https://doi.org/10.5194/egusphere-2026-3016
Preprint. Discussion started: 28 July 2026

Why are plate suture zones on the Tibetan Plateau hotspots for rockslides: A case study of Jinsha River area

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Abstract. Tectonic suture zones on the Tibetan Plateau, as structurally weak belts, commonly host numerous large to very large rockslides. However, how the material composition and structural architecture of suture zones govern the initiation and evolution of landslides remains poorly understood. This study focuses on the Jinsha River suture zone. Through systematic field geological investigations, laboratory microstructural analyses, and landslide inventory statistics, we elucidate the control of tectonic mélange belt lithology and structure on landslide development, and construct a four-stage dynamic conceptual model from initiation to triggering. The results indicate that the heterogeneous, weak lithologies and complex structures of the suture zone provide the fundamental material and structural basis for landslide initiation. Sliding surfaces are not randomly distributed but predominantly localized along sub-horizontal foliation planes or lithological interfaces. These pre-existing discontinuities, under tectonic uplift and river incision, become preferential pathways for stress release and progressive weakening, resulting in clustered landslide distribution along the suture zone. Accordingly, a four-stage initiation and evolution model is proposed, systematically explaining the complete dynamic process from suture zone formation establishing the material-structural framework, through tectonic uplift and river incision driving rock mass fracturing, freeze–thaw cycles and chemical weathering causing progressive coalescence of the sliding surface, to final triggering of catastrophic failure. This study reveals the fundamental control of suture zone lithology and structure on landslide initiation, shifting the analytical perspective from short-term triggers to long-term dynamic coupling, and from external driving conditions to intrinsic lithological-structural constraints. The findings provide a new theoretical framework for understanding clustered rockslide development on the Tibetan Plateau, and offer a material-structure-based assessment basis for major engineering site selection and early risk identification.

1 Introduction

The Tibetan Plateau, formed by the ongoing collision and amalgamation of the Indian and Eurasian plates, is the youngest, highest, and most tectonically active orogenic belt on Earth (Xu et al., 2011; Ding et al., 2022). This unique plate

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convergence setting has not only shaped its grand geomorphological framework but also rendered it a core region of frequent landslide disasters (Xu et al., 2023). Such landslides are typically characterized by large volumes, widespread distribution, sudden onset, and significant cascade effects (Korup et al., 2007; Hewitt et al., 2008; Marc et al., 2019; Shugar et al., 2021). Their failure can not only destroy buildings and infrastructure along their paths, but also block rivers to form landslide-dammed lakes, which may subsequently trigger catastrophic outburst floods (Cui et al., 2009; Yin et al., 2009; Yin et al., 2011; Zhang and Yin, 2013; Zhou et al., 2016), posing severe threats to engineering facilities, human life, and property safety (Shang et al., 2003; Froude and Petley, 2018; Lacroix et al., 2020).

Further research has revealed a distinct distribution pattern of landslides on the Tibetan Plateau, whereby the majority of landslides are densely developed along plate suture zones. For example, within the Yarlung Zangbo suture zone in the southern Tibetan Plateau, approximately 53.4% of rockslides are distributed therein (Zhao and Su, 2025); in the Hengduan Mountains of the southeastern Tibetan Plateau, numerous large to very large landslides are densely concentrated along the Jinsha River, Lancang River, and Nu River suture zones, with quantities far exceeding those in other regions (Zhang et al., 2024). Among these, the Jinsha River suture zone is particularly typical: in the upper reaches of the Jinsha River, approximately 59% of large landslides have developed within this suture zone (Zhang et al., 2020b), a proportion substantially higher than that in other lithological or tectonic units. Plate suture zone regions have thus become global hotspots for large landslide occurrence and research (Xu et al., 2023; Zhao et al., 2023b), and have long been regarded as a major challenge in geohazard research (Zhang et al., 2021; Ren et al., 2023). The 2018 Baige landslide on the Jinsha River blocked the river twice consecutively, causing economic losses exceeding 10 billion yuan (Zhang et al., 2020a,b; Fan et al., 2020; Zeng et al., 2022), and accelerated the reactivated deformation rate of the downstream Xiongba landslide by 14-18 times (Guo et al., 2021). Moreover, many very large landslides undergoing slow deformation currently exist in the upper reaches of the Jinsha River (Guo et al., 2021; Liu et al., 2021; Yao et al., 2022; Ren et al., 2023), which may similarly generate disaster chains comparable to the Baige landslide.

Traditional studies have indicated that rockslide occurrence involves the interplay of multiple factors, including geological structure, rock properties, tectonic activity, hydrogeological conditions, and climate change (Moro et al., 2011; Crosta et al., 2013; Mather et al., 2014; Zhou et al., 2013, 2016; Martino et al., 2020; Chalupa et al., 2021; Saroli et al., 2021; Zhang et al., 2023b). Systematic classification frameworks for landslides (Varnes, 1978; Alimohammadlou et al., 2013; Hungr et al., 2014; Xu et al., 2016) and numerous geomechanical models targeting specific failure modes have also been established (e.g., Zhang, 2000; Huang, 2007, 2012a; Huang et al., 2007, 2009). These achievements have greatly advanced our understanding of landslide occurrence and evolution. However, a key scientific question remains inadequately resolved: why are so many active rockslides concentrated within the plate suture zones of the Tibetan Plateau, and what spatiotemporal coupling relationship exists between the distinctive formation–evolution history, material composition, and structural architecture of suture zones and the initiation of landslides? Why plate suture zones have become a hotbed for rockslides remains an unsolved enigma. The persistence of these questions constrains our comprehensive understanding and effective prevention of rockslides in suture zones, revealing both the limitations of existing models and the urgent need to establish a novel

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Preprint. Discussion started: 28 July 2026

integrative framework. This need has become even more pressing as a series of major engineering projects, including the Sichuan–Tibet Railway and cascading hydropower stations, traverse these high-risk landslide zones (Cui et al., 2022; Wu et al., 2024; Zhang et al., 2022a).

To address the above key scientific questions, this study focuses on the Jinsha River suture zone. Through systematic field geological investigations, laboratory microstructural analyses, and landslide inventory statistics, we aim to explore, from the novel perspective of plate suture zones, how their material composition and structural architecture control the initiation of large rockslides, and to construct a conceptual model capable of delineating the complete dynamic sequence from long-term initiation to final triggering. This work is expected to deepen the understanding of the long-term initiation mechanisms of landslides in tectonically active regions such as suture zones, and to provide new analytical perspectives and scientific evidence for regional landslide risk early identification, disaster prevention, and mitigation.

2 Regional geological setting

2.1 Tectonic framework of the Tibetan Plateau

The Tibetan Plateau was formed on the basis of long-term geological activity since the Neoproterozoic, multi-stage orogeny, and Cenozoic uplift, representing the youngest, largest, and currently active continental orogenic belt on Earth (Xu et al., 2011; Ding et al., 2022). Its evolutionary history involved the opening, subduction, and closure of multiple paleo-oceans, as well as the rifting, drifting, and amalgamation of numerous paleo-continental blocks (Kapp et al., 2007; Metcalfe, 2013; Zhang et al., 2014). The evolution of paleo-oceanic basins associated with the rifting of these continental blocks resulted in the formation of several major tectonic suture zones in this region, such as the Jinsha River Suture Zone, the Longmucuo-Shuanghu-Lancang River Suture Zone, and the Bangonghu-Nujiang Suture Zone (Fig. 1A) (Deng et al., 2024). These suture zones, as key geological records of plate motion, exert significant control over the regional tectonic framework and drainage pattern.

2.2 The Jinsha River suture zone

The Jinsha River suture zone paleogeographically represents the remnant of a back-arc basin along the eastern margin of the Paleo-Tethys Ocean following its closure. It exhibits an east–west-trending arcuate geometry in the west and a north–south-trending arcuate geometry in the east (Fig. 1A), and constitutes a complex tectonic belt composed of multiple faults and metamorphosed tectonic blocks (Wang et al., 2000; Pan et al., 2012; Wang et al., 2014a; Cao et al., 2015; Zhang et al., 2021). Owing to multi-stage orogenic events (including the Indosinian, Yanshanian, and Himalayan), the suture zone hosts nearly north–south-trending ductile shear zones and schistosity zones, together with a series of approximately east–west-trending imbricate thrust nappe structures and fold structures (Cao et al., 2015; Chen et al., 2021a; Zhang et al., 2021). Seismic activity is frequent in this region (Fig. 1B). Although the earthquakes are generally weak ($M < 4.7$), such frequent seismicity may still weaken the structure of landslide bodies in the study area and accelerate their deformation.

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During the evolution of the Jinsha River Paleo-Tethys Ocean from opening to closure, remnants of oceanic crust (ophiolites) scraped off during subduction and sediments from the oceanic crust surface underwent tectonic mixing with clastic materials derived from continental crust, collectively forming the Jinsha River tectonic mélange belt. This tectonic mélange is characterized by a strongly deformed matrix surrounding tectonic blocks of varying sizes, lithologies, and deformation degrees (Bian et al., 2004; Robertson, 2004; Wang et al., 2018, 2020; Raimbourg et al., 2019; Wang et al., 2019; Tang et al., 2022). The various blocks are connected by a network of ductile to brittle-ductile faults predominantly subparallel to the strike of the tectonic belt, exhibiting the characteristics of a tectonic mélange that is locally ordered yet regionally disordered (Festa et al., 2019b; Ogata et al., 2021; Tang et al., 2022). The overall mechanical properties of the mélange are weak, rendering it susceptible to strong deformation and fragmentation under tectonic influence.

2.3 Topographical and Geomorphological Characteristics

Under the influence of multi-stage tectonic movements and intense erosion driven by crustal uplift and incision of the Jinsha River, the study area has developed a distinctive "V"-shaped topography characterized by high mountains, deep valleys, and steep terrain (Zhang et al., 2020a,b; Chen et al., 2021). The regional geomorphology is dominated by medium- to extremely undulating plateau mountains, with an average elevation of 4000–4500 m and a relative relief of 600–1000 m. The mountain slopes are steep, with gradients generally ranging from 15° to 45°. Quaternary deposits are poorly developed and predominantly consist of residual and slope-wash sandy soil layers. The Jinsha River drainage system is sinuous, with dendritic tributaries developed in the region (Fig. 1B), and the overall topography is primarily controlled by the Jinsha River and its tributary networks. The area is heavily covered by snow in winter, and vegetation development is markedly influenced by topography, exhibiting distinct vertical zonation characteristics.

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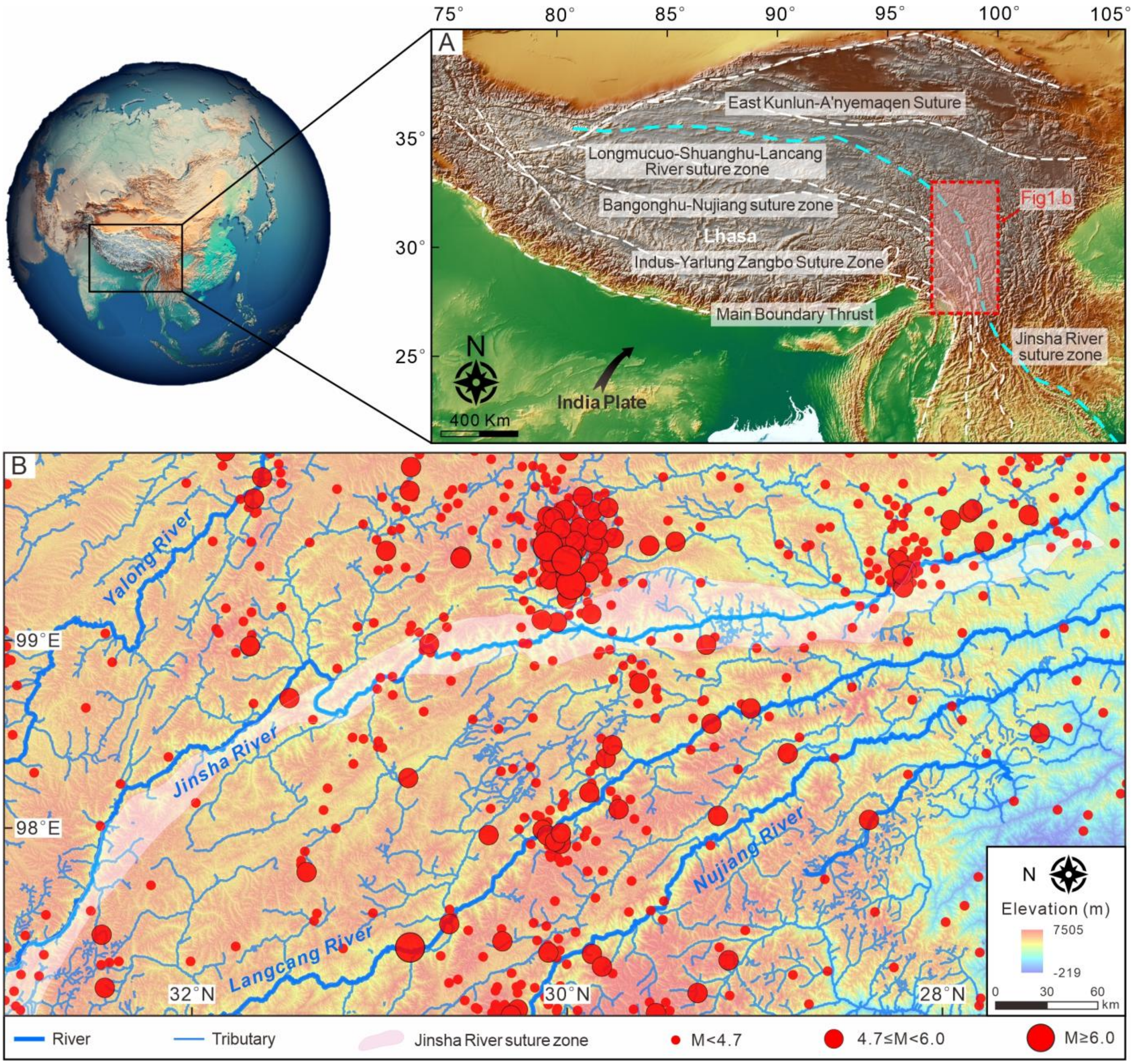

Figure 1. (A) Tectonic framework of the Tibetan Plateau and its adjacent regions; (B) Distribution of earthquakes, elevation, and river systems in the study area and its surrounding regions (the DEM data were obtained from https://www.gscloud.cn/).

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3 Methods

3.1 Landslide data compilation and analysis

The compilation of landslide data was based on previously published datasets (Liu et al., 2021; Li, 2023; Zhou et al., 2024). A total of 90 large-scale or larger landslide sites (volume > 10^6 m³) with river-blocking potential were inventoried along the upper reaches of the Jinsha River. For each site, the location, slope gradient, estimated volume, and channel width at the landslide location were recorded. And following the classification used in the compiled landslide datasets, landslides with volumes exceeding 10^6 m³ are classified as large landslides, while those exceeding 10^7 m³ are classified as very large landslides. Based on these data, statistical analyses were conducted for landslide slope gradient, volume, and channel width to reveal their distribution characteristics and interrelationships.

3.2 Field geological investigation

A systematic field investigation was conducted on two representative landslides within the Jinsha River suture zone, namely the Sela landslide and the Zhisi Mountain landslide (Fig. 3A, B). At each landslide site, the following were recorded: (1) the lithology of the landslide mass; (2) discontinuity characteristics, including the orientation, spacing, aperture, and persistence of joints, fractures, and rock foliation; (3) Sliding surface characteristics, including lithological control and the development of weak interlayers; and (4) evidence of progressive deformation of the landslide mass (tensile cracks, scarps, local subsidence, etc.).

3.3 Microstructural analysis

Thin sections were prepared from representative rock samples collected in the field. Transmitted light microscopy and cathodoluminescence (CL) imaging techniques were employed to analyze and document the mineral composition, fracture propagation paths, and the relationships between fracture development, foliation orientation, and mineral composition.

4 Results

4.1 Distribution characteristics of landslides within the Jinsha River suture zone

The landslides within the Jinsha River suture zone are predominantly large and very large in scale. Their spatial distribution is not random but is significantly controlled by the regional tectonic and geomorphological framework, exhibiting distinct clustering and zonation (Fig. 2A). It is evident that the vast majority of landslides are concentrated within the interior of the suture zone, profoundly demonstrating that the tectonic mélange within the suture zone—characterized by structurally fragmented and mechanically weak properties—constitutes the most fundamental material basis for landslide initiation, and highlighting the significant control exerted by tectonics on landslides. From the perspective of geomorphological control, landslides are strongly clustered along the main stream of the Jinsha River. Among the 90 inventoried large-scale or larger

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landslide sites with river-blocking potential in the upper reaches of the Jinsha River, 73 are located along the main stream, with slightly more on the right bank (42 sites) than on the left bank (31 sites) (Fig. 2B), directly reflecting the critical role of intense river incision as a slope-failure-promoting factor. Statistical analyses further characterize the quantitative features of these landslides: slope gradients are predominantly concentrated within the stable sliding range of 20°-40° (Fig. 2C); landslide volumes mainly range from 0 to 2×10^7 m^3 (Fig. 2D); and channel widths at landslide locations are primarily between 40 and 80 m (Fig. 2E).

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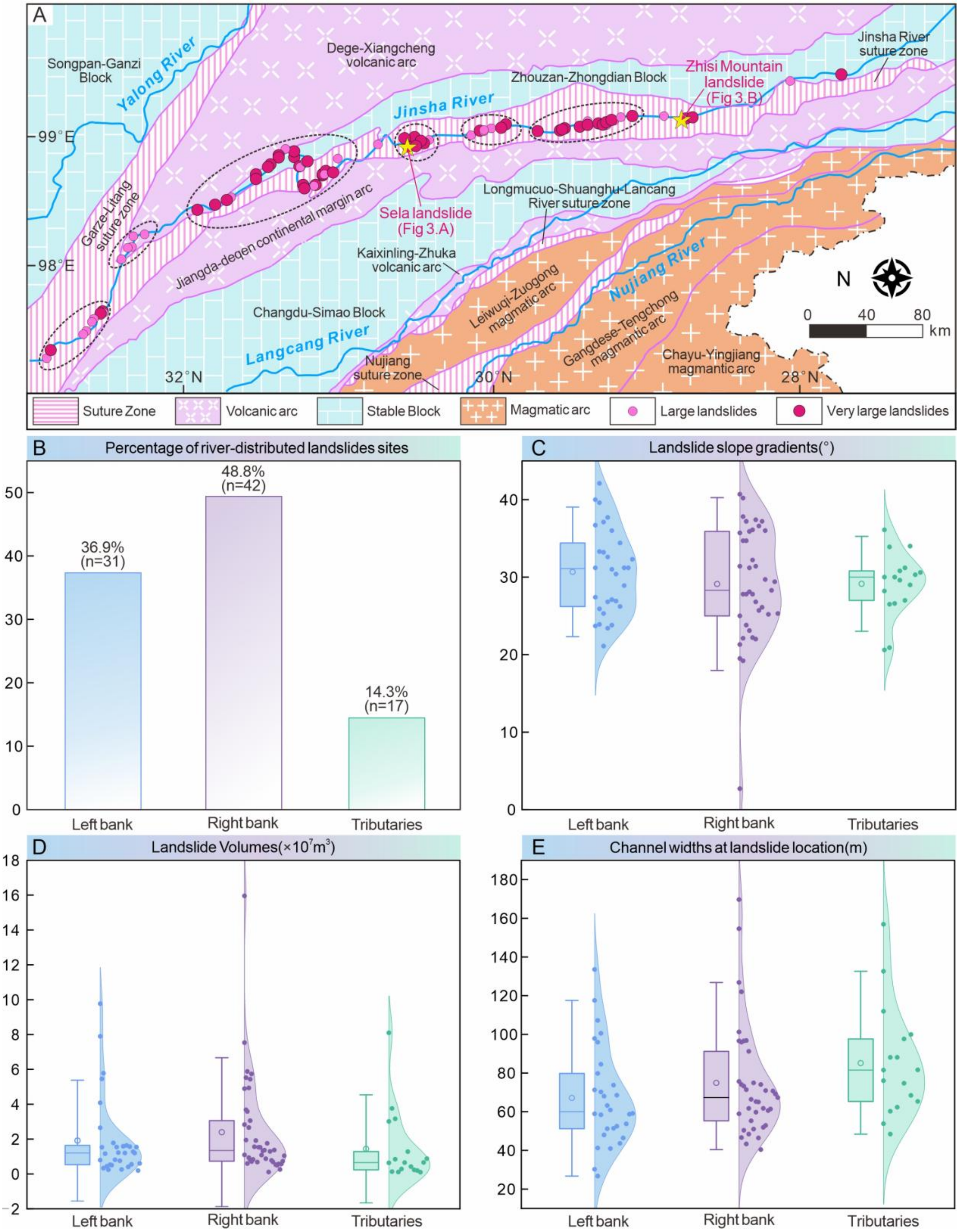

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Figure 2. (A) Distribution of large and very large landslides in the upper reaches of the Jinsha River (base map modified from Deng, 2012); (B) Distribution of landslides along the river course in the Jinsha River suture zone; (C-E) Slope gradients, landslide volumes, and river channel widths at landslide locations in the Jinsha River suture zone.

4.2 Distinctive material composition and structural architecture of the Jinsha River suture zone

Field investigations of the Sela landslide and the Zhisi Mountain landslide within the Jinsha River suture zone reveal that the landslide mass materials in the study area exhibit significant lithological associations and structural characteristics. Firstly, the landslide mass lithology primarily comprises a low- to medium-grade metamorphic rock series consisting of schist, gneiss, marble, and metamorphic quartz sandstone (Fig. 3D-G, P-R). The rocks are generally weak and prone to deformation and failure under various tectonic influences.

Secondly, the landslide mass rocks contain multiple sets of macroscopic joints and fractures, most of which are oriented subparallel to the ground surface (Fig. 3C, O). Field observations indicate that when the angle between the dominant fracture orientation and the rock bedding is excessively large, fractures tend to be poorly connected (Fig. 3D). In contrast, when the dominant fracture orientation is roughly parallel to the bedding, interconnected macroscopic tensile cracks are observed. These cracks exhibit platy or lenticular openings, with apertures generally ranging from 1 to 5 mm and locally reaching up to 2 cm. Their extension is unstable, circumventing mixed rigid blocks, gravels, and granular minerals (Fig. 3E-G, P-R), possibly indicating vertical stress release and structural relaxation of the rock mass under the long-term influence of tectonic uplift and river incision, thereby forming unloading fractures of this type. Furthermore, a series of prominent tensile cracks are pervasively developed along the rear margins of the landslides. At these crack-developed zones, the landslide mass exhibits conspicuous loosening and deformation, accompanied by local subsidence (Fig. 3H-I), indicating that the slope is currently under a strong tensile stress regime. Individual cracks can extend from tens to hundreds of meters in length, with opening widths ranging from several centimeters to several meters. Field investigations found that some cracks have even directly pulled apart the bedrock (Fig. 3J). The orientation of these cracks is parallel to the vertical joints of the rock mass (Fig. 3K), with the cracks opening along the joints. Collectively, these tensile cracks delineate the embryonic morphology of the rear boundary of the landslide.

Finally, field investigations preliminarily reveal that the development of the sliding surfaces of large landslides within the Jinsha River suture zone is significantly controlled by tectonic and lithological factors. The spatial distribution of these sliding surfaces closely coincides with specific pre-existing geological structures. The investigations indicate that the sliding surfaces of landslides in this area are predominantly and preferentially developed at two key locations: one is the physical interface between different lithologies (Fig. 3L-N), and the other is adjacent to metamorphic rock layers with subhorizontally developed foliation (dip angle typically less than 30°) (Fig. 3S-U). These locations are commonly associated with weak interlayers characterized by low friction coefficients and high susceptibility to argillization (Fig. 3M, S-U). The thickness of these weak interlayers ranges from several centimeters to several meters, contrasting sharply with the relatively intact rock masses above and below, and acting as natural "easy-slip zones" during slope evolution.

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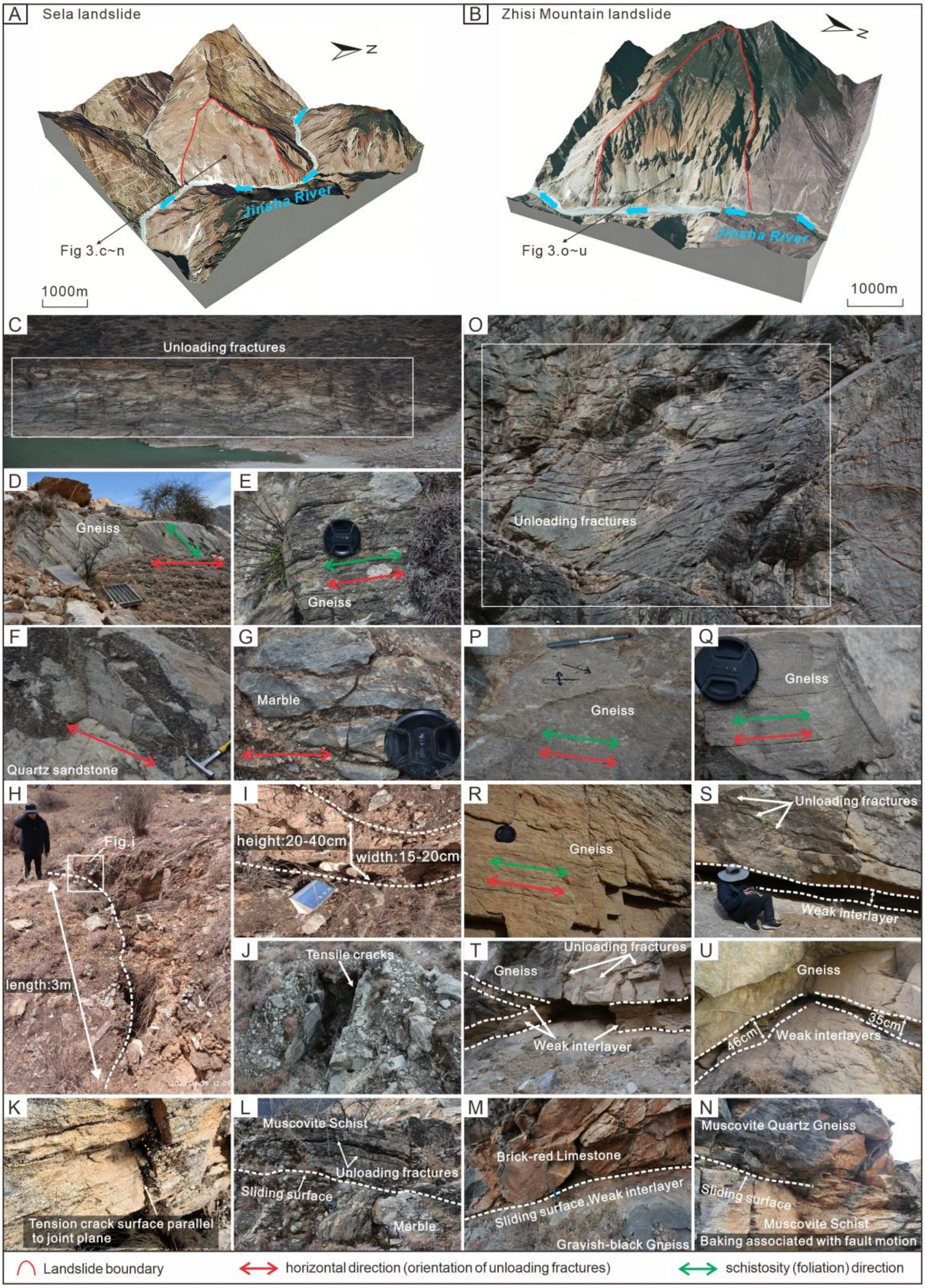

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Figure 3. (A-B) Three-dimensional geological overview and topographic maps of the Sela landslide and the Zhisi Mountain landslide; (C, O) Macroscopic (centimeter-scale) rock fractures on the bank slopes of the Jinsha River basin in the Hengduan Mountains; (D) Macroscopic fractures in gneiss with sub-vertical bedding; (E, P-R) Macroscopic fractures in horizontally bedded gneiss; (F) Macroscopic fractures in quartz sandstone; (G) Macroscopic fractures in marble; (H-I) Schematic diagrams illustrating the overall and local deformation of tensile cracks at the crown of the Sela landslide; (J) Field photograph of bedrock tensile rupture by tensile cracks; (K) Joint plane parallel to the tensile crack surface; (L-N) The sliding surface of the Sela landslide is located within metamorphic rock layers with sub-horizontal foliation and at lithological contacts; (S-U) The sliding surface of the Zhisi Mountain landslide is located at weak interlayers.

4.3 Microstructural evidence for sliding surface development along foliation

Building upon the field identification of subhorizontal macroscopic tensile fractures, laboratory analyses provide more robust microstructural evidence for systematically elucidating the origin of the pervasive subhorizontal tensile fractures in the study area. Transmitted light and cathodoluminescence (CL) images reveal that rock lithology and mineral foliation exert a critically important control on the formation of subsequent fractures. Fractures are concentrated along horizontally oriented foliation, exhibiting platy and lenticular openings, and preferentially propagate along pre-existing foliation directions (Fig. 4A-B), actively circumventing granular minerals during extension. It is further demonstrated that such fractures are most developed in rocks possessing foliated structures, such as schist and gneiss. Particularly when the foliation orientation is subhorizontal or intersects the horizontal plane at a low angle, fractures are generally capable of achieving through-going connectivity (Fig. 4A-B, G). In contrast, in massive rocks dominated by granular minerals such as quartz, including sandstone and marble, fracture development is significantly diminished or even absent. Fractures tend to terminate after repeatedly circumventing mineral grains, making it difficult for interconnected macroscopic fractures to form (Fig. 4C-D, F). These experimental results are highly consistent with field observations, collectively indicating that the pervasive subhorizontal tensile fractures in the study area are not randomly distributed but are controlled by the synergistic interplay between rock lithological characteristics and foliation structure. Specifically, the foliation orientation determines the preferential pathways for fracture propagation, whereas the mineral composition governs the through-going connectivity of fractures. In schist and gneiss with low-angle foliation development, fractures readily propagate and interconnect, forming well-connected tensile fracture networks. In contrast, in rocks dominated by massive or granular minerals, fracture propagation is inhibited, hindering the formation of macroscopic ruptures. This demonstrates that the subhorizontal tensile fractures in the study area resulted from selective rupturing of the rock mass along its inherent lithological interfaces and foliation structures under the stress release driven by long-term geological processes such as regional tectonic uplift and river incision. The location, propagation direction, and degree of connectivity of fractures are fundamentally controlled by the material composition and structural characteristics of the suture zone rock mass itself, rather than by the intensity of external driving forces. Therefore, such fractures essentially represent a direct manifestation of the response of the suture zone lithological structure to stress release, establishing a critical macroscopic structural framework for the subsequent formation of landslide sliding surfaces.

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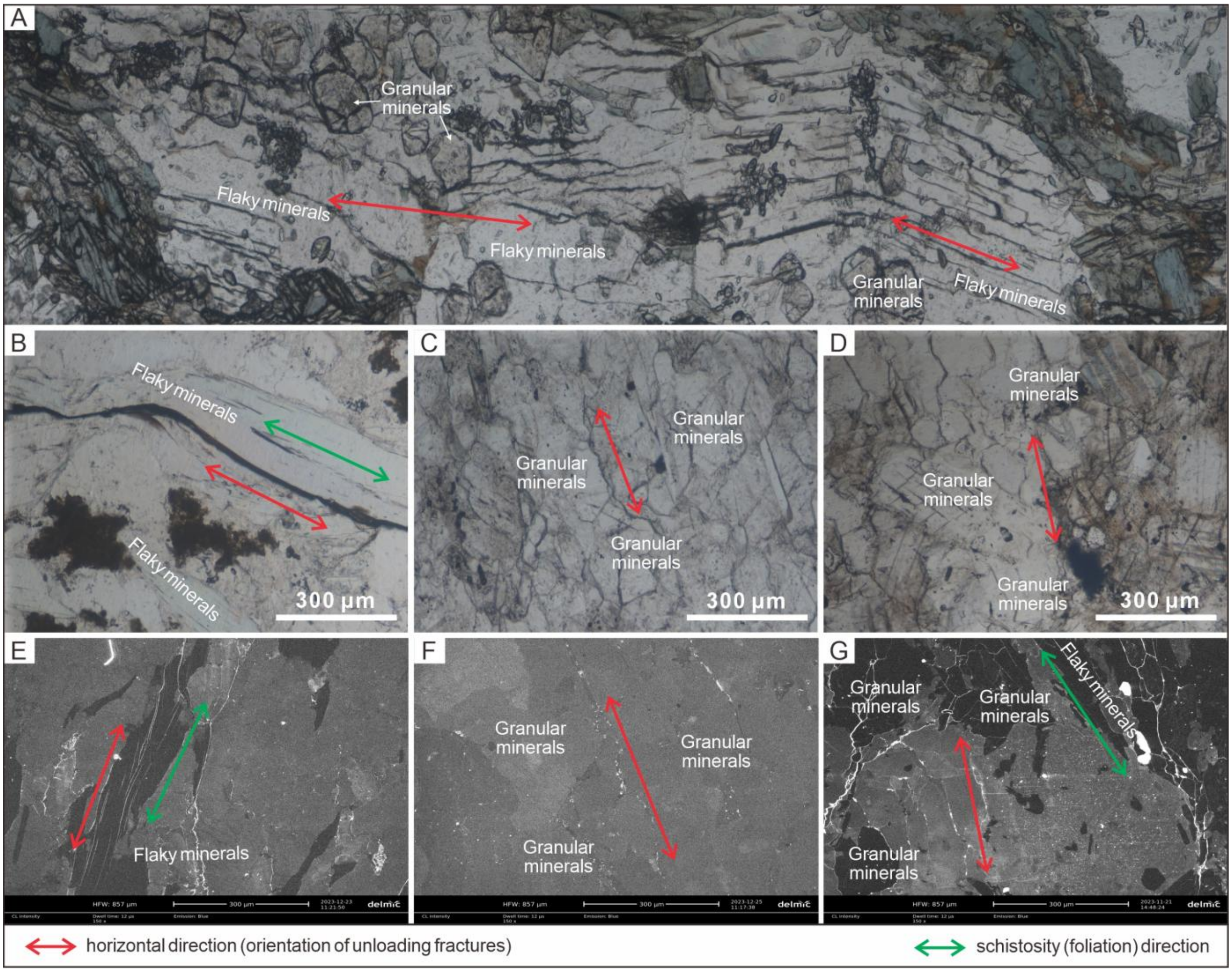

Figure 4. (A, B, E) Microfractures in horizontally bedded gneiss; (C) Microfractures in quartz sandstone; (D, F) Microfractures in marble; (G) Microfractures in steeply bedded gneiss.

5 Discussion

5.1 Why are suture zones prone to large rockslides?

The high susceptibility of the Jinsha River suture zone to large rockslides is, first and foremost, closely related to its distinctive lithological composition and tectonic attributes. As a product of the intense collision and amalgamation between the Qamdo Block and the Songpan–Garzê Block during the closure of the Jinsha River Paleo-Tethys Ocean (Cao et al., 2025), this suture zone did not form a homogeneous and intact rock mass. Instead, under the combined effects of subduction accretion, tectonic scraping, and intense shearing and mixing, remnants of oceanic crust (e.g., ophiolites), deep-sea

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sediments, exotic blocks, and mantle materials were chaotically intermingled, forming the Jinsha River tectonic mélange belt—characterized by an extremely heterogeneous structure and highly chaotic lithology (Fig. 5A; Wang et al., 2000; Zi et al., 2012). Under the sustained compressional regime following plate suturing, this belt further underwent intense metamorphism and deformation. The original rocks experienced recrystallization and mineral alignment under high-temperature and high-pressure conditions, pervasively forming schist, gneiss, and other metamorphic rocks with pronounced foliation or gneissosity (Fig. 5B). These rocks generally belong to the greenschist facies of low-to medium-grade metamorphism, and are susceptible to intense deformation under tectonic influence (Fig. 5C-F; Tang et al., 2022). This metamorphic deformation process not only shaped the dominant structural orientation controlling rock mass deformation and failure, but also rendered the rocks more prone to fracturing along foliation directions, thereby generating a series of foliation-parallel fracture systems under unloading and stress adjustment conditions. Thin-section identification further reveals that the schist, gneiss, and other rocks composing the landslide masses pervasively contain alteration minerals such as actinolite and chlorite (Fig. 5G-I). These minerals are susceptible to softening upon contact with water, possess low strength and small friction coefficients, and can significantly degrade the physical and mechanical properties of the rock mass (Zhao, 2023). Consequently, this combination of chaotic lithology, weak structure, and well-developed foliation not only provides the material source for landslide initiation, but also presets the structural framework for subsequent sliding surface formation, thereby explaining why landslides are so highly concentrated within the Jinsha River tectonic mélange belt.

In addition to lithology and metamorphic structure, the dense development of fault structures is another critical reason for the high incidence of large landslides in suture zones. Tectonic mélange belts are generally also zones of concentrated faulting (Zhou et al., 2024), and landslide susceptibility is directly linked to fault distribution and activity (Liu et al., 2021; Qin et al., 2024). Affected by multi-stage tectonic movements, this belt hosts numerous regional brittle faults (Fig. 5J; Cao et al., 2015; Zhang et al., 2022b), resulting in a highly complex structural setting (Fan et al., 2019; Zhang et al., 2020a,b). During field investigations at the two landslide sites, clear evidence of fault activity was observed, including fault slickensides, fault steps, fault breccia, and fault mirrors (Fig. 5K-R). Fault activity can persistently induce dynamic stress adjustment and redistribution at fault tips, inflection points, and other locations, generating stress concentrations and tensile environments, thereby actively initiating and propagating unloading fractures (Zhang et al., 2023b; Guo et al., 2025). Therefore, fault activity exerts a critical control on the structure and integrity of slope rock masses, significantly reducing their mechanical properties and disrupting their structural continuity (Zhang et al., 2015; Zhang et al., 2017; Dong et al., 2019). This causes the rock mass along faults to form highly persistent tectonically fractured zones, whose fragmented rock masses and low-strength structural planes provide direct landslide boundaries for large rockslides (Zhou et al., 2021, 2022).

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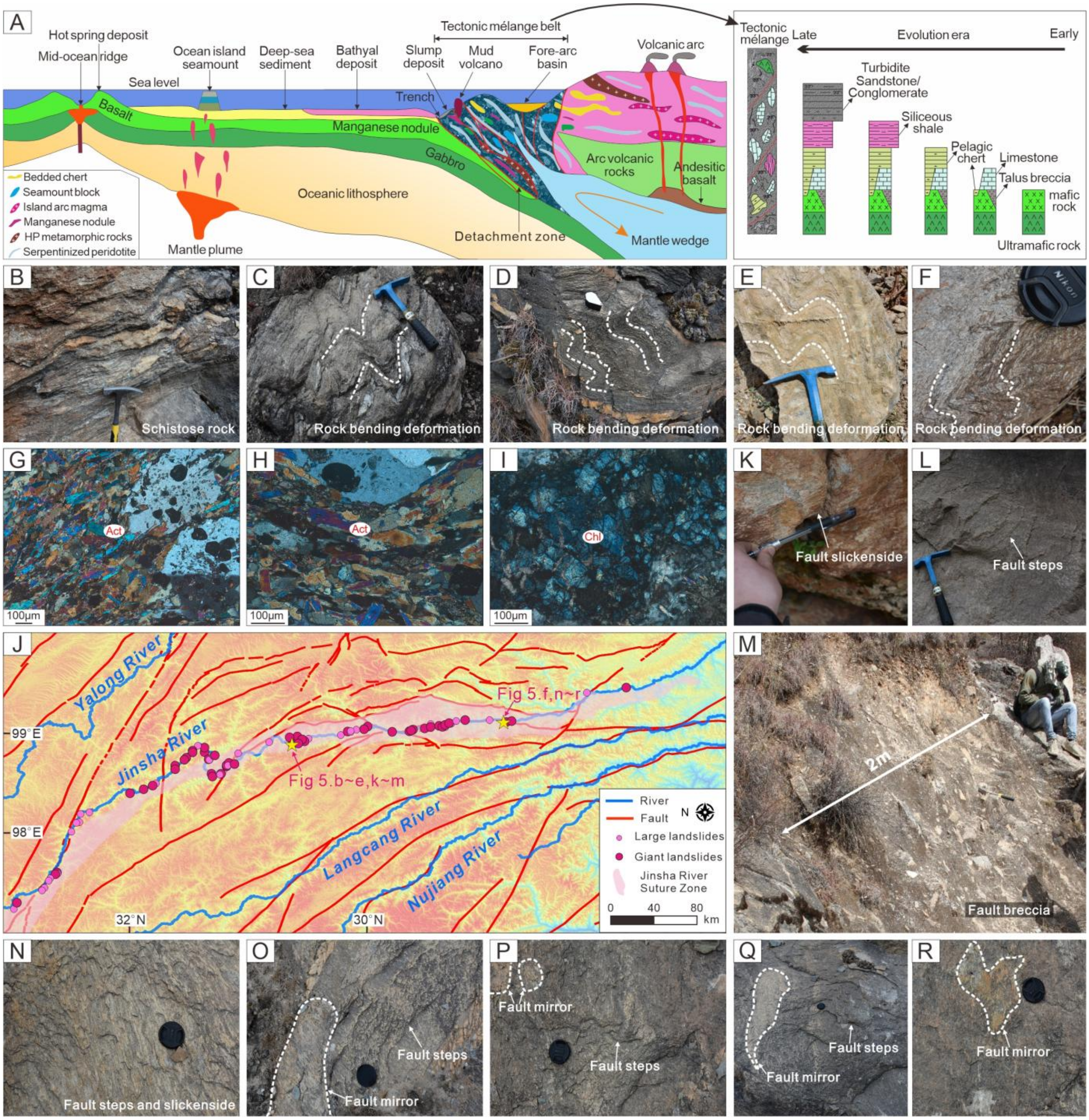

Figure 5. (A) Schematic diagram illustrating the formation mechanism of the tectonic mélange belt and tectonic mélange (modified from Wakita, 2015; Zhang et al., 2024); (B-F) Field photographs showing intense deformation of rocks within the landslide mass in the study area; (G-I) Photomicrographs of rocks from the landslide mass (cross-polarized light; Act-actinolite; Chl-chlorite); (J) Schematic diagram

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showing the spatial relationship between landslides and active faults in the Jinsha River suture zone (the DEM data were obtained from https://www.gscloud.cn/); (K-R) Field photographs showing evidence of fault activity.

Building upon the foundation of "weak rock mass and fragmented structure", the tectonic uplift driven by the India–Eurasia plate collision since the Late Cretaceous has further provided a sustained dynamic setting for rock mass fracturing and fracture propagation. Tectonic uplift has driven the Jinsha River drainage basin to rise at a rate of approximately 5.2 mm/a (Ding et al., 2022; Li et al., 2023). The phased uplift of the southeastern Tibetan Plateau during the late Eocene to early Miocene and the middle to late Miocene, during which crustal deformation—through the generation of new faults and reactivation of pre-existing faults—significantly promoted uplift (Zhang et al., 2023a); the maximum uplift rate during the Holocene even reached 15.0 mm/a (Chen et al., 2021). This rapid tectonic uplift is not only the fundamental cause of the enormous topographic relief but also leads to significant stress release and adjustment at shallow crustal levels. Owing to its inherently weak and readily deformable rock properties, the suture zone acted as a lubricant during crustal uplift, facilitating tectonic movement and generating significant tensile strain within the surface rock mass. The initial high compressive stress in the crust was thereby released, resulting in macroscopic relaxation of the rock mass structure (Zhao et al., 2023b; Guo et al., 2025). Since the Late Quaternary, tectonic deformation within the Jinsha River tectonic mélange belt has been intense, with the development of north-south-trending ductile shear mylonite zones, strongly foliated belts, and a series of east-west-trending compressional imbricate thrust nappe and fold structures (Cao et al., 2015; Pan et al., 2019). During this stage, the overall structure and fabric of the rock mass were disrupted, and the fragmentation of the slope rock mass intensified. Concurrently, rocks with well-developed foliation were prone to failure and deformation under the influence of various tectonic processes, thereby facilitating the formation of Tensile cracks and sliding surfaces.

Meanwhile, owing to its inherent tectonic weakness, the Jinsha River suture zone is highly susceptible to river incision during headward erosion, resulting in the formation of deeply incised valley topography characterized by high river longitudinal gradients, erosion rates, and steepness indices (Henck et al., 2011; Liang et al., 2013; Yang et al., 2016; Pan and Shen, 2017; Gao et al., 2025; Sun et al., 2025a). Previous studies have demonstrated that the distribution of landslides in the upper reaches of the Jinsha River exhibits a significant positive correlation with these geomorphological parameters (Yi et al., 2022). River incision creates high and steep free faces, fundamentally disrupting the original stress equilibrium of the slope rock mass and triggering pronounced stress release and adjustment (Ning et al., 2020; Qian et al., 2021). The core mechanical effects are manifested as the opening and propagation of pre-existing structural planes, such as joints and fractures, and the formation of a stress-relaxed zone along with pervasively developed tensile fracture networks within a certain depth beneath the slope surface (Yan et al., 2002; Xu et al., 2004; Lin et al., 2009, 2010; Qian et al., 2021). This fracture network not only severely compromises the integrity of the rock mass but also enhances the permeability of the slope, facilitating groundwater infiltration (Bidgoli and Jing, 2014; Zhang et al., 2025), which further reduces slope stability through pore-water pressure. Over time, the shear dislocation and tensile effects between the free-facing rock layers progressively intensify, ultimately leading to shear failure along the interconnected rupture surface under gravitational

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forcing (Zhang, 2017; Ning et al., 2020; Tu et al., 2023). Furthermore, increased discharge of the Jinsha River during the rainy season intensifies channel erosion, promoting phased acceleration of landslide deformation (Sun et al., 2025b; Yang et al., 2025). Therefore, from the perspective of long-term "uplift-incision" geomorphic evolution, the rock mass undergoes further fragmentation under sustained unloading, with unloading fractures continuously generated and propagated. The slope structure evolves toward higher degrees of fragmentation and stronger water sensitivity, providing crucial kinematic conditions and spatial accommodation for the initiation of large landslides.

After the progressive formation of the fracture network and weak plane system, the localization, coalescence, and formation of the landslide sliding surface represent the inevitable outcome of long-term modification of the pre-existing fracture network by progressive weakening processes, including temperature fluctuations, seasonal freeze-thaw cycles, and chemical weathering. Subhorizontal foliation planes and lithological interfaces, acting as inherent weak planes within the rock mass, substantially reduce the shear strength of the potential sliding surface. Under the regional stress field, these pre-existing weak planes are most susceptible to stress concentration and opening, providing preferential pathways for subsequent groundwater infiltration, softening, and the ongoing modification driven by freeze-thaw cycles. Subsequent progressive weakening processes operate predominantly along these pathways, including seasonal freeze-thaw cycling and chemical weathering alteration, both of which jointly promote landslide instability (Fischer et al., 2006; Geertsema et al., 2006; Huggel, 2009). Freeze-thaw cycles generate frost-heave pressure through repeated phase changes of water, forcing microcrack propagation (Draebing et al., 2014; Collins and Stock, 2016); during thawing stages, transient pore-water pressures are generated, continuously degrading the shear strength of structural planes and weakening the mechanical parameters of the rock mass, such as porosity, compressive strength, and elastic modulus (Ma et al., 1999; Lai et al., 2010; Zhu et al., 2011). Concurrently, chemical weathering and alteration preferentially proceed along pre-existing discontinuities such as joints and fractures, ultimately transforming into clay-rich weak layers through dissolution and the formation of secondary clay minerals. These weak layers often directly serve as the sliding surfaces of landslides (St. Clair et al., 2015; Von Voigtlander et al., 2018; Ollier, 2010; Sidle and Bogaard, 2016). Furthermore, intensely altered weathering profiles can modify local hydrological pathways, leading to pore-water pressure accumulation within the bedrock or overlying soil layers, thereby further reducing the shear strength of the rock mass (Chigira, 2001; Fernandes et al., 2004; Picarelli et al., 2005; Wakatsuki et al., 2005; Dille et al., 2019). Ultimately, the systematic modification of the weathering profile in terms of mineralogy, hydrology, and mechanical properties fundamentally governs the spatial localization of the potential sliding zone (Chigira, 2001; Andersson-Sköld et al., 2005).

Once the potential sliding surface is essentially interconnected and the locked segment has been chronically weakened, the landslide enters a phase of instantaneous triggering and initiation. At this stage, short-term, high-intensity factors, such as extreme rainfall and strong earthquakes, act as the final triggers upon the already interconnected potential sliding surface and the severely weakened locked segment. Intense rainfall causes a rapid increase in pore-water pressure within the fracture network, reducing the effective normal stress and frictional resistance; strong earthquakes ($M \geq 4.7$) impose dynamic loading that exceeds the residual shear strength of the interconnected rupture plane (Ding et al., 1999; Zhou et al., 2024). Ultimately,

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instantaneous shear failure of the locked segment occurs, and the landslide undergoes high-speed sliding along the already interconnected sliding surface.

5.2 Initiation and evolution model of landslides in suture zones

Based on the above systematic analysis of the mechanisms underlying landslide susceptibility in the Jinsha River suture zone, the initiation process of large rockslides in suture zones can be generalized into a four-stage evolution model (Fig. 6).

(1) Plate suturing and subsequent compressional metamorphism: providing the material and structural basis

During the closure of the Jinsha River Paleo-Tethys Ocean, intense plate collision and amalgamation formed the suture zone basement characterized by tectonic mélange. Under the subsequent sustained compressional regime, this mélange belt underwent greenschist-facies metamorphism and deformation, during which the original rocks experienced recrystallization and mineral alignment, pervasively developing schist, gneiss, and other rocks with pronounced foliation planes (Fig. 6A). The subhorizontal or gently dipping foliation planes formed during this stage constitute inherent weak planes within the rock mass and determine the dominant orientation of subsequent deformation and fracturing.

(2) Tectonic uplift and river incision: inducing unloading and promoting fracture network propagation

Since the Late Cretaceous, the India-Eurasia plate collision has driven rapid uplift of the Tibetan Plateau. The enormous gravitational potential energy generated thereby has promoted intense incision of the Jinsha River along the weak suture zone, jointly shaping the high-steep, deeply incised valley topography (Fig. 6B). River incision disrupts the original stress equilibrium of the slope rock mass, triggering significant stress release and adjustment. During this process, pre-existing foliation planes and unloading fractures further open and propagate, while new tensile fracture zones form at shallow depths within the valley slope. At this stage, fault activity, acting as a persistent internal driving force, not only controls the distribution of the regional stress field but also further intensifies the degree of rock mass fragmentation in valley slopes through fault-tip effects. The significantly enhanced permeability of the rock mass provides efficient pathways for subsequent modification by external agents (Fig. 6C).

(3) Freeze–thaw cycles and chemical weathering: driving progressive coalescence of the potential sliding surface

Following the formation of the fracture network and high-permeability pathways, seasonal freeze-thaw cycles and chemical weathering become the dominant external agents governing sliding surface formation. Glacial meltwater and groundwater repeatedly undergo freeze-thaw action along the network formed by foliation planes and unloading fractures; frost-heave pressure forces microcracks to propagate continuously, while pore-water pressure generated during thawing stages further reduces the shear strength of structural planes. Concurrently, chemical alteration preferentially proceeds along fractures and foliation planes, promoting the decomposition and transformation of minerals such as actinolite and chlorite, and forming clay-rich, argillized weak interlayers. The potential sliding surface progressively coalesces along the preferred structural planes, with only partially intact locked segments remaining at the slope toe or within the interior, and the slope as a whole enters a critically stable state (Fig. 6D).

(4) Triggering and catastrophic failure

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When the slope is in a state of limit equilibrium, extreme rainfall or strong earthquakes act as the final triggering factors. Intense rainfall causes water filling of the fracture network, a rapid increase in pore-water pressure, and an abrupt reduction in effective stress and frictional resistance along the sliding surface; strong earthquakes impose transient dynamic loading that exceeds the residual shear strength of the locked segment. The upper sliding mass overcomes the residual resistance of the already interconnected sliding surface and undergoes integral, high-speed failure sliding along the weak interlayer (Fig. 6E).

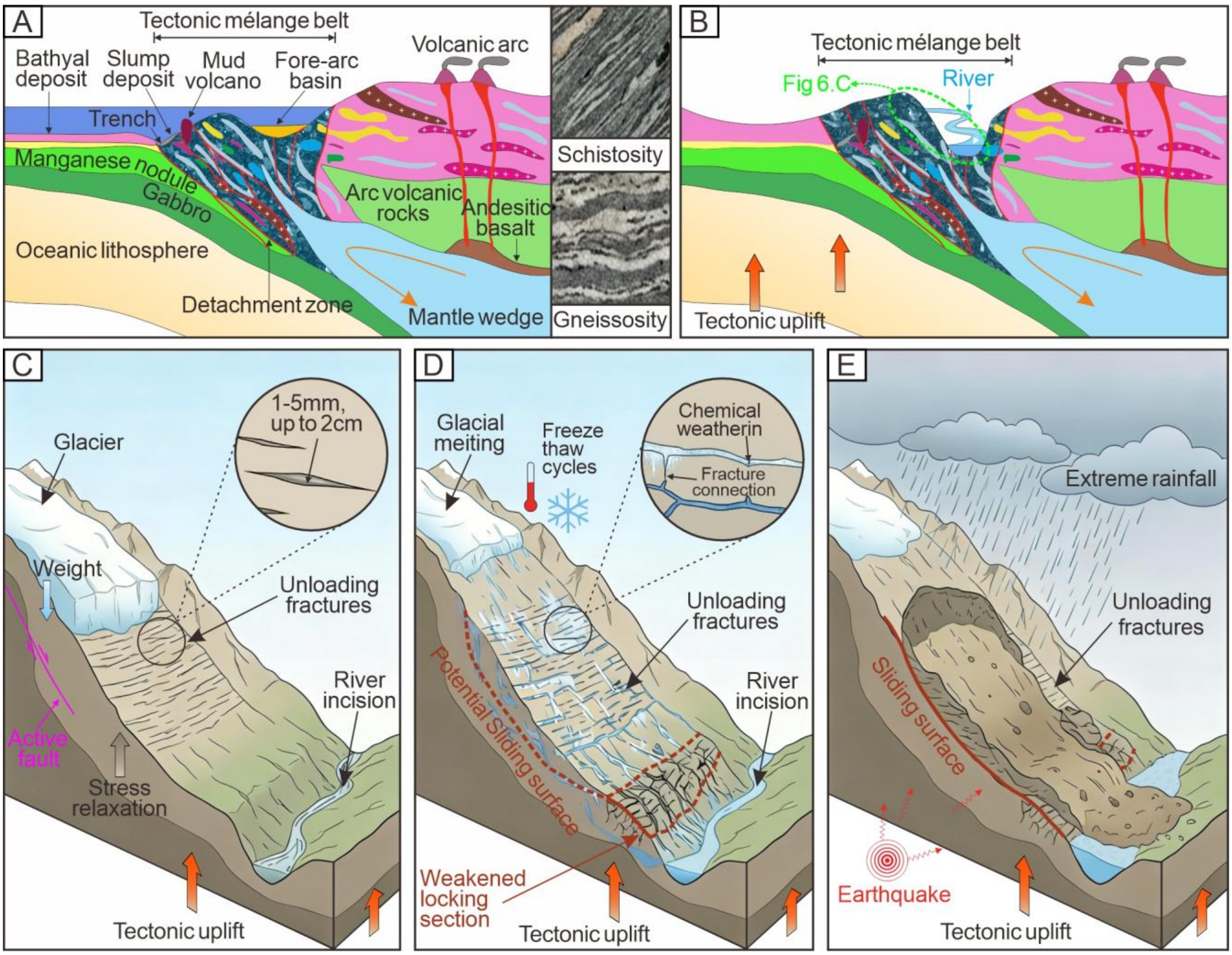

Figure 6. Schematic diagram of the preparation and evolution model of rockslides in suture zones

5.3 Limitations and broader implications

Although the Jinsha River suture zone provides an ideal natural laboratory for investigating the relationship between tectonic architecture and large rockslide development, several limitations of this study should be acknowledged. The Tibetan Plateau is characterized by unique environmental conditions, including extremely high elevation and intensive freeze–thaw cycles,

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which may enhance slope weakening and contribute to its high susceptibility to landslide development. This study demonstrates that the material composition and structural architecture of tectonic suture zones exert important influences on large rockslide development. However, this understanding is mainly derived from the specific geological and climatic context of the Tibetan Plateau, and other suture zones worldwide may not experience comparable elevation conditions or freeze–thaw environments. Thus, the extent to which the mechanisms identified in this study can be applied to other tectonically active regions requires further investigation.

Nevertheless, previous international studies indicate that the role of long-term tectonic inheritance and structural–material heterogeneity in preparing slopes for failure may extend beyond the Tibetan Plateau. Tectonic mélanges, widely developed in subduction-accretionary and collisional orogenic systems, commonly preserve complex lithological assemblages and pervasive deformation structures, which can strongly influence rock mass properties and deformation localization (Festa et al., 2019a). For example, studies of deep-seated gravitational slope deformations in the European Alps have shown that inherited fault networks, foliation structures, and lithological contrasts contribute significantly to the development and localization of large rockslides (Crosta et al., 2013). Similarly, investigations in the Himalaya have highlighted the importance of inherited tectonic structures and progressive rock mass weakening associated with long-term mountain building processes in controlling large-scale slope instability (Hewitt et al., 2008). In rapidly uplifting mountain belts such as the Southern Alps of New Zealand, the interaction between tectonic deformation, lithological variability, and geomorphic adjustment has also been recognized as an important background condition for large rockslide development (Korup and Montgomery, 2008). Collectively, these studies suggest that, although climatic and geomorphic conditions vary among different mountain belts, the coupling between tectonic inheritance and structural–material heterogeneity may represent a more general mechanism contributing to large rockslide development. These observations suggest that the dynamic sequence conceptual model proposed in this study has the potential to be further evaluated and applied in other active orogenic belts.

Future studies should conduct comparative investigations of suture zones under different climatic and geomorphic conditions (e.g., similar tectonic settings in low-elevation tropical or temperate regions) to clarify the relative contributions of intrinsic structural characteristics of suture zones and environmental factors to landslide development. Such investigations will further test and refine the dynamic sequence conceptual model proposed in this study.

6 Conclusion

This study focuses on the Jinsha River suture zone and, through systematic field geological investigations, laboratory microstructural analyses, and landslide inventory statistics, explores how the material composition and structural architecture of the suture zone itself govern the initiation of large rockslides. On this basis, a conceptual model delineating the complete dynamic sequence from long-term initiation to final triggering of rockslides in suture zones is constructed. The main conclusions are as follows:

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(1) The Jinsha River suture zone, as a product of plate collision and amalgamation during the closure of the Paleo-Tethys Ocean, contains weak and heterogeneous tectonic mélange that provides the material basis for landslide initiation. The subhorizontal foliation and lithological interfaces developed in localized areas within the suture zone provide preferential pathways for subsequent stress release and progressive weakening, thereby governing the clustered spatial distribution of large to very large rockslides along the suture zone.

(2) The sliding surfaces of landslides in the suture zone are not randomly formed but are strictly constrained by the rock mass structure, being predominantly localized adjacent to metamorphic rock layers with subhorizontal foliation or at interfaces between different lithologies. Experimental evidence further confirms that these locations are the preferential sites where fractures most readily develop and coalesce into continuous surfaces. Moreover, weak interlayers are commonly associated with these locations, providing a mechanistic explanation for the spatial preference of landslide sliding surfaces.

(3) The occurrence of landslides in suture zones follows a distinct long-term evolutionary sequence. The four-stage evolution model for suture zone landslides constructed in this study reveals the complete dynamic process: from plate collision and amalgamation forming tectonic mélange that establishes the material basis, through tectonic uplift, river incision, and other endogenic and exogenic geological processes that induce rock mass fracturing and degradation and form the sliding surface, to final catastrophic failure triggered by short-term events such as intense rainfall or earthquakes.

(4) This initiation and evolution framework shifts the analytical perspective from short-term triggers to the dynamic coupling of long-term initiation processes, and from external triggering factors to the fundamental control of internal material and structural properties. It not only provides a unified mechanistic explanation for understanding the clustered, long-term, and structurally controlled nature of large landslides on the Tibetan Plateau and in similar active orogenic belts, but also furnishes new scientific evidence and key indicators for early landslide risk identification and long-term prediction in major engineering zones within this region.

Data availability

The data will be made available on request.

Author contributions

JZ: Formal analysis, Visualization, Writing (original draft preparation). MW: Conceptualization, Investigation, Supervision, Writing (review and editing). WZ: Investigation, Writing (review and editing). CY: Investigation, Methodology. QD: Methodology, Supervision. QS: Investigation, Resources. BH: Investigation, Data curation. YZ: Investigation, Validation. ZL: Investigation, Validation.

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Competing interests

The contact author has declared that none of the authors has any competing interests.

Acknowledgements

We gratefully appreciate the editor and anonymous reviewers for their constructive reviews and suggestions, which greatly improved the quality of this manuscript. We also sincerely thank the participation of Chen Cao, Tengyue Li, Han Yin and other colleagues in the field work.

Financial support

This research has been supported by the Deep Earth Probe and Mineral Resources Exploration-National Science and Technology Major Project (grant nos. 2025ZD1006208 and 2025ZD1006103).

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