang & Burchfiel, 2000; Bai et al., 2021). This curved structural configuration is characterized by anomalous seismicity concentration and extreme topographic relief (the Yala (5,820 m) and Gongga (7,556 m) peaks) (Figures 1 and 2; Allen et al., 1991; Burchfiel et al., 1995; Zhang et al., 2017; Bai et al., 2021). The region's protracted neotectonic evolution has generated recurrent high-magnitude seismic events, including the 1786 M 7.8 Moxi earthquake that produced a >100 km surface rupture (Wen et al., 2008), the 1893 M 7.3 Bamei earthquake with extensive landslide damage (Zhou et al., 2001), and the 1955 Ms 7.5 (Earthquake Disaster Prevention Department of China Earthquake Administration, 1999; Mw 7.0 or Ms 7.1, U.S. Geological Survey, 2021; Mw 7.0, Yan et al., 2020) Zheduotang earthquake that generated significant surface deformation along a >30 km rupture zone (Li et al., 1997; Xu et al., 2022). More recent seismic activity includes the 2014 Mw 6.1 and Mw 5.7 Kangding earthquake sequence and the 2022 MW 6.7 (MS 6.8) Luding earthquake, both of which triggered numerous landslides and caused substantial infrastructure damage (Jiang et al., 2015; Fang et al., 2015; An et al., 2023). These recurring seismic events underscore the persistent strain accumulation and episodic release characterizing this tectonically-active corridor.

A distinctive feature of the Bamei-Kangding segment is the presence of significant normal faulting within the broader left-lateral strike-slip system. This is evidenced by several key observations: the ~30 m-deep Mugecuo Lake within the ~600 m-deep depression along the Selaha fault representing the local topographic minimum (Bai et al., 2021); normal faulting components along the newly identified Mugecuo fault system with fault scarps up to ~11.5 m high (Pan et al., 2020); and substantial normal displacement along the Zheduotang fault with fault scarps reaching 8-10 m in height northwest of the ZDT site (Figure 2; Yan et al., 2020; Bai et al., 2021). The Zheduotang fault, primarily constrained along the ~30 km-long rupture associated with the 1955 Zheduotang earthquake (reported as Ms 7.5, Mw 7.0, or Ms 7.1 in different sources), exhibits spatially variable late Quaternary sinistral slip rates. Multi-site studies across the rupture zone report 8.5 ± 2.0 mm/yr (Chen et al., 2008, 2016) and 4.3-6.0 mm/yr (Zhang et al., 2016), while site-specific studies within the southeastern segment yield 3.6 ± 0.3 mm/yr (Zhou et al., 2001) and 4.1 ± 0.7 mm/yr (Bai et al., 2021). This distinctive structural pattern of extensional deformation within the sinistral strike-slip dominated system provides a unique opportunity to study complex fault interactions and strain partitioning. Understanding these secondary faults' geometry, kinematics, and rupture mechanisms is crucial for regional seismic hazard assessment and infrastructure planning, particularly given the region's history of seismic recurrence (Figure 2).

4. Data and Methods

This study integrates a series of geological, geodetic, and geophysical data as described below. We delineated the detailed geometric configuration of the Bamei-Kangding segment in the Zheduo Mountain region through Google Earth imagery interpretation and field validation (Figure 3). High-precision digital elevation models (DEMs) were generated using sUAV photogrammetry for characteristic faulted moraines along the Mugecuo and

Zheduotang faults, with offsets quantified via Lateral Displacement Calculator (LaDiCaoz_v2.1), which simultaneously measures both lateral and vertical displacements (Zielke & Arrowsmith, 2012). The ages of faulted moraines were constrained using a combination of ^{10}Be Terrestrial Cosmogenic Nuclide (TCN) and Optically Stimulated Luminescence (OSL) dating techniques, with the ^{10}Be TCN dating results being systematically evaluated through Probabilistic Cosmogenic Nuclide Age Analysis Tool (P-CAAT) (Dortch et al., 2022). Late Quaternary slip rates were subsequently constrained by matching the measured displacements of faulted moraines with their exposure or burial ages. We report median rates with uncertainties at the 95.45% confidence interval (2-sigma level), following the Gaussian uncertainty model of Zechar and Frankel (2009).

This study further synthesizes multiple published datasets for comprehensive analysis. We incorporated recent high-precision ^{10}Be TCN ages from Zheduo Mountain region (Strasky et al., 2009; Bai et al., 2018, 2021; Yang et al., 2023), with statistical re-analysis using P-CAAT (Figure S6 in Supplementary Material), alongside various global paleoclimate proxies including air temperature variations from the Greenland GISP2 ice core record (Alley, 2004), $\delta^{18}\text{O}$ record from the Guliya ice core collected in 1992 in the northwestern Tibetan Plateau (Thompson et al., 1997), stalagmite $\delta^{18}\text{O}$ records from Mawmluh and Dongge Caves (Dutt et al., 2015; Dykoski et al., 2005), and Northern Hemisphere summer insolation records (Berger & Loutre, 1991). This integrated approach enables regional comparative analysis and enhances data validation. We reprocessed GNSS data from Zheng et al. (2017) and referenced InSAR observations from Huang et al. (2023) to compare geologic and geodetic slip rates and evaluate regional kinematics and strain partitioning. Finally, published clay experimental models and high-resolution S-wave velocity models were used to construct the 3D tectonic framework of the Zheduo Mountain region (Mitra & Paul, 2011; Zhao et al., 2023), which facilitated the analysis of rupture mechanisms and tectonic evolution within the Bamei-Kangding segment. Additionally, magnitudes for recent large seismicity and focal mechanisms for events with magnitude ≥ 4.0 that occurred between 1 January 1976 and 28 February 2025 were obtained from the Global Centroid Moment Tensor (GCMT) catalog at <https://www.globalcmt.org/> (Dziewonski et al., 1981; Ekström et al., 2012).

4.1. Small Unmanned Aerial Vehicle (sUAV) Photogrammetry

High-resolution topographic data are essential for quantitative analysis of active faults, particularly for measuring offsets within complex geometric structures (Liu et al., 2013; Wang et al., 2019). Small unmanned aerial vehicle (sUAV) technology has significantly enhanced our capability for micro-geomorphic interpretation through the generation of high-precision DEMs (Johnson et al., 2014; Sun et al., 2019).

Based on Google Earth imagery analysis and field surveys, we identified five representative faulted moraines along the Mugecuo (sites KA, KB, KC, KM) and northwestern Zheduotang (site KZ) faults for geometric analysis and late Quaternary slip rate determination (Figure 2b). Topographic surveys of sites KA, KB, KC and KM were conducted using a DJI Phantom 4 Pro RTK sUAV, with optimized parameters (80% forward photo overlap, 70% lateral photo overlap, <100 m flight altitude) to ensure data quality in the high-altitude terrain. High-resolution DEMs and orthophotos (2-3 cm/pixel) were generated

using PhotoScan software, which integrates Structure from Motion (SfM) algorithms (Johnson et al., 2014). For site KZ, located near Kangding Airport where aviation restrictions prevented sUAV deployment, topographic analysis was directly conducted using high-resolution Google Earth imagery.

4.2. Geochronological Methods

Recent advances in geochronological techniques have significantly enhanced dating precision in tectonic studies (Ran et al., 2014). While radiocarbon dating (^{14}C) is commonly preferred over ^{10}Be TCN and OSL dating, the alpine glacial sedimentary environment of our study area limits its application. The high elevation and low shielding coefficient make ^{10}Be TCN dating particularly suitable (Lifton et al., 2014). We supplemented this with two OSL samples from fine-grained deposits to strengthen our chronological framework.

4.2.1. ^{10}Be TCN Dating

^{10}Be TCN dating effectively determines exposure ages of quartz-rich deposits across various terrestrial settings, demonstrating remarkable efficacy across temporal scales ranging from millennia to millions of years, with analytical precision typically within 5-7% uncertainty (Kong, 2002). The method quantifies cosmogenic nuclide accumulation from cosmic ray bombardment, with production rates controlled by burial depth, altitude, and geomagnetic latitude (Stone, 2000).

We collected 41 quartz-rich granite samples (≥ 2 kg each) from five sites along the Mugecuo (sites KA, KB, KC, KM) and northwestern Zheduotang (site KZ) faults (Figure 2b; Table 1). Samples were obtained from the top 5 cm of exposed upper surfaces of stable, semi-embedded granite boulders on offset moraine crests (primarily horizontal with minor vertical displacement) (Figures S1-S5 in Supplementary Material). Sample preparation included quartz purification at Langfang Shangyi Rock Detection Company (Hebei Province, China), with a minimum of 20 g purified quartz per sample, followed by chemical treatment and target preparation at the Key Laboratory of Compound and Chained Natural Hazards Dynamics, Ministry of Emergency Management of China (Beijing, China), with subsequent elemental analyses performed at CEREGE (Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement, Aix-en-Provence, France). The ^{10}Be exposure ages were calculated using Cosmic-Ray Produced Nuclide Systematics (CRONUS v3) (Balco et al., 2008), adopting the LSDn (Lifton-Sato-Dunai neutron) time-dependent production rate model for its superior performance at high-altitude and low-latitude locations (Table 1; Lifton et al., 2014). For comparison, we also computed ages utilizing both the St (Lal (1991)/Stone (2000) time-independent) and Lm (Lal (1991)/Stone (2000) time-dependent) production rate models (Table S1 in Supplementary Material). Although ages derived from these models show overlapping external and internal uncertainties, the LSDn-derived ages demonstrate notably smaller uncertainties compared to those calculated using the St and Lm models (Table S1).

4.2.2. OSL Dating

Luminescence dating includes thermoluminescence (TL) and optically stimulated luminescence (OSL) techniques. OSL dating quantifies optically stimulated radiation-induced

signals from minerals such as quartz and feldspar accumulated during burial (Aitken, 1985). This technique achieves analytical uncertainties typically below 10% (Wang et al., 2006; Yang, 2013) and is particularly effective for well-sorted fine-grained sediments collected from fresh sections within 30 cm depth of terrace deposits, though its accuracy may be compromised in poorly sorted or rapidly deposited materials (Ran et al., 2014).

Two OSL samples, consisting of fine sand, were collected from a faulted terrace along the southern branch of Mugecuo fault (site KC) using steel tubes (5 cm diameter, 20 cm length) (Figure 2b; Table 2). Sample preparation and analysis were conducted at the Key Laboratory of Compound and Chained Natural Hazards Dynamics, Ministry of Emergency Management of China (Beijing, China). The equivalent dose values were determined using the Single Aliquot Regenerative-dose (SAR) protocol (Murray & Wintle, 2000; 2003), while U, Th, and K concentrations were measured from the remaining sample material for environmental dose rate determination. The dose rates were corrected for water content, and the final ages were calculated following the procedures outlined in Aitken (1998).

4.3. Displacement and Age Constraint

Determination of robust late Quaternary slip rates requires precise quantification of both displacement and chronology. To enhance the accuracy of offset measurements, we implemented the LaDiCaoz_v2.1 software package, a semi-automated analytical tool specifically designed for displacement analysis. The LaDiCaoz workflow consists of sequential steps: data import, zoom box definition, fault tracing, profile plotting, offset feature tracking, optimal offset identification, and back-slipping analysis (Zielke & Arrowsmith, 2012). A distinctive capability is its morphological reconstruction of faulted landforms through DEM "clipping" and "sliding back" operations, while generating curves for error assessment. The tool's effectiveness relies on precise fault location and strike determination, coupled with strategic selection of appropriate linear geomorphic features (Kang et al., 2020). Four high-resolution DEMs (sites KA, KB, KC and KM) were produced from sUAV imagery using PhotoScan software for subsequent LaDiCaoz offset analysis.

¹⁰Be TCN ages commonly exhibit uncertainties due to pre- or post-exposure events and sampling/analytical errors, potentially resulting in over- or underestimated exposure ages (Ivy-Ochs et al., 2007; Heyman et al., 2011). To address dispersed data and anomalous values, we employed the P-CAAT for reliable age constraints (Dortch et al., 2022). P-CAAT uses Monte Carlo simulations to extract Gaussian components from probability density estimates (composite PDE) derived from multiple exposure ages ($n \geq 3$). The software integrates internal and external uncertainties, analyzing age clustering to resolve geological and anthropogenic uncertainties. It provides three bandwidth estimators (Mean, Std/IQR (standard deviation and interquartile range), and MADD (mean absolute Dortch deviants)) for optimized age analysis. Following the strategies across the Tibetan Plateau (Cui et al., 2023; Wang et al., 2023) and Tianshan range (Zhao et al., 2023), we utilized P-CAAT to evaluate our new ¹⁰Be TCN dating results from the eastern Tibetan Plateau (Figure 4). To maintain methodological consistency, we further applied P-CAAT to evaluate published ¹⁰Be TCN ages from the Zheduo Mountain region (Strasky et al., 2009; Bai et al., 2018, 2021). Previous studies employed varying statistical approaches for exposure age determination: mean values

(TG; Bai et al., 2018), oldest reliable ages after outlier removal (SLH, YJG; Bai et al., 2018; ZDT, MX; Bai et al., 2021), and age ranges (KAN; Strasky et al., 2009). Our P-CAAT reanalysis shows good agreement with the original determinations for most sites, with recalculated ages either falling within the age ranges after outlier removal or closely matching the final exposure ages. For these published datasets, we use the P-CAAT-recalculated values in our regional age compilation, while providing detailed comparisons with the original published values in the Supplementary Material for reference (Figure S6 in Supplementary Material).

5. Results

5.1. Southern Branch of the Mugecuo Fault

5.1.1. Geometry

The Mugecuo fault developed on the northeastern slope of Zhedo Mountain between the Selaha fault and Zheduotang fault. Consisting of two primary branches (southern (F5-1) and northern (F5-2)), this ~24 km-long, N30°-60°W-trending structure forms a 3-km-wide deformation zone south of Mugecuo Lake (Figure 2). Each branch comprises secondary segments ranging from tens to hundreds of meters with right-stepping en-echelon character. The northwestern termini of these branches converge and spatially align with the Selaha fault. This fault system subsequently extends southward through moraines, ridges, and terraces, forming distinct offsets and fault scarps. Their southeastern termini gradually merge and finally connect with the Selaha fault before traversing the Yangjiagou (YJG) site (Figure 2b; Bai et al., 2018).

The northwestern terminus of the Mugecuo fault exhibits a single, linear trace where the main fault is primarily characterized by normal-slip scarps, with no discernible horizontal offset in geomorphic features (Figures 3a and 3b). Moving southward, the fault divides into two strands (F5-1 and F5-2), with secondary ruptures developing along both margins (Figures 3c and 3d). Although no apparent horizontal offsets are identified in this segment, field investigations by Pan et al. (2020) reported that the main fault cuts through granite bedrock, exhibiting significant deformation associated with leftward extrusion.

In the middle-northern segments of the southern branch (F5-1), the principal fault trace extends through Holocene glacial deposits for over 1 km at approximately 30.118°N, 101.814°E (Figures 3e and 3f). Field investigations reveal predominantly northeast-tilting linear scarps. sUAV photogrammetric analysis indicates a vertical scarp height of approximately 8 meters (Pan et al., 2020; topographic profile shown as orange dashed line in Figure 3e), which may result from either progressive normal faulting or multiple seismic events. Geomorphic evidence of strike-slip motion remains minimal in this segment.

The middle segment displays significant left-lateral displacement at the KA site, where a valley and its adjacent right-bank moraine exhibit clear horizontal offset (Figures 5a and 5b). Associated linear trough and scarp developed on the moraine provides evidence of concurrent normal faulting (Figure 5c). To the southeast, sUAV surveys reveal right-stepping en-echelon patterns along the main fault trace, characterized by push up, oriented gravels, and secondary fractures that indicate significant left-lateral strike-slip movement (Figures 5a and 5e). Field

investigations documented approximately 3-meter-high scarps in glacial deposits (Figure 5e), demonstrating predominantly strike-slip motion with a subordinate normal component. The well-preserved nature of these scarps, including fresh free faces, suggests recent formation, possibly associated with regional seismic activity. Continuing southward, the F5-1 fault system consists of multiple segments displaying left-stepping en-echelon geometry with sinistral motion. These segments produce lateral offsets of ridge crests with displacements of approximately 50 m and 90 m, respectively (Figures 3g and 3h).

From the displaced ridge southward to the KB site, the fault trace extends along the boundary between bedrock ridge and piedmont moraine platform (Figure 6a), characterized by oriented gravels and sag ponds along distinct fault traces (Figures 6b and 6c). Left-lateral displacements are well preserved in moraines and gullies, accompanied by southwest-dipping scarps (Figure 6d). At the KC site, the fault intersects a sequence of geomorphic features including moraines, fluvial deposits, and alluvial terraces, generating pronounced left-lateral offset (Figures 7a and 7b). This segment demonstrates pure left-lateral strike-slip motion with minimal vertical displacement.

5.1.2. Late Quaternary Slip Rate

In the middle segment of the southern branch (F5-1) at the KA site, a valley and its right-bank moraine display a prominent left-lateral offset, with a discernible linear groove preserved on the moraine surface due to sustained fault activity (Figures 5b and 5c). Eight samples were collected from exposed upper surface of granite boulders on the moraine crest for ^{10}Be TCN dating, targeting large, stable, semi-embedded boulders to minimize inheritance and erosion effects (Figure 5d; Table 1; Figure S1). P-CAAT analysis revealed tightly clustered ages, with the MADD bandwidth estimator providing optimal goodness of fit (R^2), yielding an exposure age of 13.07 ± 0.15 ka (Figure 4a). Based on high-resolution DEM from sUAV photogrammetry, LaDiCaoz measurements using the moraine's southern margin as a displacement marker reveal left-lateral and vertical offsets of 16 ± 0.5 m and 1.5 ± 0.5 m respectively (Figures 5f and 5g). Integration of chronological data and displacement measurements indicates left-lateral and vertical slip rates of 1.2 ± 0.1 mm/yr and 0.1 ± 0.1 mm/yr.

In the southeastern segment at the KB site, the fault exhibits predominant left-lateral strike-slip motion without significant vertical offset (Figure 6). A stream-incised U-shaped gully through the piedmont glacial platform shows lateral displacement, with associated grooves and minor scarps on the right-bank moraine (Figures 6c and 6d). Six granite boulder samples from the right-bank moraine yielded consistent ^{10}Be TCN ages (Figure 6d; Table 1; Figure S2), with P-CAAT analysis (MADD) indicating an exposure age of 13.24 ± 0.1 ka (Figure 4b). Based on high-resolution sUAV-derived DEM, LaDiCaoz analysis determined a left-lateral offset of 17 ± 0.5 m, using the gully thalweg as a displacement marker, with 0.5 m vertical offset attributed to topographic variation (Figures 6d and 6e). The chronological constraint and offset measurement demonstrates a primary left-lateral slip rate of 1.3 ± 0.1 mm/yr for this fault segment.

At the KC site, the fault traverses glacial landforms including moraines, stone rivers, and small terraces, creating linear grooves and minor scarps (Figures 7a and 7b). ^{10}Be TCN dating of eight granite boulder samples collected from the faulted moraine crest yielded tightly clustered ages (Figure 7a; Table 1; Figure S3). P-CAAT analysis with the Std/IQR bandwidth estimator indicated an exposure age of 13.66 ± 0.3 ka (Figure 4c). Quantitative analysis of sUAV-derived DEM using LaDiCaoz revealed a left-lateral displacement of 13.5 ± 0.5 m of the moraine crest, coupled with a subordinate vertical component of 1.5-2 m (Figures 7c and 7d). This precise age constraint and measurement of displacement yields left-lateral and vertical slip rates of 1.0 ± 0.1 mm/yr and 0.1 mm/yr, respectively.

Adjacent to the faulted moraine crest at the KC site, we observed approximately 3 m of sinistral offset in a southward-flowing stone river, while a nearby T1 terrace exhibits a minor scarp with 3-4 m sinistral displacement (Figures 7b and 7e). A 1.3 m-deep sampling pit on the T1 terrace exposed 0.9 m of floodplain deposits and soil overlying subangular gravel (Figure 7f). Two fine sand samples (OSL-1 and OSL-2) were collected for OSL dating from depths of 1.0 m and 1.2 m, respectively, at the upper and lower boundaries of the gravel layer. These samples yielded ages of 13.93 ± 0.95 ka and 16.00 ± 1.20 ka, respectively (Figure 7f; Table 2). The subsequent estimated terrace age of ~ 13 ka, integrated with the measured displacement, implies a sinistral slip rate of ~ 0.3 mm/yr, which is significantly lower than the rate derived from the adjacent faulted moraine. If the OSL ages are reasonable, this discrepancy may be attributed to two possible factors. First, possible fault bifurcation in this area suggests that this rate could represent only one secondary fault strand rather than the entire fault zone, potentially leading to an underestimation of the total slip rate across the complete fault system. Second, the ~ 3 m sinistral offset observed at this site may represent displacement from a single seismic event, while the larger offsets (>10 m) documented at the adjacent faulted moraine could reflect cumulative displacement from multiple earthquakes over the same time period. However, the similar ages (~ 13 ka) obtained from both sites also raise questions about the relationship between terrace formation and fault displacement. Alternative explanations include: (1) the terrace deposits may record the initial surface formation, while the measured offsets reflect subsequent deformation that occurred after terrace abandonment; or (2) post-depositional processes or incomplete bleaching during sediment transport could have affected the OSL age accuracy.

Based on our precise age constraints and displacement measurements, left-lateral slip rates are 1.2 ± 0.1 mm/yr at KA site, 1.3 ± 0.1 mm/yr at KB site, and 1.0 ± 0.1 mm/yr at KC site. Statistical analysis of these three slip rates from offset moraines distributed along different segments of the southern branch yields a late Pleistocene (~ 13.6 ka) left-lateral slip rate of 1.2 ± 0.1 mm/yr, which represents the weighted mean considering both central values and their associated uncertainties. Measurements of vertical slip rate at two sites (KA and KC) yield identical values of 0.1 mm/yr, suggesting a subordinate vertical component of motion along the southern branch.

5.2. Northern Branch of the Mugecuo Fault

5.2.1. Geometry

High-resolution satellite imagery analysis and field investigations reveal significant vertical displacement across the middle-northern segments of the northern branch (F5-2), where the southwest block shows distinct uplift relative to the northeast block, forming a series of sub-parallel northeast-dipping scarps in the overlying Quaternary glacial deposits (Figures 3c and 3d). This segment demonstrates predominantly normal faulting with no clear strike-slip geomorphic features. High-resolution DEM analysis derived from sUAV photogrammetry indicates that two prominent scarps at 101.7917°E, 30.15216°N exhibit vertical offsets of approximately 4 m (Pan et al., 2020; topographic profile shown as orange dashed line in Figure 3c).

The middle segment traverses the western hillside of Mugecuo Lake, where the northeast-dipping fault plane creates a clear linear topographic expression (Figures 8a and 8b). At the KM site, the northwest-trending main fault displays characteristic structural features, systematically offsetting moraine and gully sequences with sinistral and vertical displacements exceeding 10 m in the major moraine crest (Figure 8b). The northeastern glacial platform exhibits notably smaller displacement magnitudes in both horizontal and vertical components, suggesting spatial and temporal variations in slip distribution. Structural analysis reveals that while sinistral strike-slip motion dominates the kinematic regime of this segment, a substantial normal component is present, likely indicating localized extension. Toward the southeast, the fault cuts across the topographic ridge, forming a well-defined trough before merging with the Selaha fault system (Figure 2b). The southeastern segment displays kinematic characteristics similar to the southern branch (F5-1), with strike-slip motion serving as the primary deformation mechanism.

5.2.2. Late Quaternary Slip Rate

The KM site provides an ideal faulted marker for detailed slip rate constraint along the northern branch, where the northwest-trending main fault intersects a well-preserved sequence of moraines and gully systems, producing clearly defined offsets and scarps (Figures 8a and 8b). To establish reliable chronological constraints while minimizing potential effects of inheritance and post-depositional erosion, we implemented a systematic sampling strategy, collecting eight samples from the large, stable, semi-embedded granite boulders on the crest of the largest moraine for ^{10}Be TCN dating (Figure 8a; Table 1; Figure S4). The dating results were relatively concentrated, and statistical analysis using P-CAAT with bandwidth estimators set to Std/IQR yields a well-constrained exposure age of 14.74 ± 0.37 ka (Figure 4d). Utilizing the morphology of the largest moraine as a reliable displacement marker, sUAV surveys combined with comprehensive LaDiCaoz analysis reveal a sinistral offset of 15.5 ± 0.5 m and a vertical displacement of approximately 11.5 ± 0.5 m (Figures 8c and 8d). Integration of these chronological constraints with the horizontal displacement measurement indicates a late Quaternary strike-slip rate of 1.1 ± 0.1 mm/yr for this segment. Notably, when integrating the exposure age with the vertical displacement, this segment exhibits a significantly higher vertical slip rate compared to the southern branch, reaching 0.8 ± 0.1 mm/yr.

Overall, these well-constrained slip rates, derived from geomorphic offset markers dated to 13-15 ka, collectively indicate the predominant left-lateral strike-slip nature of the

Mugecuo fault system within the bending Bamei-Kangding segment, albeit with a subordinate normal component that varies along strike, suggesting complex kinematics. The cumulative left-lateral slip rate of the Mugecuo fault system, integrating measurements from both southern (1.2 ± 0.1 mm/yr) and northern (1.1 ± 0.1 mm/yr) branches, yields a statistical late Pleistocene rate of 2.3 ± 0.2 mm/yr. The vertical slip rate shows a notable northward-increasing trend from 0.1 mm/yr in the southern branch to 0.8 ± 0.1 mm/yr in the northern branch, potentially indicating the orientation of the extensional center. These rates provide crucial constraints for regional kinematic and deformation pattern analysis.

5.3. The Zheduotang Fault

5.3.1. Geometry

High-resolution satellite imagery interpretation coupled with systematic field mapping has revealed previously undocumented traces of the Zheduotang fault (F4) north of Kangding Airport (Figure 2; Ma et al., 2020). Using the Zheduo mountain pass as a natural geographic boundary, we divide the Zheduotang fault into two distinct segments: a 15 km-long northwestern segment and a 30 km-long southeastern segment (Ma et al., 2020). The northwestern segment encompasses both previously mapped fault traces near Kangding Airport and the newly discovered northwestern extension to Duoriagamo village identified by Ma et al. (2020) (Figure 2). Geomorphic expression varies substantially along strike, with the northwestern segment displaying relatively subdued features compared to the southeastern counterpart. The southeastern segment exhibits well-developed fault-related geomorphic features along the hillslopes adjacent to National Route 318 between Zheduo mountain pass and Zheduotang village, including systematic fault scarps, tectonic grooves, and sag ponds. Linear geomorphic markers, including gullies, alluvial terraces, and topographic ridges, display clear evidence of both strike-slip and normal displacement components. Field investigations by Yan et al. (2020) documented vertical offsets of 0.2-0.8 m, with maximum vertical displacement along the newly identified 6-km-long southeastern terminal segment. Bai et al. (2021) reported prominent fault scarps reaching 8-10 m northwest of their ZDT site. The fault extends southeastward for approximately 2 km beyond Zheduotang village before becoming difficult to trace in the valley (Figure 2; Bai et al., 2021).

As a secondary branch of the Bamei-Kangding segment, the Zheduotang fault defines the southwestern boundary of the Bamei-Kangding stepover and exhibits predominantly sinistral strike-slip kinematics with a concurrent normal component (Allen et al., 1991; Wen et al., 2008; Yan et al., 2020; Bai et al., 2021; Xu et al., 2025). The well-preserved surface expressions, particularly the systematic offset of geomorphic markers, serve as optimal indicators for quantifying deformation rates and reconstructing paleoseismic history (Li, 1997; Zhou et al., 2001; Chen, 2008; 2016; Zhang et al., 2016; Yan et al., 2020; Bai et al., 2021), simultaneously demonstrating distinctive segmentation patterns in geomorphology, late Quaternary slip rates, and seismic behaviors (Ma et al., 2020).

5.3.2. Late Quaternary Slip Rate

At the KZ site along the northwestern segment of the Zheduotang fault, we documented characteristic offset geomorphic markers that provide robust constraints for quantifying late

Quaternary slip rates. Fluvial incision has generated multiple NE-SW-oriented gullies (G1, G2, G3) across the glacial platform on the southwestern slope of Zheduo Mountain, systematically offset by the northwest-trending fault (Figures 9a, 9b, and 9d). The northeastern block shows relative uplift, producing a southwest-facing fault scarp (Figures 9b and 9c). The KZ site, located approximately 6 km southeast of Kangding Airport within the northwestern segment, provides optimal conditions for quantifying the strike-slip motion representative of the entire northwestern segment. We sampled eleven granite samples from the well-preserved moraine crest adjacent to offset gullies for ^{10}Be TCN dating (Figures 9c and 9d; Table 1, Figure S5). P-CAAT analysis with bandwidth estimators set to Std/IQR showed exceptional age clustering, yielding a well-constrained exposure age of 14.85 ± 0.36 ka (Figure 4e). Due to aviation restrictions near Kangding Airport preventing sUAV deployment (Figure 9a), displacement measurements were directly conducted using high-resolution Google Earth imagery. Morphological reconstruction using the gully G2 as the displacement marker revealed a left-lateral offset of 100 ± 10 m (Figures 9d and 9e). Integration of these chronological and displacement data constrains the sinistral slip rate of the northwestern segment to 6.7 ± 1.4 mm/yr.

Previous slip rate determinations for the Zheduotang fault segment exhibit considerable variability. Zhou et al. (2001) obtained slip rates of 3.6 ± 0.3 mm/yr using ^{14}C and TL ages from offset terraces near Zheduotang Village. Chen et al. (2008; 2016) calculated a slip rate of 8.5 ± 2.0 mm/yr by integrating: (1) approximately 140 m of cumulative displacement with an OSL age of 16.4 ± 1.3 ka near Zheduo Mountain pass, and (2) 22 m of offset with a ^{14}C age of 2338 ± 28 cal yr BP near Zheduotang Village. Using ^{14}C dating of offset gullies (25 m offset, ~ 4 ka) and moraine dams (15.5 m offset, ~ 6.4 ka), Zhang et al. (2016) derived rates of 6 mm/yr and 4.3 mm/yr for northwestern and southeastern segments respectively, suggesting an average of 5 ± 1 mm/yr. These disparities likely reflect variations in age control, topographic data resolution, and measurement techniques. Bai et al. (2021) obtained ^{10}Be TCN chronology from nine granite boulder samples collected from sub-rounded lateral moraine crest at the ZDT site, yielding ages ranging from 12.7 ± 1.0 ka to 15.9 ± 1.2 ka. Using sUAV-derived DEM data, they documented a 65 ± 10 m strike-slip displacement across the fault (Figure 2). These measurements correspond to a calculated left-lateral slip rate of 4.1 ± 0.7 mm/yr. Recent fault activity north of Kangding Airport suggests segment-specific rates (Ma et al., 2020). Collectively, high-resolution quantitative constraints from our KZ site (6.7 ± 1.4 mm/yr) and Bai et al.'s (2021) ZDT site (4.1 ± 0.7 mm/yr) reveal a systematic southeastward decrease in slip rates along the fault system.

6. Discussion

6.1. Correlation of ^{10}Be TCN Exposure Ages with Post-LGM Climate Events in the Zheduo Mountain Region

The formation and preservation of moraines are highly dependent on climate fluctuations (e.g., Benn & Evans, 2010; Owen et al., 2009). During cold glacial periods, decreased temperature and altered precipitation patterns promote glacier expansion, with ice advancing downvalley, eroding bedrock and transporting vast amounts of debris. This sediment accumulates at glacier margins forming terminal and lateral moraines, marking the

maximum extent of ice advance. Conversely, during warming periods, glaciers retreat rapidly, exposing these moraine deposits to subaerial weathering and cosmogenic nuclide accumulation. Unlike river terraces which form primarily during the transition from glacial to interglacial periods (Li et al., 2021), moraines typically represent the culmination of glacial advances, with their abandonment and exposure ages marking the onset of glacier retreat driven by warming events. Obviously, these moraines serve as valuable chronological markers of past climate fluctuations and, when offset by active faults, provide critical temporal constraints for measuring deformation rates, as the moraine abandonment ages are normally considered to mark the onset of displacement accumulation.

The active Xianshuihe fault cuts through the Zheduo Mountain region, offsetting numerous moraines. Our study contributes 41 ^{10}Be TCN exposure ages from five faulted moraines, integrating them with previously published ^{10}Be TCN exposure ages to enhance the regional geochronological framework and demonstrate the reliability of our chronological constraints for fault slip rate calculations (Figure 10a). The comprehensive ^{10}Be TCN exposure ages from the Zheduo Mountain region cluster into three distinct age groups that correlate remarkably well with known climate events since the Last Glacial Maximum (LGM) (Figure 10). The oldest moraines at Kangding Airport (20.0 ± 3.2 ka; Yang et al., 2023), Jiangbagou (19.3 ± 2.8 ka; Yang et al., 2023, combining data from the same moraine also named Selaha in Bai et al., 2018), Selaha (19.16 ± 2.52 ka; P-CAAT recalculated from Bai et al., 2018), and Yangjiagou (17.49 ± 2.44 ka; P-CAAT recalculated from Bai et al., 2018) represent the terminal phase of the LGM (26.5-19 ka) (Clark et al., 2009, Yang et al., 2023), mark the maximum ice extent during this sustained cold period. The MX moraine (16.08 ± 1.23 ka; P-CAAT recalculated from Bai et al., 2021) aligns with Heinrich event 1 (H1; 17.5-16 ka) (Heinrich, 1988; Hemming, 2004), likely representing brief glacier stabilization or minor readvances during this period of abrupt climate change. Our new 41 ^{10}Be exposure ages document the third and youngest age group from both Zheduo Mountain slopes. Along the southern branch of the Mugecuo fault (northeastern slope, 4450-4500 m), sites KA, KB, and KC yielded tightly clustered ages of 13.07-13.66 ka (Figures 4a, 4b, and 4c), while site KM along the northern branch (northeastern slope, 4150-4200 m) dated to 14.74 ± 0.37 ka (Figure 4d). Similarly, the KZ site along the NW Zheduotang fault (southwestern slope, 4350-4400 m) yielded an exposure age of 14.85 ± 0.36 ka (Figure 4e). These moraines, with exposure ages concentrated between 15-13 ka, together with the TG debris flow levee (12.46 ± 0.64 ka; P-CAAT recalculated from Bai et al., 2018), the ZDT moraine (14.33 ± 1.70 ka; P-CAAT recalculated from Bai et al., 2021), and Zheduo Valley (13.63 ± 0.83 ka; P-CAAT recalculated from Strasky et al., 2009), represent deglaciation-related landforms during the Bølling-Allerød warming period (BA; 14.7-12.9 ka) (Figures 10a, 10b, and S6; Rasmussen et al., 2014; Clark et al., 2012). Unlike the older, more extensive terminal moraines formed during the LGM, these younger, higher-elevation landforms mark positions where retreating glaciers temporarily stabilized during the overall warming trend, creating distinct deglaciation-related complexes. Critically, these glacier-related landforms are offset by the Xianshuihe fault, and their well-constrained exposure ages provide reliable temporal markers for calculating fault slip rates.

The reliability of our chronology is further strengthened by its correlation with multiple independent climate proxies: (1) the rapid warming recorded in the GISP2 ice core beginning at 14.7 ka (Figure 10b; Alley, 2000; Severinghaus & Brook, 1999), (2) enhanced monsoon strength evident in speleothem $\delta^{18}\text{O}$ records after ~ 14.5 ka (Figure 10c; Dutt et al., 2015; Wang et al., 2001), and (3) peak-approaching Northern Hemisphere summer insolation at ~ 14 ka (Figure 10d; Berger & Loutre, 1991). Corresponding fluctuations are also observed in the $\delta^{18}\text{O}$ record from the Guliya ice core in the northwestern Tibetan Plateau (Figure 10b; Thompson et al., 1997). Additionally, OSL dating results from the southern branch of the Mugecuo fault indicate a burial age of ~ 13 ka for an offset terrace, providing independent confirmation of this glacial retreat event following the Bølling-Allerød warming. The remarkable consistency between our ^{10}Be exposure and OSL ages across multiple sites, coupled with their strong correlation to established post-LGM climate events, robustly validates the reliability of our chronological framework. This multi-dataset approach—combining our new exposure ages with previously published chronologies and global climate proxies—provides a robust framework for understanding eastern Tibetan Plateau climate evolution since the Last Glacial Maximum (Cui et al., 2021; Yang et al., 2021) and offers reliable temporal constraints for regional fault slip rates.

6.2. Geometry and Kinematics of the Bamei-Kangding Segment

Accurate slip partitioning analysis requires detailed examination of branching fault geometries. Traditional interpretations suggesting the northwestern Xianshuihe fault splits into the en-echelon Yalahe, Selaha, and Zheduotang faults southeast of Huiyuansi Basin requires revision in light of the newly identified Mugecuo (Pan et al., 2020; Bai et al., 2021) and northwestern extension of Zheduotang faults (Ma et al., 2020) within the Bamei-Kangding segment (Figure 2). Our geometry analysis reveals that both the Mugecuo and Zheduotang faults are located at considerable distance (~ 45 km and ~ 30 km, respectively) from the Huiyuansi Basin (Figure 2). We propose the northwestern Xianshuihe fault firstly branches into two major structures: the Yalahe and Selaha faults. The northwestern Selaha fault subsequently divides into three secondary branches south of Duoriagamo village: the southeastern Selaha fault, the Mugecuo fault, and the Zheduotang fault (Figure 2). This revised model treats the Selaha, Mugecuo, and Zheduotang faults as a system equivalent to the Yalahe fault within the Bamei-Kangding segment. Thermochronological evidences reveal initial XSHF propagation occurred along the Yalahe fault (~ 9 –4 Ma) (Zhang et al., 2017), followed by a significant decrease in Yala Mountain exhumation rates concurrent with increased activity along the Selaha and Zheduotang faults (~ 4 Ma) (Zhang et al., 2017; Bai et al., 2021; Ma et al., 2024). These segmentation evolution evidences are highly consistent with our geometry model. According to pertinent metrics for quantitatively assessing fault structural maturity—corrugation level and step-over density (Manighetti et al., 2021)—we suggest that the Bamei-Kangding segment exhibits higher corrugation levels and more frequent step-overs compared to the northwestern XSHF and the Moxi fault (Figure 2), indicating its lower degree of maturity and ongoing tectonic evolution.

Based on ^{10}Be TCN ages and sUAV-derived DEM measurements, we constrained left-lateral slip rates along the southern branch of the Mugecuo fault from offset moraines:

1.2 $\pm$ 0.1 mm/yr (site KA), 1.3 $\pm$ 0.1 mm/yr (site KB), and 1.0 $\pm$ 0.1 mm/yr (site KC). Statistical analysis of these measurements yields a weighted mean slip rate of 1.2 $\pm$ 0.1 mm/yr. Vertical displacement measurements at sites KA and KC reveal consistent slip rates of 0.1 mm/yr. In conjunction with measurements from the northern branch at site KM (horizontal: 1.1 $\pm$ 0.1 mm/yr; vertical: 0.8 $\pm$ 0.1 mm/yr), our results demonstrate that the Mugecuo fault system has been characterized by predominant horizontal slip since the late Pleistocene, yielding a statistically derived cumulative left-lateral slip rate of 2.3 $\pm$ 0.2 mm/yr across both branches, with a secondary vertical component that exhibits a northward increase from the southern to northern branches. Furthermore, we quantified the horizontal slip rate for the northwestern Zheduotang fault to 6.7 $\pm$ 1.4 mm/yr (KZ). Integration of recent high-precision studies by Bai et al. (2018, 2021) with our new measurements reveals spatial variations in horizontal slip rates of secondary faults within the Bamei-Kangding segment: the Selaha fault decreases from 9.6-9.9 mm/yr at the TG and SLH sites (northwestern) to 3.9-4.9 mm/yr at the YJG site (southeastern), while the Zheduotang fault decreases from 6.7 $\pm$ 1.4 mm/yr at the KZ site (northwestern) to 3.4-4.8 mm/yr at the ZDT site (southeastern) (Bai et al., 2018, 2021). This spatial slip partitioning provides important insights on the kinematic evolution of the fault system within the regional tectonic framework.

To provide a comparison, we analyzed the geodetic slip rates along the entire XSHF by reprocessing the comprehensive GNSS velocity field from Zheng et al. (2017), which combines 1556 CMONOC-I/II stations with 1020 stations from Kreemer et al. (2014) in a consistent Eurasia-fixed reference frame. Considering fault geometry, we established six fault-perpendicular profiles: Luhuo, Daofu, Bamei, North Bamei-Kangding, South Bamei-Kangding, and Moxi (Figure 11). These profiles, extending 200 km bilaterally from the fault trace with widths of 40, 40, 40, 30, 25, and 40 km respectively, yield sinistral slip rates of 8.03 $\pm$ 0.61, 7.26 $\pm$ 0.50, 7.91 $\pm$ 0.57, 9.32 $\pm$ 0.60, 10.88 $\pm$ 0.55, and 11.23 $\pm$ 1.13 mm/yr from northwest to southeast (Figure 11), showing a clear southeastern increase. This GNSS-derived trend is validated by late Quaternary data, and the geodetic rates themselves align with the lower bounds of geological estimates (Allen et al., 1991; Li et al., 1997; Zhou et al., 2001; Xu et al., 2003; Chen et al., 2008; 2016; Zhang, 2013; Zhang et al., 2016; Bai et al., 2018, 2021; Liang et al., 2020; Wang et al., 2020; Qiao et al., 2021). Earlier geological studies reporting higher rates likely encountered methodological limitations in dating, displacement marker identification, age-displacement relationships, and distributed deformation assessment (Zhang et al., 1988; Allen et al., 1991; Cowgill, 2007; Li et al., 2009).

The southward increase of slip rate is consistent with the InSAR results. Qiao and Zhou (2021) showed that the slip rate is from 8.8-9.4 mm/yr on the Luhuo-Daofu segment, increasing to 10.1-10.3 mm/yr on the Bamei segment, 9.9-14.3 mm/yr on the Bamei-Kangding segment, and up to 17.9 mm/yr on the Moxi segment. The recent analysis by Huang et al. (2023) yielded a slip rate of 13.9 $\pm$ 0.4 mm/yr for the Bamei-Kangding segment in accordance with previous geodetic and geological constraints. They confirmed that the Selaha and Zheduotang faults are the dominant structures, accounting for over 90% of the total slip along the Bamei-Kangding segment, while the Selaha fault exhibits a

significant sinistral slip gradient (Figure 12a). This gradient corresponds to the decrease in late Quaternary sinistral slip rate along the Selaha fault. Such decrease results from fault branching, whereby the northwestern Selaha fault (9.6-9.9 mm/yr) bifurcates into the southeastern Selaha, Mugecuo, and Zheduotang faults. These subordinate structures collectively exhibit a cumulative slip rate of ~ 10 mm/yr, with the Zheduotang fault accommodating the predominant deformation (6.7 ± 1.4 mm/yr in the northwestern segment and 4.1 ± 0.7 mm/yr in the southeastern segment). This convergence of geological and geodetic evidence indicates the progressive dominance of the Zheduotang fault in regional crustal deformation and strain accommodation. The systematic decrease in strike-slip rate along the Zheduotang fault likely reflects progressive strain partitioning from strike-slip to normal faulting along its southeastern segment. This kinematic transformation is further corroborated by field investigations (Yan et al., 2020; Bai et al., 2021) that documented significant vertical displacements, including 8-10 m fault scarps northwest of the ZDT site.

These observations, based on improved methodologies and comprehensive datasets, demonstrate the long-term stability of the Xianshuihe fault from late Quaternary to present. The integration of high-precision late Quaternary slip rate constraints along multiple secondary faults with geodetic measurements of the whole Bamei-Kangding segment indicates a geological slip rate of approximately 1-2 mm/yr along the Yalahe fault. This rate is inferred from slip budget calculations, where the sum of rates for the Mugecuo (2.3 ± 0.2 mm/yr), southeastern Selaha (3.9–4.9 mm/yr; Bai et al., 2018), and Zheduotang (3.4–4.8 mm/yr; Bai et al., 2021) faults (~ 9.5 – 12 mm/yr total) is subtracted from the geodetic slip rate of ~ 10 – 14 mm/yr (Qiao and Zhou, 2021; Huang et al., 2023). While its northwestern trace extends ~ 7 km near Huiyuansi Basin, the Yalahe fault becomes indistinct southeast of Yala Mountain, possibly due to reduced activity or dense vegetation (Zhang et al., 2017; Bai et al., 2021; Ma et al., 2022). Our new constraints provide the first complete characterization of slip distribution across all major branches of the fault system in this critical segment of the Xianshuihe fault zone.

6.3. 3D Tectonic Model of the Bamei-Kangding Segment

The Xianshuihe fault forms a structural bend in the Zheduo Mountain region, characterized by predominantly sinistral strike-slip motion and major seismic recurrence (Allen et al., 1991; Zhang et al., 2017; Bai et al., 2021). Within the Bamei-Kangding segment, the linear northwestern XSHF bifurcates into four en-echelon faults: Yalahe (F2), Selaha (F3), Mugecuo (F5), and Zheduotang (F4) faults (Figure 12; Ma et al., 2020; Pan et al., 2020). Thermochronological evidence indicates rapid Yala Range exhumation (~ 1.85 mm/yr) at ~ 9 Ma, marking the original deformation center of the Bamei-Kangding segment and the initial propagation of the Xianshuihe fault along the Yalahe fault (Zhang et al., 2017). The subsequent exhumation rate decrease (at ~ 4 Ma) coincided with the activation of the Selaha and Zheduotang faults, shifting the focus of deformation southward (Cook et al., 2018). This transition aligns with Ma et al.'s (2024) tectonic evolution model of the bending fault system (Ganzi-Yushu-Xianshuihe-Xiaojiang) following a Euler rotation pole near the eastern Himalayan syntaxis (Figure 1). The evolution demonstrates initial deformation dominated by the Yalahe fault (28° radius relative to the eastern Himalayan syntaxis) followed by migration

to the Selaha fault (20° radius) and then to the Zheduotang fault (17° radius), representing classic fault system "short-cutting" to establish more geometrically smooth configurations with decreasing radial distance from the rotation pole (Figure 12a; Ma et al., 2024). The Zheduotang fault, serving as the southwestern boundary of the Bamei-Kangding stepover (Xu et al., 2025), shows 6.7 ± 1.4 mm/yr slip rate at KZ site, supported by InSAR observations (Huang et al., 2023), indicating its inheritance of primary deformation from the northwestern Selaha fault. Higher slip rates on the Zheduotang fault and northwestern Selaha fault, combined with lower pathway radii (17°) and frequent seismic events (e.g., the 2014 Mw 6.1 and Mw 5.7 Kangding earthquake sequence and the 1955 Zheduotang earthquake (Ms 7.5; Mw 7.0; Ms 7.1)), suggest their emergence as primary deformation pathways of the whole curved fault system (Figure 12a; Bai et al., 2018; Ma et al., 2024).

The ~30 m-deep Mugecuo Lake within the ~600 m-deep depression along the Selaha fault and ~10 m-high scarps along the Zheduotang and Mugecuo faults indicate significant normal components (Yan et al., 2020; Pan et al., 2020; Bai et al., 2021). Our analysis reveals that the NW Xianshuihe fault (north of Bamei) and the Moxi fault (south of Kangding) exhibit a left-stepping sinistral configuration, creating an extensional environment within the sinistral strike-slip Bamei-Kangding bend and forming a releasing stepover that accommodates the secondary faults and explains the widespread normal components. (Figures 2 and 12a). Initially, the regional left-stepping arrangement of the NW Xianshuihe fault (Bamei segment) and the Yalahe fault facilitated the formation of the Huiyuansi pull-apart basin (Allen et al., 1991). Liang (2019) documented that the Zhonggu fault, a secondary fault between these two main faults, forms the southern boundary of the basin and exhibits normal faulting. Subsequently, fault activity migrated to the S-shaped Selaha fault, where the internal geometric complexity facilitated the development of the extensional Mugecuo Lake. The evolutionary process of the S-shaped Selaha fault continues, where its "short-cutting" mechanism has led to the development of the Mugecuo fault along the hillslope on its south margin, facilitating stress release and progressively optimizing the geometric configuration of the Selaha fault system (Ma et al., 2024).

This transtensional configuration is corroborated by clay analog experiments (Mitra & Paul, 2011), wherein two left-lateral strike-slip faults were preset in a left-stepping pattern to simulate the evolution of a 45° oblique releasing bend—a geometric framework analogous to that exhibited by the NW Xianshuihe fault (north of Bamei) and the Moxi fault (south of Kangding). The experimental results revealed a sequential tectonic evolution characterized by an initial broad depression bounded by oppositely dipping faults, which subsequently developed into an S-shaped main fault system accompanied by inward-dipping parallel secondary normal faults, ultimately culminating in pull-apart basin formation. Importantly, these simulations generated secondary structures that develop in right-stepping patterns, exactly matching the observed right-stepping arrangement of the Yalahe, Selaha, Mugecuo, and Zheduotang faults within the Bamei-Kangding segment. This experimental framework perfectly explains the observed structural features: the formation of Mugecuo Lake, the development of two-branch Mugecuo fault with normal components, and the extensive normal components along the Zheduotang fault (Figures 12a and 12b). The structural

framework suggests that the Mugecuo system evolved within a transtensional configuration, with its extension process may have facilitated magmatic upwelling in the Zheduo Mountain region.

Fresh fault scarps (dip $>70^\circ$) with free faces along the Mugecuo fault (Figure 5e), although not as fresh as those from the 1955 earthquake on the Zheduotang fault (Bai et al., 2021), suggest that the 1725 M 7.0 earthquake, likely originated on the southeastern Selaha fault (Li et al., 1997; Wen et al., 2008), also ruptured the previously unrecognized Mugecuo fault (Bai et al., 2021). Seismic array studies by Zhao et al. (2023) revealed a low-velocity anomaly (ZDSL) beneath Zheduo Mountain (Figure 12c). The ZDSL, bounded by southern Selaha fault (north and east) and Zheduotang fault (south), exhibits low S-wave velocity structure compared with the Yala Mountain region, indicating high current fault activity. Integrated geophysical analysis, including magnetotelluric sounding (Li et al., 2021), earthquake distribution (Li et al., 2020), and aftershock relocation data (Yi et al., 2015), reveals a negative flower structure formed by secondary faults converging at depth (Figure 12c). Combined with seven overlapping Holocene events in the region (Ma et al., 2022), this structure indicates high potential for cascading ruptures and capability of larger magnitude seismicity (Shao, 2018; Liu et al., 2024).

7. Conclusions

Our study provides new constraints on fault kinematics and slip distribution within the bending Bamei-Kangding segment of the Xianshuihe fault zone, offering insights into complex fault interactions and regional tectonic evolution. Key conclusions are:

- (1) The Mugecuo fault and Zheduotang fault exhibit significant normal displacements of 1.5-11.5 m and ~ 10 m, respectively, demonstrating complex fault kinematics with prominent extensional components within the predominantly sinistral strike-slip system.
- (2) The Mugecuo fault system exhibits a cumulative left-lateral slip rate of 2.3 ± 0.2 mm/yr (southern and northern branches: 1.2 ± 0.1 mm/yr and 1.1 ± 0.1 mm/yr, respectively), while the northwestern Zheduotang fault exhibits 6.7 ± 1.4 mm/yr. Variable slip rates within the Bamei-Kangding segment reflect ongoing strain partitioning and progressive deformation migration from the Yalahe fault to the Selaha and Zheduotang faults, where the Zheduotang fault's high slip rate indicates both its inheritance of primary deformation from the northwestern Selaha fault and its function as a dominant pathway within the multiple-branch segment. As the southwestern boundary of the Bamei-Kangding stepover, the Zheduotang fault exhibits southeastward decreasing sinistral slip rates due to strain transformation.
- (3) The regional left-stepping configuration of the NW Xianshuihe fault (north of Bamei) and the Moxi fault (south of Kangding) creates a releasing stepover that forms the fundamental transtensional environment of the Bamei-Kangding segment. The releasing stepover accommodates right-stepping secondary faults (Yalahe, Selaha, Mugecuo, and Zheduotang) and explains the widespread normal faulting. The Mugecuo Lake represents the extensional center of this multi-scale stepover configuration.

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9. Data Availability Statement

The key geochronological results are summarized in Tables 1 and 2. Representative field photographs of the sampled boulders and complete ^{10}Be Terrestrial Cosmogenic Nuclide dating results are available in the Supplementary Material. All these data can be downloaded online at <https://doi.org/10.5281/zenodo.17143692>. The Lateral Displacement Calculator (LaDiCaoz_v2.1) can be accessed at <http://dx.doi.org/10.1130/GES00686.S1>. The Probabilistic Cosmogenic Nuclide Age Analysis Tool (P-CAAT) is available at kgs.uky.edu/anorthite/PCAAT. GISP2 ice core data are retrieved from <https://doi.org/10.25921/36sb-3355>. Guliya ice core data are downloaded from <https://www.ncei.noaa.gov/access/paleo-search/study/12426>. Stalagmite $\delta^{18}\text{O}$ records from Mawmluh and Dongge Caves are accessed from <https://doi.org/10.1002/2015GL064015> and <https://doi.org/10.1016/j.epsl.2005.01.036>, respectively. Northern Hemisphere summer insolation records are obtained from [https://doi.org/10.1016/0277-3791\(91\)90033-Q](https://doi.org/10.1016/0277-3791(91)90033-Q). GNSS data are available at <https://doi.org/10.1002/2017JB014465>. The Global Centroid Moment Tensor (GCMT) catalog is available at <https://www.globalcmt.org/>.

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11. Figures

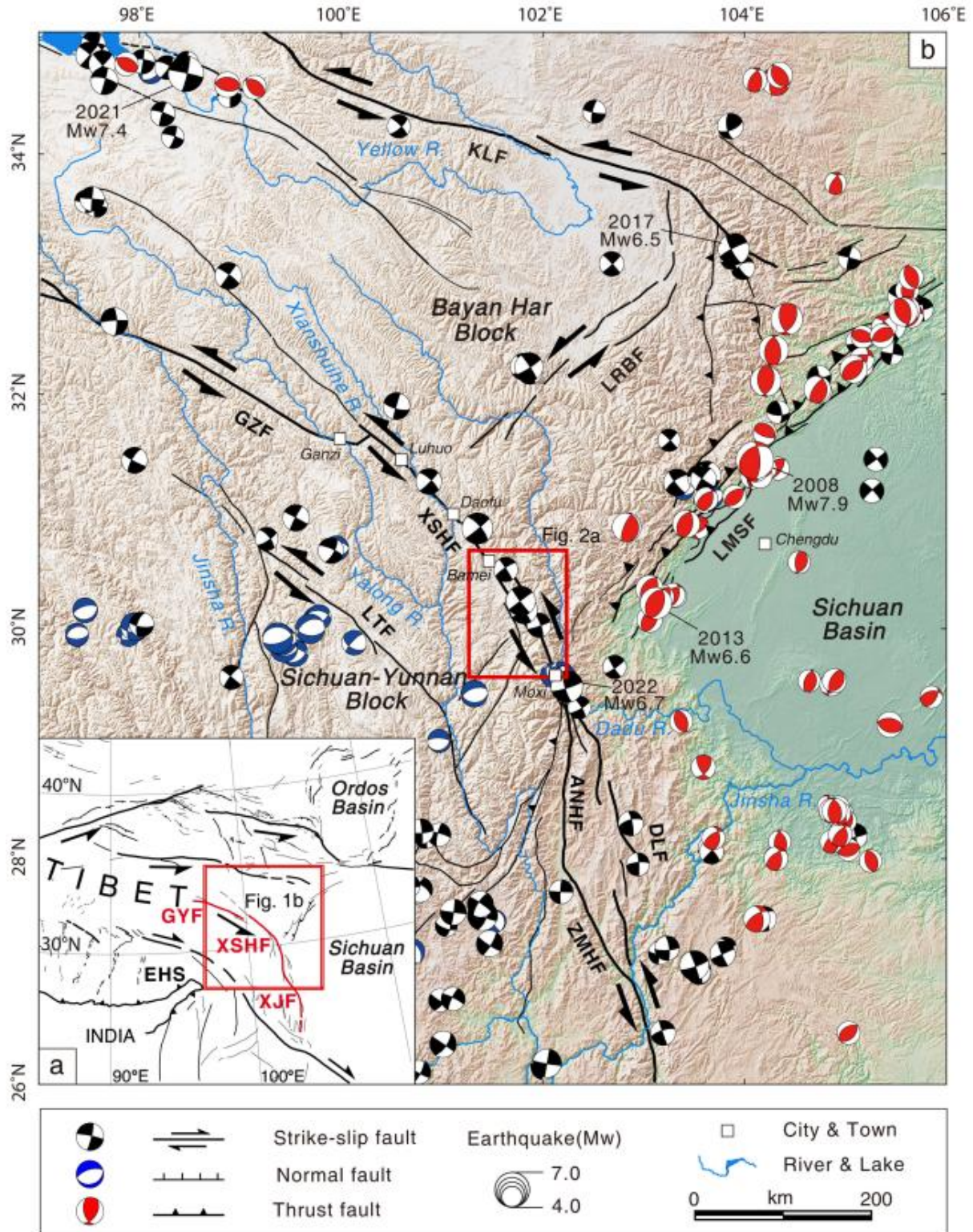


Figure 1. The Xianshuihe fault (XSHF) in the eastern Tibetan plateau. Major fault locations are from Ren et al. (2013) and Ren et al. (2022). (a) The inset map (lower left) shows the study area (red rectangle) and illustrates the spatial relationship between the XSHF and other major active faults in the region. Abbreviations: GYF - Ganzi-Yushu fault; XSHF - Xianshuihe fault; XJF - Xiaojiang fault; EHS - Eastern Himalayan syntaxis (b) Tectonic framework of the eastern Tibetan Plateau, displaying focal mechanisms of earthquakes

(Mw > 4) from the GCMT catalog (1976-2025). Notable seismic events include the 2008 Wenchuan (Mw 7.9), 2013 Lushan (Mw 6.6), 2017 Jiuzhaigou (Mw 6.5), 2021 Maduo (Mw 7.4), and 2022 Luding (Mw 6.7) earthquakes. The map also shows major secondary blocks, active faults, and river systems. Abbreviations: GZF - Ganzi fault; ANHF - Anninghe fault; DLF - Daliangshan fault; ZMHF - Zemuhe fault; LRBF - Longriba fault; LMSF - Longmenshan fault; KLF - Kunlun fault; LTF - Litang fault.

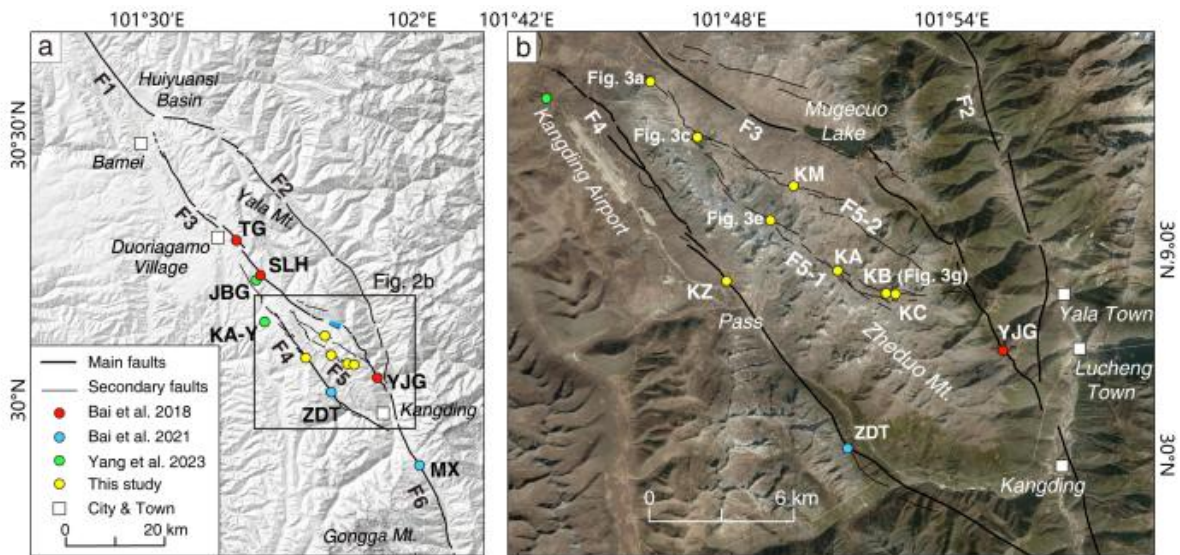


Figure 2. The Bamei-Kangding segment and associated secondary faults. (a) Hillshade image of the Bamei-Kangding area (location shown in red box in Figure 1b). The main trace of the NW Xianshuihe fault (F1) splays into four secondary faults: the Yalahe (F2), Selaha (F3), Zheduo (F4), and Mugecuo (F5) faults, which subsequently reconverge into the Moxi fault (F6) south of Kangding city. Survey sites from previous studies utilizing Terrestrial Cosmogenic Nuclide dating for exposure age determination are marked by red, blue, and green dots (Bai et al., 2018; 2021; Yang et al., 2023). To avoid nomenclature confusion, the Kangding Airport site (originally labeled as KA in Yang et al., 2023) is marked as KA-Y in this study. Yellow dots mark survey sites from this study. (b) Google Earth imagery of the Zheduo Mountain region with interpreted secondary Xianshuihe fault traces (location shown in black box in Figure 2a). The Mugecuo fault system (F5) consists of two distinct branches (southern (F5-1) and northern (F5-2)) predominantly distributed along the northeastern slope of Zheduo Mountain. Four sampled moraines are displaced by the Mugecuo fault (F5), while one sampled moraine is offset by the Zheduo (F4).

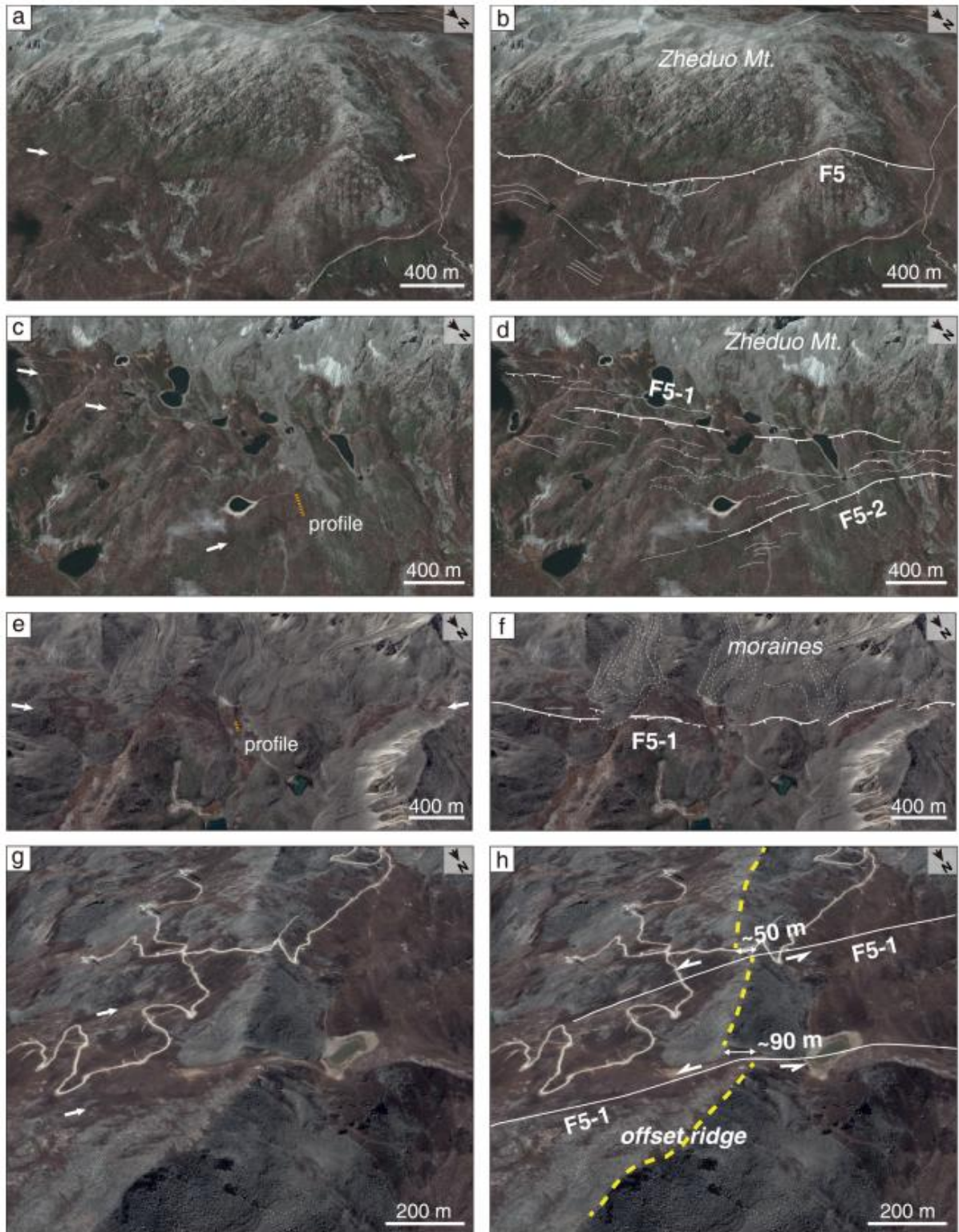


Figure 3. Tectonic geomorphology along the Mugecuo fault as observed in Google Earth imagery. The Mugecuo fault system (F5) divides into two primary branches (F5-1 and F5-2). (a) and (b), (c) and (d), (e) and (f), and (g) and (h) represent paired images and corresponding interpretations of distinct fault segments, respectively (location shown in Figure 2b). White solid lines show reliable fault traces. Orange dashed lines in (c) and (e) show topographic profiles from Pan et al. (2020). White dashed lines in (d) may outline terminals of Holocene

alluvial-proluvial deposits, and in (f) outline Holocene moraines (Pan et al., 2020). The fault zone exhibits characteristic deformation features including fault scarps, displaced moraines, and offset ridges, indicating a combination of normal and strike-slip faulting.

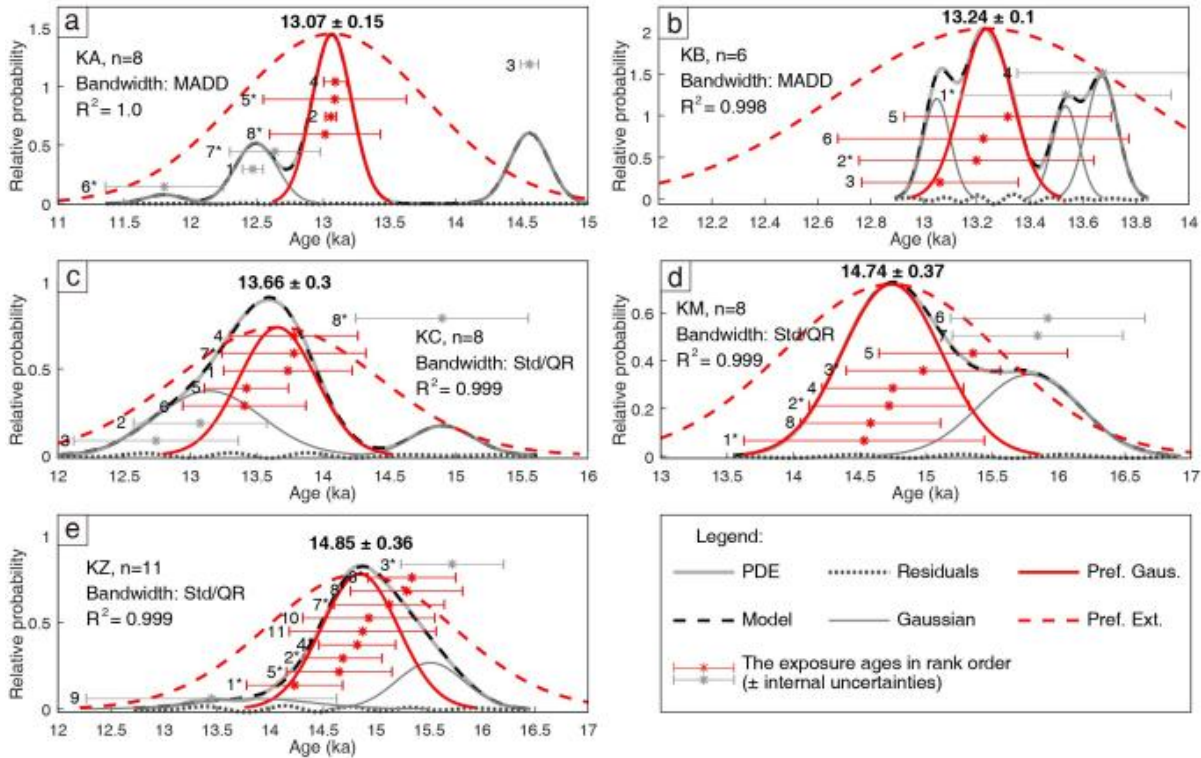
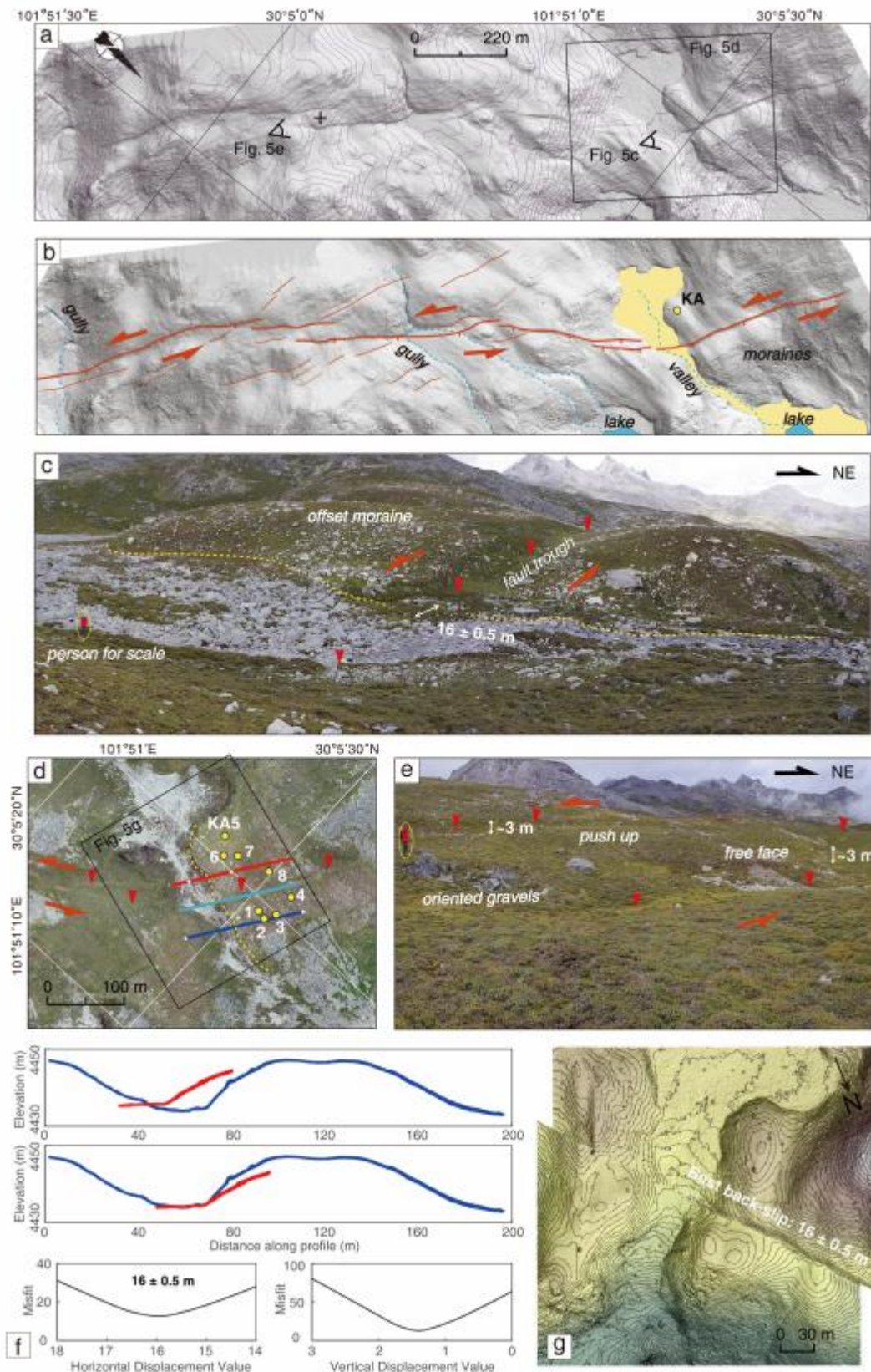


Figure 4. Gaussian separation analysis of ^{10}Be TCN ages for faulted moraines KA (a), KB (b), KC (c), KM (d), and KZ (e). Following P-CAAT guidelines, the exposure age is determined by selecting either the highest amplitude component (< 21 ka) or the oldest probability component (> 21 ka) of the probability density estimate (PDE) (Dortch et al., 2022). The PDE is represented by the gray-and-black dashed curve, while lower probability components are indicated by gray curves. Exposure ages corresponding to preferred Gaussian distributions (red curves) are displayed in bold black font. Additional parameters displayed include sample quantities (n), bandwidth estimation patterns (MADD or Std/QR), and model fit quality (R^2). Asterisked numbers indicate samples collected upstream of the moraines (Table 1; Supplementary Material).



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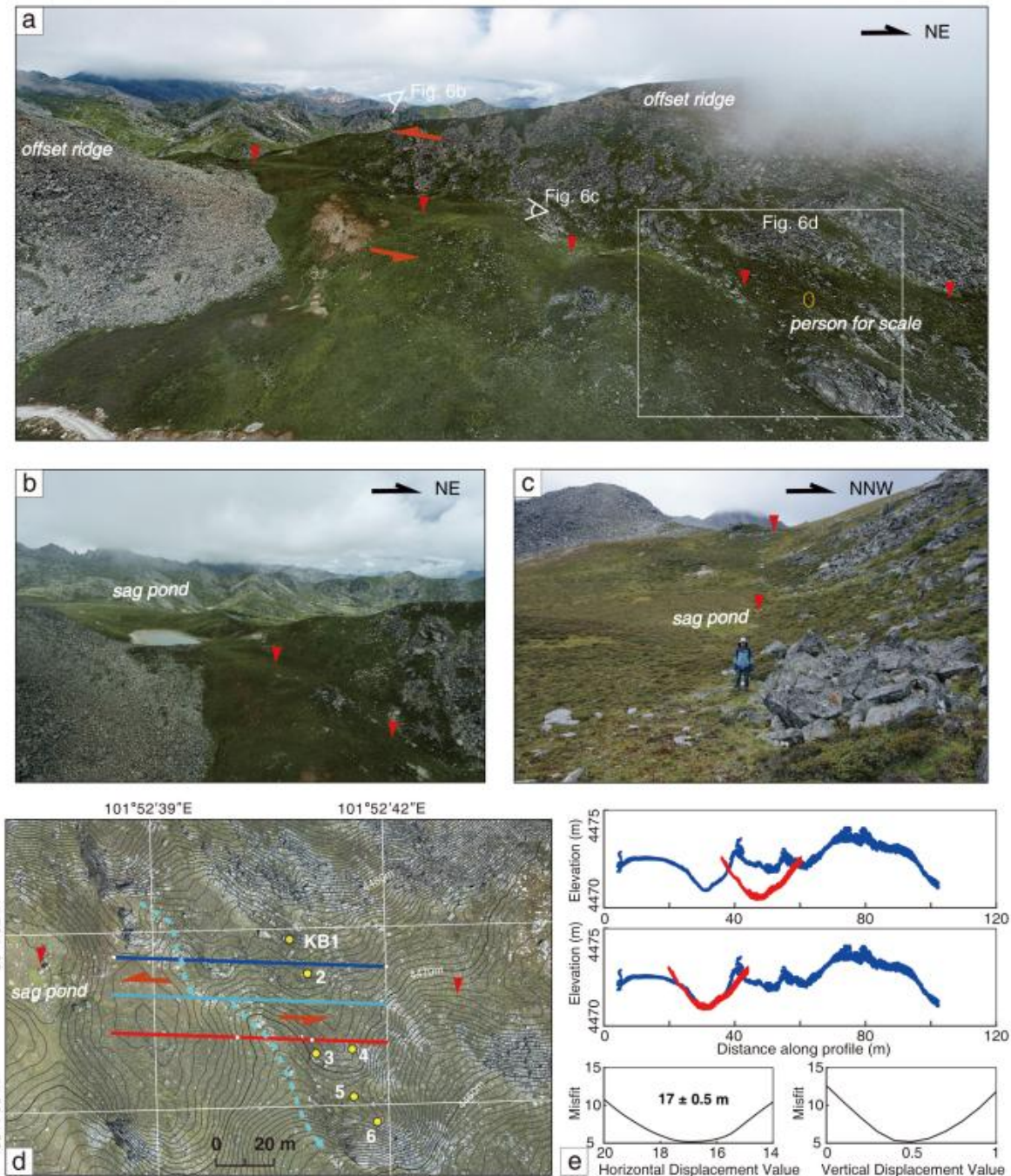
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Figure 5. Southern branch of the Mugecu fault (F5-1) and KA site (location shown by yellow dot in Figure 2b). (a) Hillshade model generated from drone photogrammetry with purple contour lines and "+" symbols marking push up areas. (b) Interpreted hillshade image illustrating sinistral-compressional characteristics of F5-1, with main fault traces (thick red

lines) and secondary fractures (thin red lines). Yellow patch indicates an offset valley and blue dashed lines indicate offset small gullies. (c) Field photograph showing offset stone river and moraine at the KA site, with fault trace indicated by red triangles (viewing perspective shown in Figure 5a). (d) UAV orthophoto of offset stone river and moraine at the KA site (location shown in black box in Figure 5a). Yellow dashed lines mark the southern margin of the displaced moraine, and yellow dots indicate ^{10}Be TCN sampling locations. White dots along red and blue lines represent terrain profile measurement points, with the cyan line denoting the fault trace. (e) Field evidence along F5-1 showing fault scarp, push up, oriented gravels, and free faces (viewing perspective shown in Figure 5a). (f) Topographic profiles corresponding to the red and blue lines shown in Figure 5d, which reveal a lateral offset of 16 ± 0.5 m when using the offset moraine's southern margin as the displacement marker. (g) Back-slip reconstruction showing restored moraine continuity, generated using LaDiCaoz_v2.1 software (Zielke & Arrowsmith, 2012).



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1297 Figure 6. Southern branch of the Mugecu fault (F5-1) and KB site (location shown by
 1298 yellow dot in Figure 2b). (a) Drone photograph of the KB site showing fault trace marked by
 1299 red triangles. (b) Drone photograph revealing sag pond development along the fault (viewing
 1300 perspective shown in Figure 6a). (c) Field photograph showing sag pond and oriented gravels
 1301 along the fault trace (viewing perspective shown in Figure 6a). (d) UAV orthophoto of the
 1302 KB site with arrow-headed cyan dashed lines indicating offset geomorphic features (gully
 1303 thalweg). Yellow dots mark ^{10}Be TCN sampling locations. White dots along red and blue
 1304 lines represent terrain profile measurement points, with cyan line denoting the fault trace. (e)
 1305 Topographic profiles corresponding to the red and blue lines shown in Figure 6d, which
 1306 reveal a lateral offset of 17 ± 0.5 m when using the gully thalweg as the displacement marker

(Zielke & Arrowsmith, 2012).

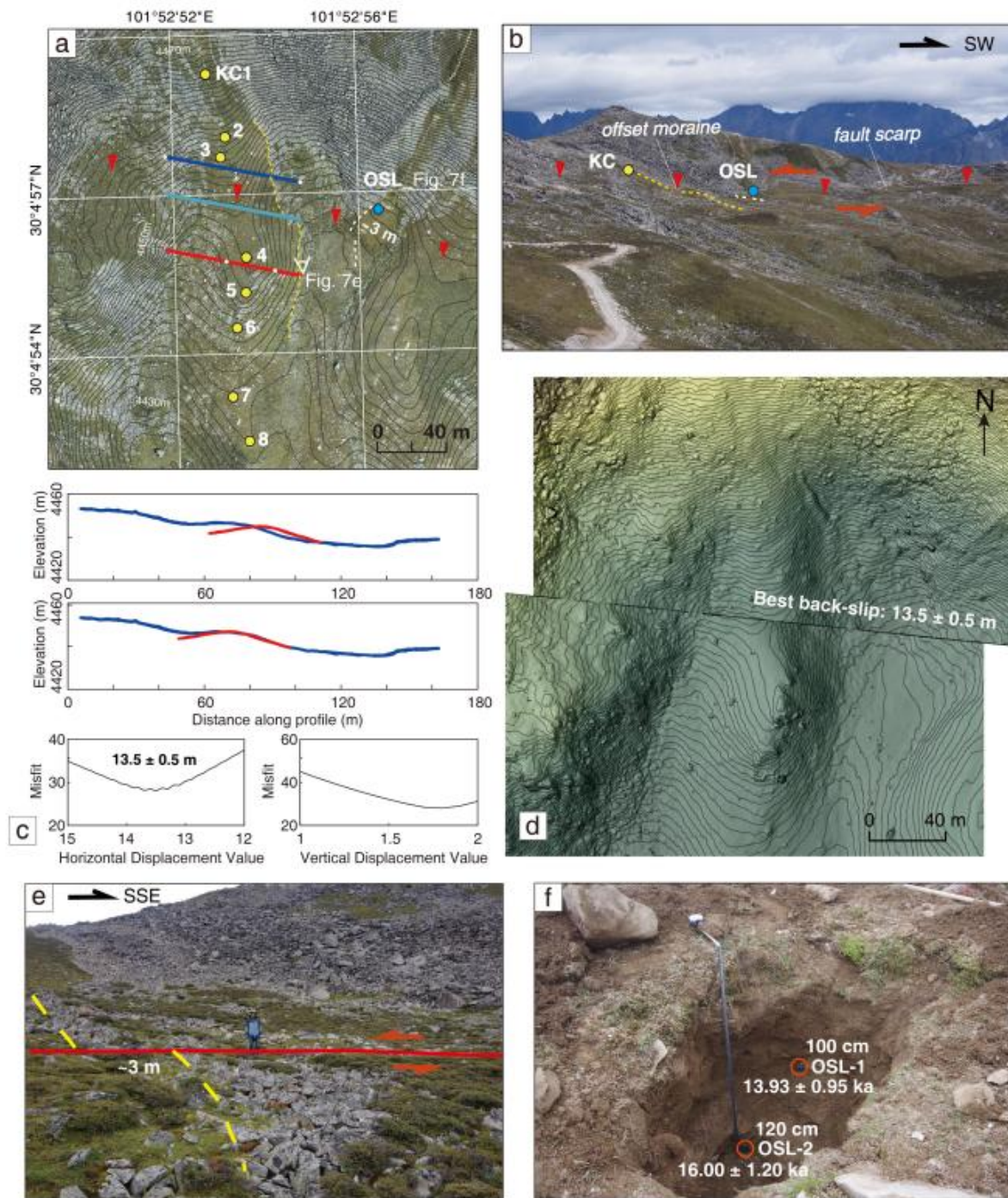


Figure 7. Southern branch of the Mugecuo fault (F5-1) and KC site (location shown by yellow dot in Figure 2b). (a) UAV orthophoto of the KC site showing ^{10}Be TCN sampling locations (yellow dots) and OSL sampling site (blue dot). White dots along red and blue lines represent terrain profile measurement points, with fault trace indicated by cyan line and red triangles. White dashed lines outline the extent of the terrace, and yellow dashed lines outline the extent of the offset stone river. (b) Field photograph of the KC site showing fault trace

(red triangles), offset moraine (yellow dashed lines), and terrace extent (white dashed lines). (c) Topographic profiles corresponding to the red and blue lines shown in Figure 7a, which reveal a lateral offset of 13.5 ± 0.5 m when using the moraine crest as the displacement marker. (d) Back-slip reconstruction model demonstrating restored moraine continuity, generated using LaDiCaoz software (Zielke & Arrowsmith, 2012). (e) Field photograph showing offset stone river adjacent to the displaced moraine, with fault trace marked by red line and displacement indicated by yellow dashed lines (viewing perspective shown in Figure 7a). (f) OSL sampling details and dating results from the offset terrace adjacent to the KC offset moraine.

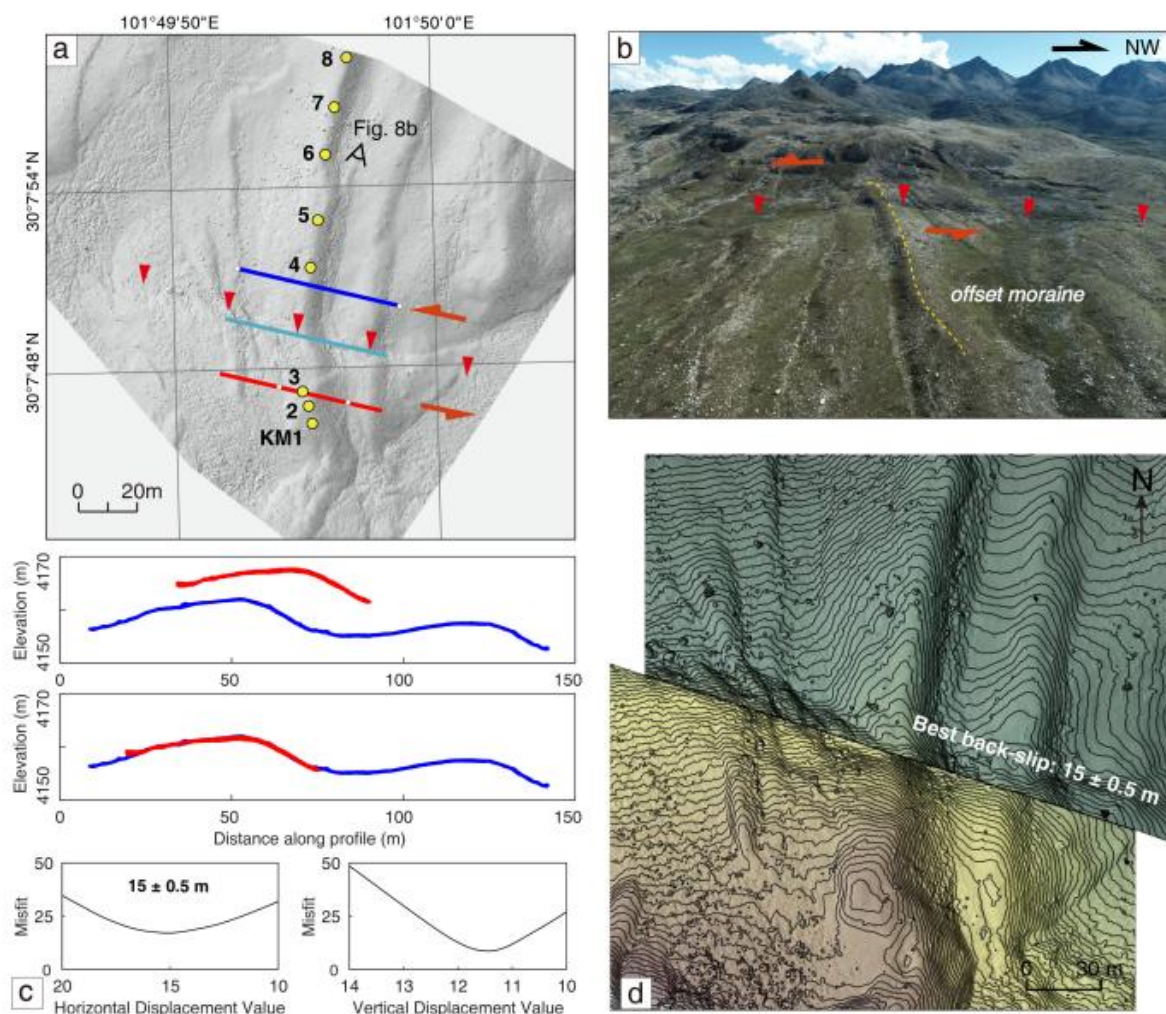
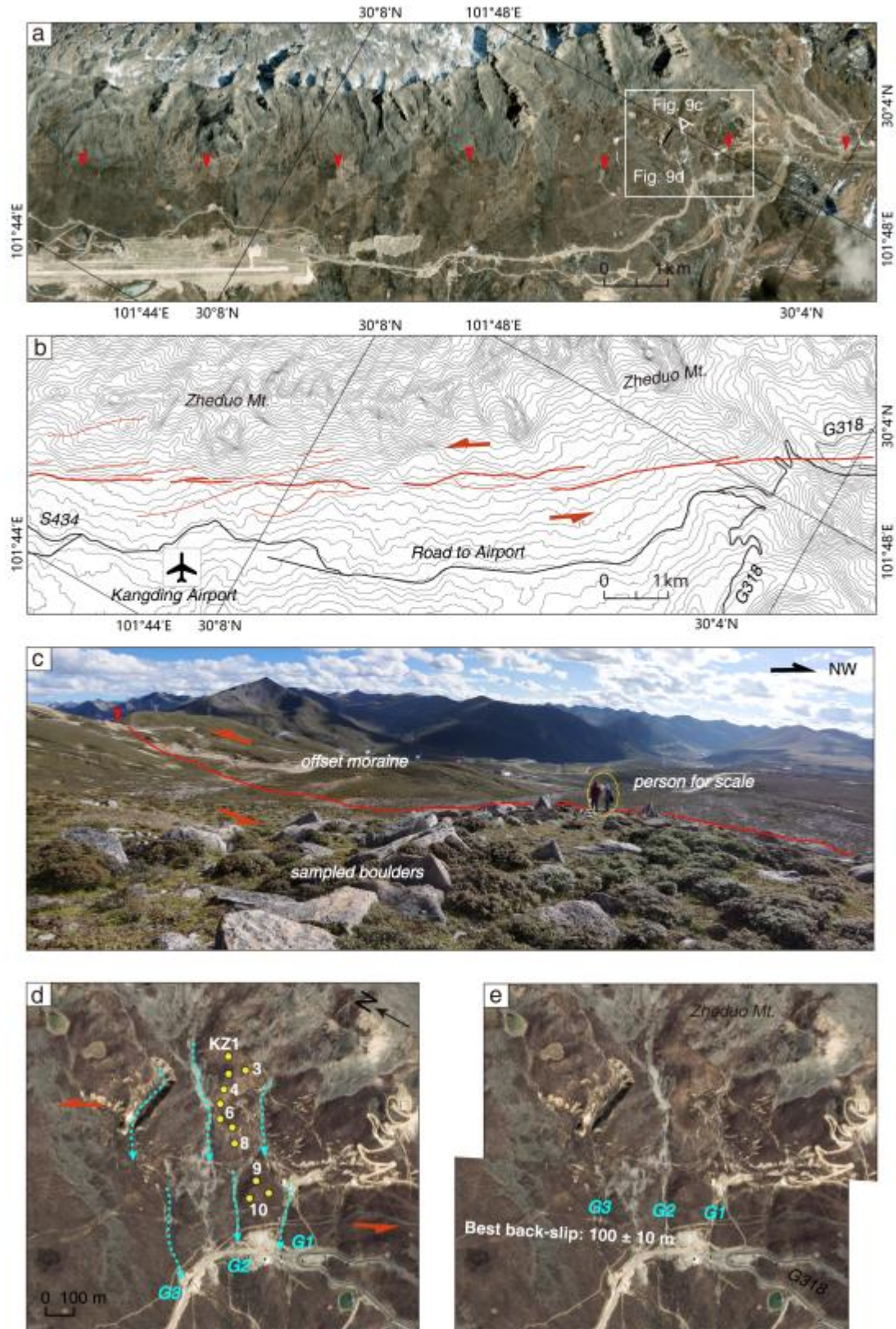


Figure 8. Northern branch of the Mugecuo fault (F5-2) and KM site (location indicated by yellow dot in Figure 2b). (a) UAV-derived hillshade image of the KM site showing ^{10}Be TCN sampling locations (yellow dots) and fault trace (red triangles and cyan line). White dots along red and blue lines indicate terrain profile measurement points. (b) Drone photograph of the KM site illustrating the fault trace (red triangles) and moraine crest (yellow dashed lines) (viewing perspective shown in Figure 8a). (c) Topographic profiles corresponding to the red and blue lines shown in Figure 8a, which reveal a lateral offset of 15 ± 0.5 m when using the

1334 moraine crest as the displacement marker. (d) Back-slip reconstruction model demonstrating
1335 restored moraine continuity, generated using LaDiCaoz software (Zielke & Arrowsmith,
1336 2012).

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Figure 9. Northern segment of the Zheduotang fault (F4) and KZ site (location indicated by yellow dot in Figure 2b). (a) Google Earth imagery of the KZ site showing the fault trace (red triangles). The white rectangle highlights characteristic faulting geomorphic features, detailed

in Figure 9d. (b) Tectonic interpretation of Figure 9a. Bold red lines represent the main fault, thin red lines indicate secondary faults, and the black solid line denotes the road network. (c) Field photograph of the KZ site (viewing perspective shown in Figure 9a) with the fault trace indicated by a red solid line. (d) Offset gullies (dashed cyan lines with arrow) and moraines at the KZ site. The three major gullies are labeled as G1, G2, and G3. Yellow dots mark the ^{10}Be TCN sampling locations on the crest of the offset moraine. (e) Back-slip reconstruction based on Google Earth imagery, which reveals a sinistral displacement of 100 ± 10 m when using the gully G2 as the displacement marker.

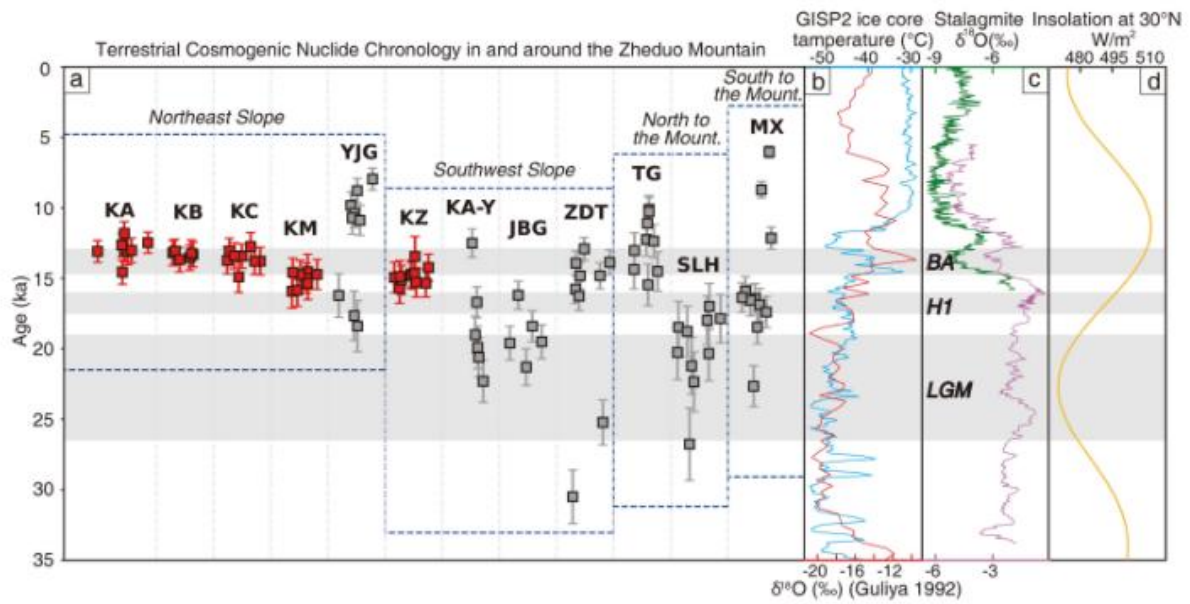


Figure 10. Global paleoclimate proxies compared with ^{10}Be TCN dating from the Zheduo Mountain region. Notes: Red dots represent the glacial chronology constrained by ^{10}Be TCN dating in this study, while gray dots indicate results from previous studies (Bai et al., 2018, 2021; Yang et al., 2023). Light gray horizontal bands indicate climate events (BA: Bølling-Allerød period, 14.7-12.9 ka (Rasmussen et al., 2014; Clark et al., 2012); H1: Heinrich event 1, 17.5-16 ka (Heinrich, 1988; Hemming, 2004); LGM: Last Glacial Maximum, 26.5–19 ka (Clark et al., 2009)). (a) Glacial chronology based on ^{10}Be TCN dating from southwestern and northeastern slopes of Zheduo Mountain and adjacent regions. Study sites include: KA, KB, KC, KM, and KZ (this study); YJG, TG, and SLH (Bai et al., 2018); ZDT and MX (Bai et al., 2021); JBG and KA-Y (Yang et al., 2023). Site locations are shown in Figure 2a. (b) Air temperature variations from the Greenland GISP2 ice core record (blue; Alley, 2004) and $\delta^{18}\text{O}$ record from the Guliya ice core collected in 1992 in the northwestern Tibetan Plateau (red; Thompson et al., 1997). (c) Stalagmite $\delta^{18}\text{O}$ records from Mawmluh Cave (purple) and Dongge Cave (green; Dutt et al., 2015; Dykoski et al., 2005). (d) Northern Hemisphere summer insolation at 30°N over the past 35 ka (Berger & Loutre, 1991).

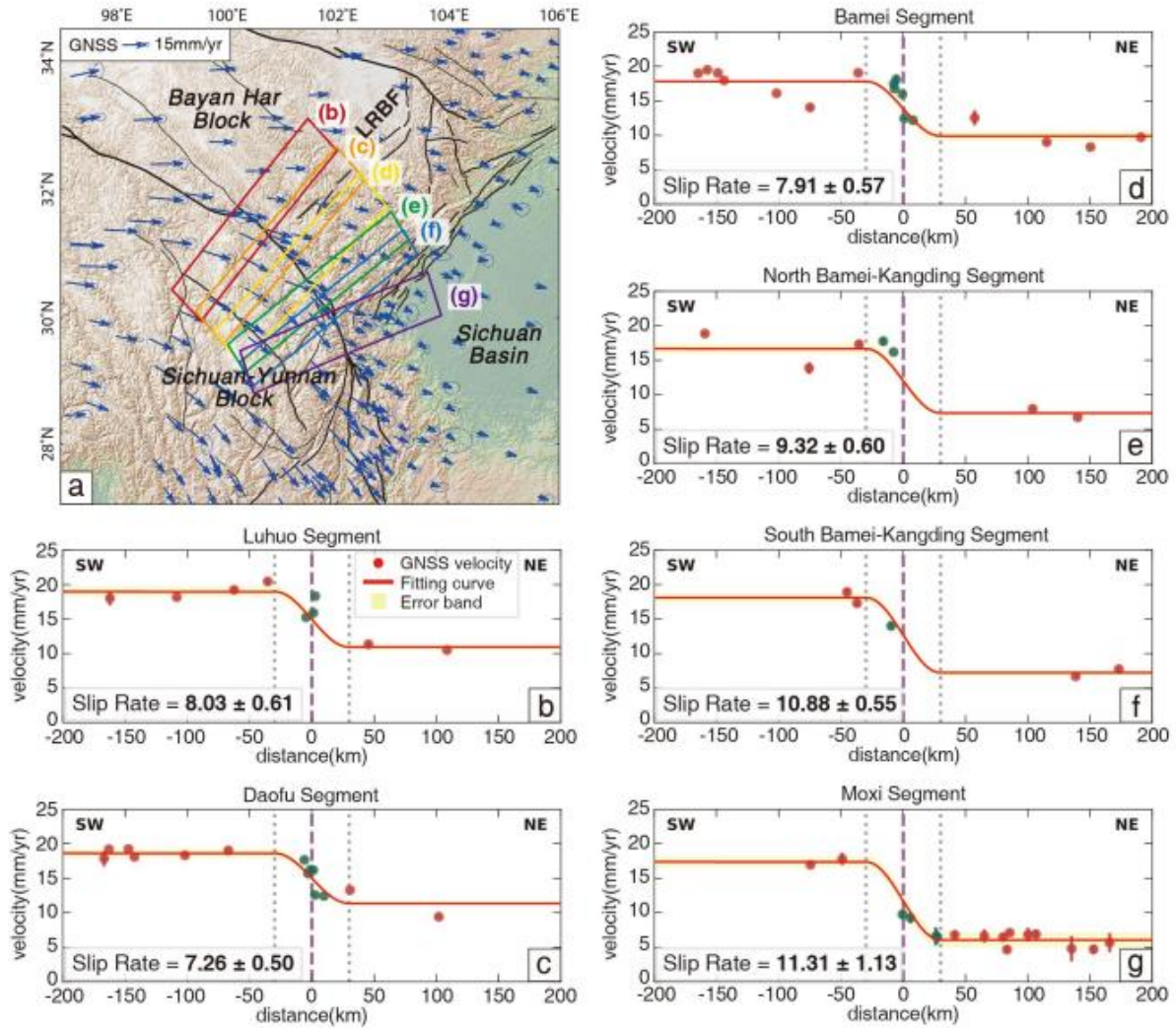


Figure 11. (a) Interseismic GNSS velocity field across the eastern Tibetan Plateau relative to stable Eurasia. Blue arrows represent horizontal GNSS velocities from Zheng et al. (2017), with 95% confidence interval error ellipses. Labeled boxes indicate profile locations shown in Figures 11b-11g. Abbreviations: LRBF - Longriba fault. (b-g) GNSS velocity profiles perpendicular to different segments of the Xianshuihe fault. Each profile extends 200 km bilaterally from the fault trace, with segment-specific widths: 40 km for the Luhuo (b), Daofu (c), Bamei (d), and Moxi (g) segments; 30 km for the north Bamei-Kangding segment (e); and 25 km for the south Bamei-Kangding segment (f). Purple dashed lines indicate the fault trace ($x=0$), and grey dashed lines at ± 30 km roughly mark the deformation zone. Horizontal GNSS velocities are shown as colored dots (green dots represent GNSS stations within the deformation zone). Red solid lines represent the best-fitting curves with yellow shading indicating error bands.

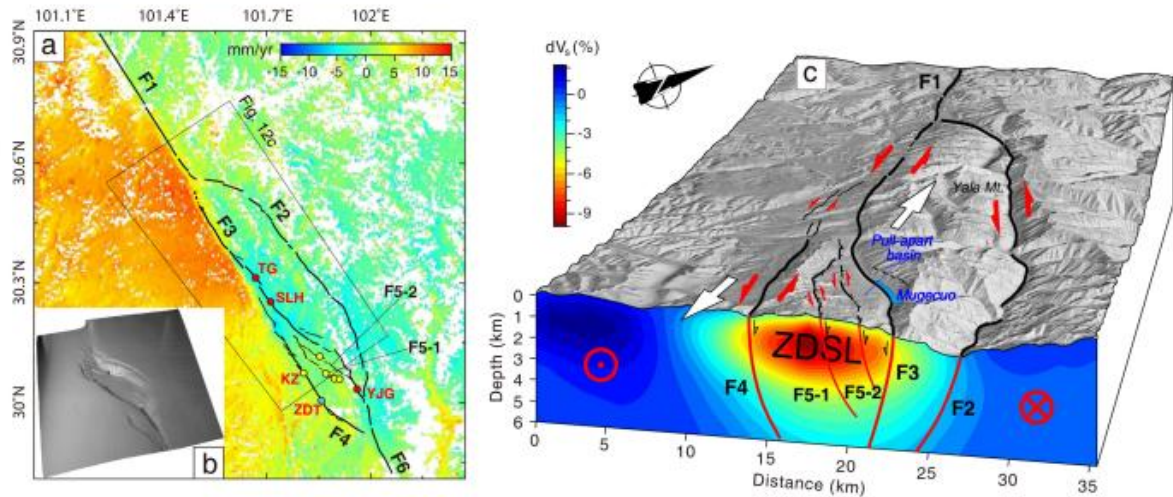


Figure 12. Geometry, kinematics, and deep structure of the Bamei-Kangding segment. Major faults include: the NW Xianshuihe fault (F1), Yalahe fault (F2), Selaha fault (F3), Zheduotang fault (F4), the southern (F5-1) and northern (F5-2) branches of the Mugecuo fault, and Moxi fault (F6). (a) InSAR observations modified from Huang et al. (2023). Positive values indicate southeastward motion, and negative values indicate northwestward motion. Red, yellow, and blue dots represent survey sites where late Quaternary slip rates were calculated using ^{10}Be TCN dating, from Bai et al. (2018), this study, and Bai et al. (2021), respectively. (b) Clay experimental model of 45° oblique releasing bend modified from Mitra and Paul (2011). (c) Three-dimensional model of the Bamei-Kangding segment. The S-wave velocity profile is modified from Zhao et al. (2023), with the color scale indicating perturbations relative to the average S-wave velocity at different depths. ZDSL represents the Zheduo Mountain low-velocity anomalies. The secondary faults cut through the ZDSL, probably connect at depth, and vertically form a negative flower structure.

Table 1
Key ¹⁰Be Terrestrial Cosmogenic Nuclide Dating results from sites along the Mugecuo fault (KA, KB, KC, KM) and Zheduotang fault (KZ)

Sample	Lat	Long	Elev	Quartz	Shielding	Be carrier	¹⁰ Be/ ⁹ Be	¹⁰ Be	LSDn (yr)		
name	(°N)	(°E)	(m)	(g)	factor	(mg)	(10 ⁻¹⁵)	(10 ⁶ atom/g)	Age	Inter	Exter
KA Site											
KA1	30.09192605	101.8501891	4463	19.4783	0.997958	0.25448	736 ± 33	0.643 ± 0.029	12470	77	742
KA2	30.09205375	101.8502227	4460	23.0061	0.997933	0.23707	992 ± 32	0.683 ± 0.022	13058	42	774
KA3	30.09213466	101.8500345	4460	19.4776	0.997508	0.23923	954 ± 42	0.783 ± 0.035	14557	68	865
KA4	30.09211554	101.8497106	4464	21.1232	0.996425	0.29854	727 ± 35	0.686 ± 0.033	13092	86	780
KA5	30.09100151	101.849681	4474	21.3110	0.996517	0.22674	970 ± 40	0.690 ± 0.028	13089	539	944
KA6	30.09111562	101.8499095	4472	19.8640	0.997074	0.27513	659 ± 25	0.610 ± 0.023	11803	445	828
KA7	30.0912605	101.8498127	4474	19.6730	0.997292	0.26018	742 ± 20	0.655 ± 0.018	12637	341	822
KA8	30.09169538	101.8496555	4474	21.0195	0.997727	0.25782	834 ± 27	0.684 ± 0.022	13015	417	876
KB Site											
KB1	30.08106726	101.8779099	4510	19.6726	0.995604	0.25733	836 ± 24	0.731 ± 0.021	13536	397	894
KB2	30.08095939	101.8779717	4507	19.2503	0.996233	0.26421	774 ± 26	0.710 ± 0.024	13199	443	898
KB3	30.08071453	101.8779824	4502	20.6909	0.997073	0.26077	827 ± 19	0.697 ± 0.016	13061	295	827
KB4	30.08072162	101.8781167	4501	19.3802	0.997008	0.28979	739 ± 17	0.738 ± 0.017	13676	323	872
KB5	30.08057309	101.8781275	4498	20.6605	0.997513	0.28605	773 ± 23	0.715 ± 0.021	13317	390	879
KB6	30.08049425	101.8782094	4496	19.6958	0.997374	0.26362	792 ± 33	0.708 ± 0.029	13225	549	956
KC Site											
KC1	30.08120853	101.8814538	4466	19.6871	0.996945	0.24995	860 ± 30	0.730 ± 0.026	13735	484	947
KC2	30.08144171	101.8813611	4468	20.3538	0.996403	0.24926	839 ± 32	0.686 ± 0.026	13074	503	923
KC3	30.0818015	101.881396	4472	19.6588	0.996043	0.27740	700 ± 34	0.660 ± 0.032	12740	621	977
KC4	30.08198491	101.8814538	4474	20.0271	0.995358	0.24385	903 ± 35	0.735 ± 0.029	13780	542	980
KC5	30.08216944	101.8814605	4477	23.1386	0.994604	0.27346	90 ± 21	0.712 ± 0.017	13422	316	855
KC6	30.08269503	101.8813208	4488	19.5603	0.992961	0.25772	810 ± 28	0.714 ± 0.025	13406	464	919
KC7	30.0827995	101.8813504	4491	23.1048	0.992794	0.25949	985 ± 34	0.739 ± 0.026	13781	481	947
KC8	30.08313131	101.8812416	4502	19.9763	0.991117	0.2567	951 ± 41	0.817 ± 0.035	14898	650	1096
KM Site											
KM1	30.12948587	101.8319296	4201	20.2532	0.996181	0.24680	840 ± 52	0.684 ± 0.043	14534	907	1250
KM2	30.1296482	101.8318959	4199	20.4667	0.996559	0.24867	853 ± 35	0.693 ± 0.028	14722	604	1061
KM3	30.12978263	101.8318341	4198	19.1168	0.996716	0.25595	793 ± 31	0.709 ± 0.027	14979	580	1060
KM4	30.13092422	101.831951	4178	19.8495	0.997784	0.26658	766 ± 28	0.687 ± 0.025	14750	534	1024
KM5	30.13135936	101.8320411	4172	19.2509	0.998162	0.28605	728 ± 34	0.723 ± 0.033	15356	711	1154
KM6	30.1319627	101.8321365	4165	19.2955	0.998368	0.28448	760 ± 35	0.749 ± 0.034	15919	732	1194
KM7	30.1323967	101.8322441	4161	20.8033	0.998496	0.26815	863 ± 35	0.744 ± 0.030	15843	643	1138
KM8	30.13363123	101.8324564	4147	19.8453	0.998779	0.25231	788 ± 28	0.669 ± 0.024	14582	528	1012
KZ Site											
KZ1	30.08879264	101.8026498	4409	18.8658	0.99589	0.25743	816 ± 26	0.744 ± 0.024	14232	452	956
KZ2	30.08820572	101.8020987	4395	20.5980	0.996462	0.26185	899 ± 23	0.763 ± 0.019	14687	369	945
KZ3	30.0880739	101.8023864	4397	20.2465	0.996366	0.26618	945 ± 29	0.830 ± 0.026	15718	485	1050
KZ4	30.08834516	101.800779	4375	25.0012	0.996822	0.26697	1071 ± 26	0.764 ± 0.019	14822	361	949
KZ5	30.08826112	101.8004699	4371	20.2324	0.996925	0.24444	932 ± 32	0.753 ± 0.025	14652	497	1000
KZ6	30.08787133	101.7998181	4361	19.6003	0.99738	0.25398	918 ± 25	0.795 ± 0.021	15338	413	998
KZ7	30.08728948	101.7995184	4352	20.4268	0.997553	0.23962	993 ± 34	0.778 ± 0.027	15123	521	1036
KZ8	30.08697453	101.7992201	4345	20.3290	0.997754	0.32855	727 ± 25	0.786 ± 0.027	15288	528	1048

KZ9	30.08429517	101.7985818	4297	20.9446	0.997459	0.23962	854 ± 75	0.653 ± 0.057	13448	1181	1424
KZ10	30.08429885	101.7979596	4292	20.5356	0.997896	0.25359	898 ± 37	0.741 ± 0.031	14931	623	1082
KZ11	30.08398156	101.7984018	4295	22.2065	0.997694	0.25939	946 ± 44	0.738 ± 0.034	14874	692	1120

Note: The ^{10}Be TCN samples were processed at the Key Laboratory of Compound and Chained Natural Hazards Dynamics, Ministry of Emergency Management of China (Beijing, China), with $^{10}\text{Be}/^9\text{Be}$ ratios measured at CEREGE (Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement, Aix-en-Provence, France). All samples were collected from the uppermost exposed surface (~2 cm) of in situ granitic boulders ($\rho = 2.7 \text{ g/cm}^3$). Exposure ages were calculated using the CRONUS v3 calculator (Balco et al., 2008). The calculations were performed using the revised ICN standard of 07KNSTD (Nishiizumi et al., 2007). No erosion rates were applied following recent regional studies (Yang et al., 2023; Bai et al., 2018, 2021), as samples were collected from large, stable granite boulders in a cold, arid, high-elevation environment where erosion effects are minimal over the post-LGM timescale. Topographic shielding factors were calculated using the ArcGIS toolbox developed by Li (2018) based on 30-m ASTER DEM data following Yang et al. (2023). The LSDn ages and their external uncertainties (in years), highlighted in bold, were used to calculate the late Quaternary slip rates in this study (LSDn stands for Lifton et al. (2014) production rate model; external uncertainties include both analytical and production rate uncertainties (Balco et al., 2008), reported at the 1σ confidence level).

Table 2
Optically Stimulated Luminescence (OSL) Dating results from the southeastern segment of the southern Mugecuo fault branch

Sample number	Depth (m)	U (μg/g)	Th (μg/g)	K (%)	Water content (%)	Grain size (μm)	Analytical method	Ambient dose (Gy/ka)	Equivalent dose (Gy)	OSL Age (ka)
OSL-1	1	2.78 ± 0.02	36.50 ± 0.06	3.84 ± 0.02	14.22	90~125	SAR	6.41 ± 0.41	89.25 ± 2.28	13.93 ± 0.95
OSL-2	1.2	2.98 ± 0.04	45.30 ± 0.48	3.41 ± 0.02	15.48	90~125	SAR	6.48 ± 0.45	103.63 ± 3.05	16.00 ± 1.20

Note: The OSL samples were processed at the Key Laboratory of Compound and Chained Natural Hazards Dynamics, Ministry of Emergency Management of China (Beijing, China). Fine-grained sand samples were collected from a faulted terrace adjacent to the KC moraine along the southern branch of the Mugecuo Fault using cylindrical steel tubes (5 cm in diameter, 20 cm in length). All luminescence measurements and subsequent analyses were conducted at the aforementioned laboratory.

**Normal Faults and Tectonic Model of the Bamei-Kangding Segment within the Southern
Xianshuihe Fault Zone in Eastern Tibet**

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Contents of this file

Figure S1 to S5

Text S1

Figure S6

Table S1

Introduction

The supplemental material provides Figure S1 to S5, Text S1, Figure S6, and Table S1. Figures S1 to S5 show field photographs and dimensions of boulders sampled for ¹⁰Be Terrestrial Cosmogenic Nuclide dating from sites along the Mugecuo fault (KA, KB, KC, KM) and Zheduotang fault (KZ). Text S1 reveals possible causes of boulder coloration differences observed in the field photographs from the perspectives of rock composition, environmental exposure effects, and photographic conditions. Figure S6 presents P-CAAT statistical reanalysis of published ¹⁰Be exposure ages from Zheduo Mountain region. Table S1 presents complete ¹⁰Be Terrestrial Cosmogenic Nuclide (TCN) dating results.

1. Field photographs and dimensions of boulders sampled for ^{10}Be Terrestrial Cosmogenic Nuclide dating from sites along the Mugecuo fault (KA, KB, KC, KM) and Zheduotang fault (KZ).



Figure S1. Representative field photographs of sampled boulders from the KA site along the southern branch of the Mugecuo fault. Boulder dimensions (length, width, and height in meters) are annotated, with geological hammer shown for scale.

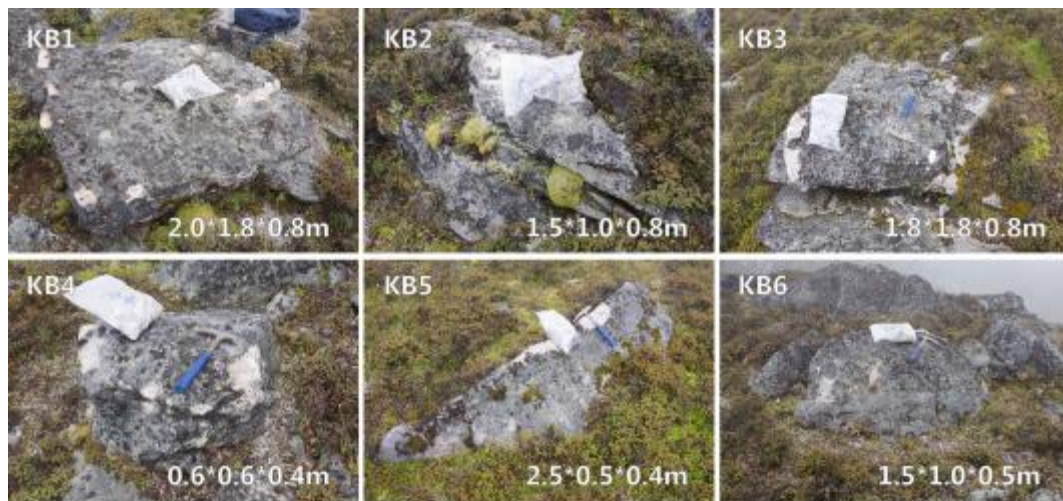


Figure S2. Representative field photographs of sampled boulders from the KB site along the southern branch of the Mugecuo fault. Boulder dimensions (length, width, and height in meters) are annotated, with geological hammer shown for scale.

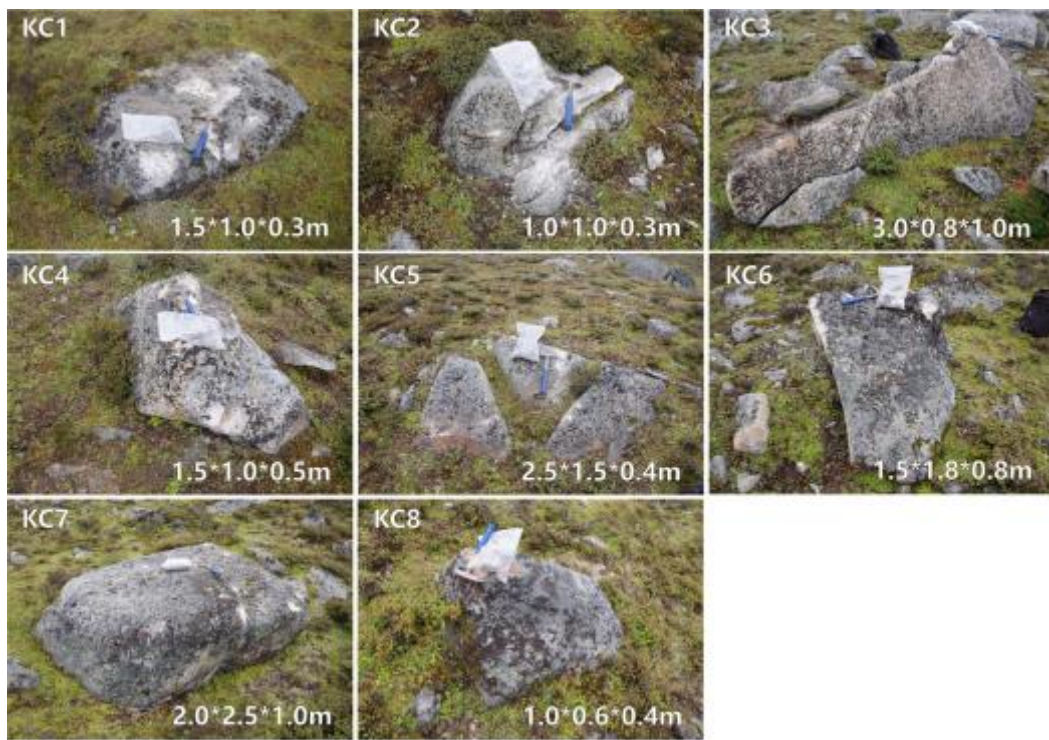


Figure S3. Representative field photographs of sampled boulders from the KC site along the southern branch of the Mugecuo fault. Boulder dimensions (length, width, and height in meters) are annotated, with geological hammer shown for scale.



Figure S4. Representative field photographs of sampled boulders from the KM site along the northern branch of the Mugecuo fault. Boulder dimensions (length, width, and height in meters) are annotated, with geological hammer shown for scale.



Figure S5. Representative field photographs of sampled boulders from the KZ site along the northwestern segment of the Zheduotang fault. Boulder dimensions (length, width, and height in meters) are annotated, with geological hammer shown for scale.

2. Text S1. Possible Explanations of Boulder Coloration Differences in Field Photographs

The field photographs in Figures S1-S5 show variations in boulder surface coloration, particularly the white appearance of boulders in Figures S1 and S4 compared to other sites. These differences can be attributed to several factors:

Rock type variations: Local variations in granite composition, particularly quartz and feldspar content, can result in different surface colors and weathering patterns.

Environmental and exposure effects: The lighter coloration may reflect different degrees of surface weathering and lichen growth influenced by slope orientation (Figures S1-S4 are from the northeastern slope of Zheduo Shan, while Figure S5 is from the southwestern slope), elevation differences, and variations in local microclimate, snow cover duration, and UV exposure in this high-altitude, arid environment (4,100-4,500 m asl).

Photographic conditions: Differences in lighting conditions, sun angle, and photographic timing during fieldwork can significantly affect the apparent color of rock surfaces. Figure S4 was photographed in the afternoon with oblique sunlight directly illuminating the boulder surface, resulting in the bright appearance.

However, the specific reason for the color differences in these particular boulders is not definitively determined from our field observations alone. For our ^{10}Be analysis, all samples were collected from stable, well-embedded granite boulders regardless of their surface coloration, following standard sampling protocols for cosmogenic nuclide dating.

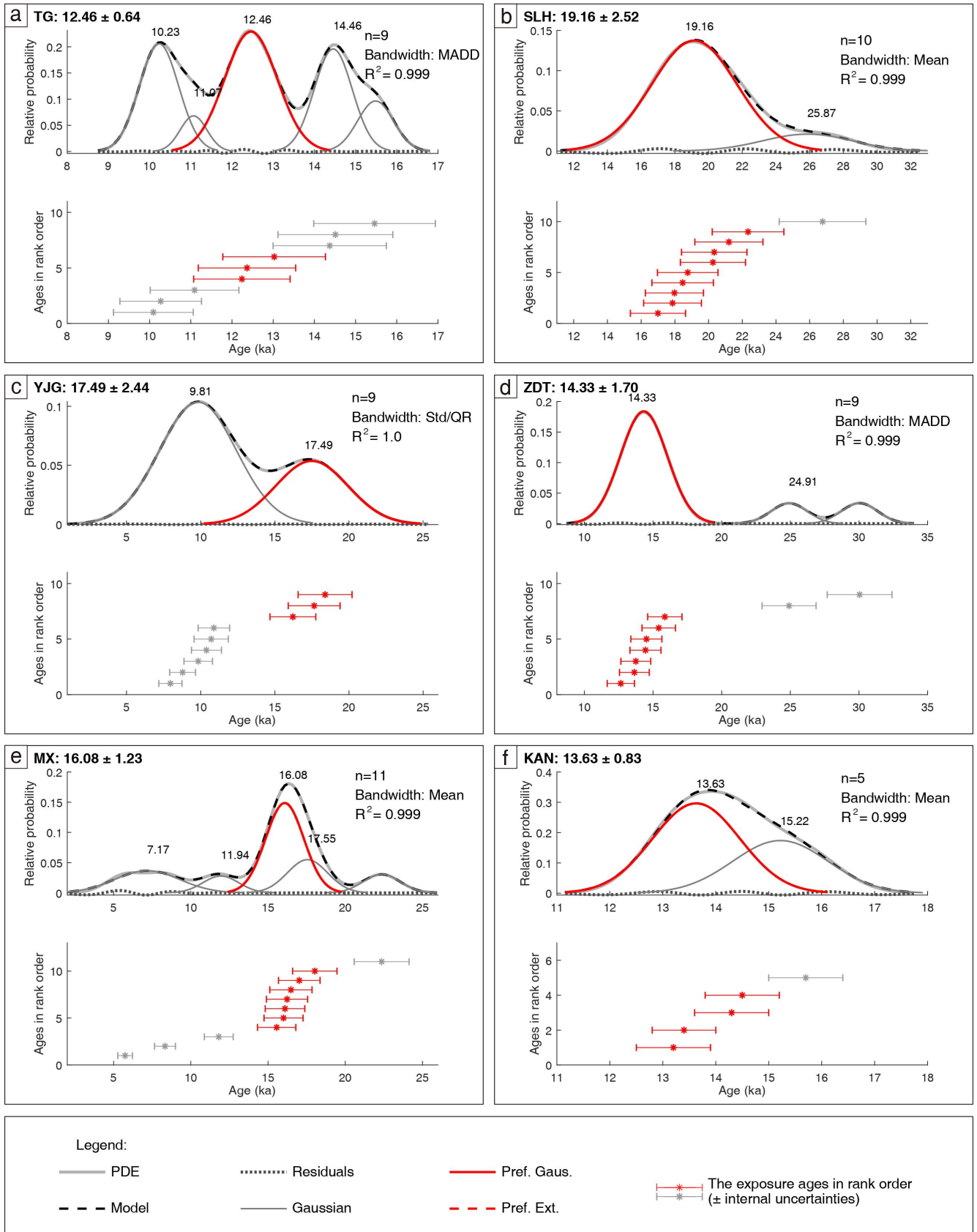


Figure S6. P-CAAT reanalysis of published ^{10}Be TCN ages and comparison with original exposure age determinations. Recalculated exposure ages: TG (12.46 ± 0.64 ka), SLH (19.16 ± 2.52 ka), YJG (17.49 ± 2.44 ka), ZDT (14.33 ± 1.70 ka), MX (16.08 ± 1.23 ka), and KAN (13.63 ± 0.83 ka). Original studies reported: TG (no outliers removed, reported range: 10–15 ka), SLH (raw range: 17–27 ka, refined range: 17–22 ka after removing outlier of 26.8 ka), YJG (raw range: 8–18 ka, refined range: 16–18 ka after selecting the older cluster), ZDT (raw range: 12.7–30.0 ka, refined range: 12.7–15.9 ka after removing outlier of two oldest samples), MX (raw range: 5.7–22.3 ka, refined range: ~15.6–18 ka after removing outlier of three youngest and one oldest samples), and KAN (reported range: 13.4–16.3 ka). Original studies determined final exposure ages using different approaches: mean values (TG: 12.5 ka), oldest

109 reliable ages after outlier removal (SLH: 22 ± 2 ka; YJG: 18 ± 2 ka; ZDT: 15.9 ± 1.2 ka; MX: 18.0 ± 1.4 ka), and age
110 ranges (KAN: 13.4-16.3 ka). P-CAAT reanalysis shows good agreement with the original determinations for most
111 sites, with recalculated ages either falling within the age ranges after outlier removal or closely matching the final
112 exposure ages. However, for SLH, P-CAAT guidelines suggest selecting the younger cluster (6 samples) over the
113 older cluster (3 samples). For regional age compilation, we use these P-CAAT-recalculated values to maintain
114 methodological consistency across all datasets. Data sources: TG, SLH, and YJG from Bai et al. (2018); ZDT and
115 MX from Bai et al. (2021); KAN from Strasky et al. (2009) in Zheduo Valley. Figure elements as described in Figure
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4. Complete ¹⁰Be Terrestrial Cosmogenic Nuclide (TCN) Dating results

Table S1

Complete ¹⁰Be Terrestrial Cosmogenic Nuclide (TCN) Dating results from sites along the Mugecuo fault (KA, KB, KC, KM) and Zheduotang fault (KZ)

Name	Lat	Long	Elev	Quartz	Be carrier	¹⁰ Be/ ⁹ Be	¹⁰ Be	St	Internal	External	Lm	Internal	External	LSDn	Internal	External
	(°N)	(°E)	(m)	(g)	(mg)	(10 ⁻¹²)	(10 ^{^6})at/g	(years)	uncert. (yrs)	uncert. (yrs)	(years)	uncert. (yrs)	uncert. (yrs)	(years)	uncert. (yrs)	uncert. (yrs)
KA Site																
KA1	30.09192605	101.8501891	4463	19.4783	0.25448	736 ± 33	0.643 ± 0.029	11677	72	928	12339	76	932	12470	77	742
KA2	30.09205375	101.8502227	4460	23.0061	0.23707	992 ± 32	0.683 ± 0.022	12428	40	986	12986	42	978	13058	42	774
KA3	30.09213466	101.8500345	4460	19.4776	0.23923	954 ± 42	0.783 ± 0.035	14258	66	1132	14500	67	1094	14557	68	865
KA4	30.09211554	101.8497106	4464	21.1232	0.29854	727 ± 35	0.686 ± 0.033	12485	82	993	13027	86	984	13092	86	780
KA5	30.09100151	101.849681	4474	21.311	0.22674	970 ± 40	0.690 ± 0.028	12482	514	1115	13026	537	1118	13089	539	944
KA6	30.09111562	101.8499095	4472	19.864	0.27513	659 ± 25	0.610 ± 0.023	11046	416	969	11718	441	986	11803	445	828
KA7	30.0912605	101.8498127	4474	19.673	0.26018	742 ± 20	0.655 ± 0.018	11851	320	992	12510	338	1000	12637	341	822
KA8	30.09169538	101.8496555	4474	21.0195	0.25782	834 ± 27	0.684 ± 0.022	12360	396	1056	12937	414	1058	13015	417	876
KB Site																
KB1	30.08106726	101.8779099	4510	19.6726	0.25733	836 ± 24	0.731 ± 0.021	13023	381	1101	13473	395	1088	13536	397	894
KB2	30.08095939	101.8779717	4507	19.2503	0.26421	774 ± 26	0.710 ± 0.024	12654	425	1089	13151	442	1084	13199	443	898
KB3	30.08071453	101.8779824	4502	20.6909	0.26077	827 ± 19	0.697 ± 0.016	12442	281	1025	13001	293	1021	13061	295	827
KB4	30.08072162	101.8781167	4501	19.3802	0.28979	739 ± 17	0.738 ± 0.017	13191	312	1091	13617	322	1074	13676	323	872
KB5	30.08057309	101.8781275	4498	20.6605	0.28605	773 ± 23	0.715 ± 0.021	12783	374	1080	13258	388	1071	13317	390	879
KB6	30.08049425	101.8782094	4496	19.6958	0.26362	792 ± 33	0.708 ± 0.029	12679	527	1135	13168	547	1132	13225	549	956
KC Site																
KC1	30.08120853	101.8814538	4466	19.6871	0.24995	860 ± 30	0.730 ± 0.026	13256	467	1150	13666	482	1136	13735	484	947
KC2	30.08144171	101.8813611	4468	20.3538	0.24926	839 ± 32	0.686 ± 0.026	12454	479	1097	13006	500	1099	13074	503	923
KC3	30.0818015	101.881396	4472	19.6588	0.2774	700 ± 34	0.660 ± 0.032	11967	583	1113	12617	615	1131	12740	621	977
KC4	30.08198491	101.8814538	4474	20.0271	0.24385	903 ± 35	0.735 ± 0.029	13319	524	1179	13719	540	1165	13780	542	980
KC5	30.08216944	101.8814605	4477	23.1386	0.27346	90 ± 21	0.712 ± 0.017	12892	303	1066	13351	314	1053	13422	316	855
KC6	30.08269503	101.8813208	4488	19.5603	0.25772	810 ± 28	0.714 ± 0.025	12879	445	1114	13341	462	1105	13406	464	919
KC7	30.0827995	101.8813504	4491	23.1048	0.25949	985 ± 34	0.739 ± 0.026	13327	465	1154	13727	479	1139	13781	481	947

KC8	30.08313131	101.8812416	4502	19.9763	0.2567	951 ± 41	0.817 ± 0.035	14673	640	1328	14872	648	1294	14898	650	1096
KM Site																
KM1	30.12948587	101.8319296	4201	20.2532	0.2468	840 ± 52	0.684 ± 0.043	14152	883	1428	14373	897	1405	14534	907	1250
KM2	30.1296482	101.8318959	4199	20.4667	0.24867	853 ± 35	0.693 ± 0.028	14338	588	1280	14541	596	1247	14722	604	1061
KM3	30.12978263	101.8318341	4198	19.1168	0.25595	793 ± 31	0.709 ± 0.027	14689	569	1297	14852	576	1258	14979	580	1060
KM4	30.13092422	101.831951	4178	19.8495	0.26658	766 ± 28	0.687 ± 0.025	14359	520	1252	14557	527	1216	14750	534	1024
KM5	30.13135936	101.8320411	4172	19.2509	0.28605	728 ± 34	0.723 ± 0.033	15148	701	1391	15209	704	1344	15356	711	1154
KM6	30.1319627	101.8321365	4165	19.2955	0.28448	760 ± 35	0.749 ± 0.034	15734	723	1443	15731	723	1388	15919	732	1194
KM7	30.1323967	101.8322441	4161	20.8033	0.26815	863 ± 35	0.744 ± 0.030	15656	635	1395	15660	635	1340	15843	643	1138
KM8	30.13363123	101.8324564	4147	19.8453	0.25231	788 ± 28	0.669 ± 0.024	14184	513	1236	14394	521	1202	14582	528	1012
KZ Site																
KZ1	30.08879264	101.8026498	4409	18.8658	0.25743	816 ± 26	0.744 ± 0.024	13906	441	1188	14167	449	1157	14232	452	956
KZ2	30.08820572	101.8020987	4395	20.598	0.26185	899 ± 23	0.763 ± 0.019	14366	361	1195	14592	366	1158	14687	369	945
KZ3	30.0880739	101.8023864	4397	20.2465	0.26618	945 ± 29	0.830 ± 0.026	15614	482	1329	15650	483	1274	15718	485	1050
KZ4	30.08834516	101.800779	4375	25.0012	0.26697	1071 ± 26	0.764 ± 0.019	14523	354	1205	14740	359	1166	14822	361	949
KZ5	30.08826112	101.8004699	4371	20.2324	0.24444	932 ± 32	0.753 ± 0.025	14324	486	1235	14549	494	1201	14652	497	1000
KZ6	30.08787133	101.7998181	4361	19.6003	0.25398	918 ± 25	0.795 ± 0.021	15195	410	1273	15271	412	1221	15338	413	998
KZ7	30.08728948	101.7995184	4352	20.4268	0.23962	993 ± 34	0.778 ± 0.027	14942	515	1292	15062	519	1247	15123	521	1036
KZ8	30.08697453	101.7992201	4345	20.329	0.32855	727 ± 25	0.786 ± 0.027	15133	523	1309	15216	526	1260	15288	528	1048
KZ9	30.08429517	101.7985818	4297	20.9446	0.23962	854 ± 75	0.653 ± 0.057	12874	1130	1523	13313	1169	1540	13448	1181	1424
KZ10	30.08429885	101.7979596	4292	20.5356	0.25359	898 ± 37	0.741 ± 0.031	14653	612	1313	14834	619	1277	14931	623	1082
KZ11	30.08398156	101.7984018	4295	22.2065	0.25939	946 ± 44	0.738 ± 0.034	14571	677	1339	14772	687	1307	14874	692	1120

Note: The ¹⁰Be samples were processed at the Key Laboratory of Compound and Chained Natural Hazards Dynamics, Ministry of Emergency Management of China (Beijing, China), with ¹⁰Be/⁹Be ratios measured at CEREGE (Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement, Aix-en-Provence, France). All samples were collected from the uppermost exposed surface (~2 cm) of in situ granitic boulders (ρ = 2.7 g/cm³). Ages were calculated with the CRONUS v3 calculator. The calculations were performed using the revised ICN standard of 07KNSTD (Nishiizumi et al., 2007). No erosion rates were applied following recent regional studies (Yang et al., 2023; Bai et al., 2018, 2021), and topographic shielding factors were calculated accordingly (Yang et al., 2023; see Table 1 for details). St = Lal (1991)/Stone (2000) time-independent production rate model, Lm = Lal (1991)/Stone (2000) time-dependent production rate model, LSDn = Lifton et al. (2014) production rate model. Each sampling site had one procedural blank for blank correction. External uncertainties (analytical and production rate, Balco et al., 2008) are reported at the 1σ confidence level.

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152