Journal of 山地科学学报(英文)
Mountain Science

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View online: https://doi.org/10.1007/s11629-020-6573-6

J. Mt. Sci. (2021) 18(8): 2094-2107 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-020-6573-6

Original Article

Landslide distribution and sliding mode control along the Anninghe fault zone at the eastern edge of the Tibetan Plateau

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Citation: Zhou HF, Liu B, Ye F, et al. (2021) Landslide distribution and sliding mode control along the Anninghe fault zone at the eastern edge of the Tibetan Plateau. Journal of Mountain Science 18(8). https://doi.org/10.1007/s11629-020-6573-6

Abstract: Tibetan Plateau is known as the roof of the world. Due to the continuous uplift of the Tibetan Plateau, many active fault zones are present. These active fault zones such as the Anninghe fault zone have a significant influence on the formation of special geomorphology and the distribution of geological hazards at the eastern edge of the Tibetan Plateau. The Anninghe fault zone is a key part of the Y-shaped fault pattern in the Sichuan-Yunnan block of China. In this paper, high-resolution topographic data, multitemporal remote sensing images, numerical calculations, seismic records, and comprehensive field investigations were employed to study the landslide distribution along the active part of the Anninghe. The influence of active faults on the lithology, rock mass structures and slope stress fields were also studied. The results show that the faults within the Anninghe fault zone have damaged the structure and integrity of the slope rock mass, reduced the mechanical strength of the rock mass and controlled the slope failure modes. The faults have also controlled the stress field, the distribution of the plastic strain zone and the maximum shear strain zone of the slope, thus have promoted the formation and evolution of landslides. We find that the studied landslides are linearly distributed along the Anninghe fault zone, and more than 80% of these landslides are within 2-3 km of the fault rupture zone. Moreover, the Anninghe fault zone provides abundant substance for landslides or debris flows. This paper presents four types of sliding mode control of the Anninghe fault zone, e.g., constituting the whole landslide body, controlling the lateral boundary of the landslide, controlling the crown of the landslide, and constituting the toe of the landslide. The results presented merit close attention as a valuable reference source for local infrastructure planning and

Received: 06-Nov-2020
Revised: 19-Feb-2021
Accepted: 08-May-2021

engineering projects.

Keywords: Tibetan Plateau; Anninghe fault zone; Landslide distribution; Sliding mode control

1 Introduction

Due to the northward subduction of the Eurasian Plate by the Indian Plate and the uplift of the Tibetan Plateau (Tang et al. 2016), a series of large-scale active fault zones with extension lengths of several hundred kilometers have developed on the eastern edge of the Tibetan Plateau. In recent years, the relationship between active faults and geological hazards has attracted the widespread attention of scholars (Lee and Dan 2005; Osmundsen et al. 2009), especially after the 2008 Ms 8.0 Wenchuan earthquake, during which thousands of landslides and collapses were directly induced. Destructive earthquakes exhibit the widest range and induce many geohazards (Yin 2009). After the Wenchuan earthquake, scholars have carried out research on the relationship between earthquake-triggered landslides (including rock avalanches) and the Longmenshan fault zone and have obtained rich research results (Huang and Li 2014; Fu et al. 2009; Xu and Li 2010).

In recent years, the site selection of some major engineering projects, e.g., urban planning, requires not only evaluations of foundation bearing capacity and slope stability but also of the influence of internal and external dynamic effects (Peng 2006). Landslides that are induced by active fault zones and the corresponding prevention techniques are currently major geological engineering problems, which should be urgently solved and have attracted wide attention from academic and management departments (Zhang et al. 2015; Fu and Liao 2010). There are two main types of active fault modes, i.e., slow creep deformation and rapid dislocation deformation (earthquakes). The former mode exhibits a relatively long period of creep deformation and causes landslides due to the fragmentation and disintegration of the rock mass that is close to the fault zone. The latter mode releases enormous amounts of energy and instantaneously triggers large numbers of mass movements. Although most researchers agree that geological structures, especially active faults, play the role of controlling or predisposing factors of geological disasters (Chalupa et al. 2018; Dong et al. 2019), fault deformations are usually slow and difficult to observe directly. Most deformation that is due to fault activity can only be judged and qualitatively studied on the basis of the deep experience of experts (Zhang et al. 2016).

Existing studies have shown that landslides are not only triggered by earthquakes but are also controlled by faults (Guo et al. 2015). On April 9, 2000, a large high-speed long-distance landslide occurred in Yigong town, Bomi County, Tibet, and the sliding body blocked the Yigongzangbu River after long-distance sliding. A deposit with a volume of 3×10^9 m^3 formed at the mouth of Zhamulong Valley (Yin and Xing 2011). Xu et al. (2012) proposed that this landslide was influenced by the Yigongzangbu-Palongzangbu fault zone. Moreover, the Mogangling landslide, which was triggered by the Moxi earthquake in 1786 AD, is closely related to the western branch of the Detou fault (Zhou et al. 2017). The Gelongbu landslide, with a volume of 5.4×10^8 m^3, is present in the reservoir area of the Jishixia Hydropower Station on the upper reaches of the Yellow River. The Gelongbu landslide blocked the Yellow River for hundreds of years after the occurrence of high-speed sliding, and the thickness of the landslide deposit was approximately 30 m. Zhou et al. (2009) demonstrated that the Gelongbu landslide was controlled by faults at the toe of the slope. Stead and Wolter (2015) summarized eight types of sliding modes that are controlled by faults or structural planes and described the characteristics of each control mode. Vick et al. (2020) analyzed the entire process of rock slope deformation and evolution in northern Norway.

Large numbers of landslides have been triggered by historical earthquakes or long-term creep along faults that are distributed near the Anninghe fault zone and Zemuhe fault zone at the eastern edge of the Tibetan Plateau. Although the failure mechanisms of these landslides vary, they are linearly distributed along the fault zone and exhibit a strong relationship with the fault zone (Feng et al. 2018; Wei 2014). Wang et al. (2015) carried out an investigation large-scale landslides around the middle reaches of the Weihe River and found that large-scale landslides are mainly distributed along both sides of the Baoji-Xianyang fault after four key historical strong earthquakes. Scheingross et al. (2013) analyzed earth flows, which are slow-moving landslides, and the creeping section of the San Andreas fault, and 75% of these slow-moving landslides are distributed within 2 km of the fault zone. Zhang et al. (2010) conducted research on the 2007 Ms 6.4 Ninger earthquake in Yunnan Province of China and found that earthquake-induced landslides are affected not only by terrain landforms, geological structures, rock and soil types, and human engineering activities but also by the intensity of earthquake acceleration and the direction of motion. Furthermore, strong neotectonic movements have formed the topography of the alpine gorge region, and active faults have also laid the foundation for the differential uplift of geological bodies, which have formed high, steep slopes due to river undercutting. Tectonic movement induces the fragmentation of rock masses and reduces their mechanical strength, which creates favorable conditions for landslide formation (Avouac 2007; Parker et al. 2011).

These studies demonstrate that the disastrous effects of the landslides triggered by active faults are reflected not only by seismogeological disasters and changes in terrain and landforms but also by the long-term evolution of the slope rock structure, mechanical characteristics and regional tectonic stress (Stead and Eberhardt 2013; Stead and Wolter 2015). Consequently, the triggering effect of active faults on landslide formation cannot be ignored because active regional faults control earthquakes and active faults influence slope stability (Yao et al. 2017; Murphy 2006).

Because the Anninghe fault zone is an important fault zone on the eastern edge of the Tibetan Plateau and the southern part of the North-South seismic belt, it has attracted much attention from scholars, and preliminary studies have already been conducted on the development characteristics and landslide occurrences (He 2017; Luo 2019). However, these studies do not address the influence and control of the fault on the local stress fields of slopes and have not summarized the slide control model of the active fault. By using the results of a regional engineering geological survey around the Anninghe active fault zone, this paper employs data collection, ground surveys, remote sensing, numerical analysis, and high-precision GPS measurements. Based on the spatial distribution characteristics of the Anninghe active fault zone, we analyze the landslide distribution within the Anninghe active fault zone and discuss the control modes of the active fault zone on landslides. The results presented merit close attention as a valuable reference source for local infrastructure planning and engineering projects.

2 Geological Setting

The Anninghe fault zone is located at the junction of the Chuan-Dian and Liangshan massifs on the eastern edge of the Tibetan Plateau, which is the transition of the Tibetan Plateau to the Sichuan Basin and the Yunnan-Guizhou Plateau. The overall terrain is high in the north and west and is low in the south and east. The drainage and mountain range are controlled by regional tectonic evolution. The direction of maximum principal stress of the tectonic stress field in the study area is generally NNW, as the relatively rigid South China Block was squeezed eastward from the Tibetan Plateau (Fig. 1).

The Anninghe fault zone generally consists of a north-south fault that originated in the Jinningian and is located on the east and west sides of the modern Anning River. The fault zone begins near Tianwan in Shimian County in the north, passes Mianning County, Xichang City, Dechang County and Miyi County, and ends at the Jinsha River in Panzhihua City in the south. The total length of the Anninghe fault zone is approximately 350 km. In the east-west direction, the Anninghe fault zone can broadly be divided into the east and west branches, and the Anning River forms the boundary. The Anninghe fault zone, in a narrow sense, is the active fault that was generated in the late Pleistocene and continued through the Holocene. It begins at Tianwan in the north, passes Xieluo, Yihai, Mianning, Linli, Shilong, Lugu, Yuehua, and Lizhou, and ends at Xichang in the south. Its total length is approximately 170 km. Actually, the Anninghe fault zone, in a narrow sense, belongs to the middle and northern sections of the Anninghe fault zone in a broader sense and is usually called the active part of the Anninghe fault zone. Based on a field geological survey, the active part of the Anninghe fault zone can further be subdivided into 17 active Holocene faults, e.g., F1-F17 (Fig. 2).

3 Landslide Distribution Along the Fault Zone

Landslide distributions along active fault zones

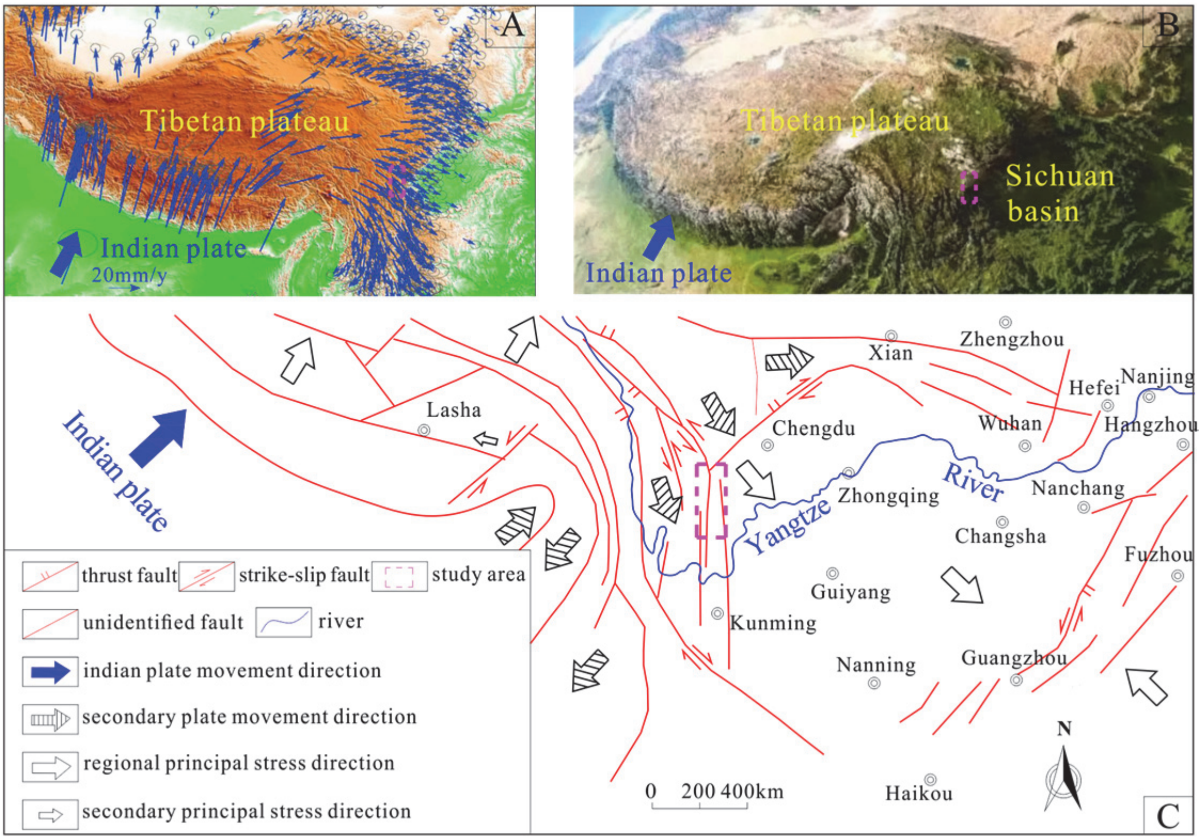

Fig. 1 Location of the study area, (a) Velocity vector map of crustal movement of the study area; (b) 3D topography of the study area; (c) Main structures of the study area.

are an important part of geological hazard investigation and research (Guo et al. 2020). Active faults have an important impact on local terrain landforms, stratigraphic lithology, geological structures, earthquakes, tectonic stress fields, new tectonic movements, and geological hazard types (Brideau et al. 2009; Humair et al. 2013).

The corresponding physical and chemical changes occurred in the rock mass around the Anninghe active fault zone with slow deformation. From the perspective of geological hazards, creep deformation causes new tension cracks in the fault, which induce subsidence faults and rock mass deformation in the fault zone. These changes can lead to local stress concentrations and exacerbate or even cause landslides. Alternatively, the rock mass close to the fault can be crushed or stretched due to slow fault deformation. The rock masses on the slope that are close to creep faults undergo deformation, cracking, breaking, and disintegration processes, and slope stability decreases correspondingly (Stead and Wolter 2015). Consequently, the active fault zone plays a key role in the formation and distribution of landslides.

3.1 Effect on lithology and rock mass structure

The Anninghe fault extends to a great depth below the ground surface. Due to the relative displacement of the fault, the lithologies on the footwall and hanging wall are different. The Shayemahaizi fault is a good example. It is a typical thrust fault located at Zhoujiabaozi in Mianning County, and the fault strikes NNE, with an occurrence of 292°∠61°. The eastern plate of the fault is Xigeda (Q_1x) siltstone, while the western block is Precambrian (Anε) white rhyolite. The eastern block of Xigeda siltstone thrusts above the western plate of rhyolite (Fig. 3), and the width of the fault fracture zone is 1.5-2.0 m. In addition, a fault lens was found on the rhyolite side. On the side with the Xigeda stratum, a cleavable siltstone zone formed under the action of the geological structure.

Due to the different physical and mechanical properties between the fault zone and surrounding bedrock, weathering-induced fissures and unloading joints often appear in the fault zone (Vick et al. 2020).

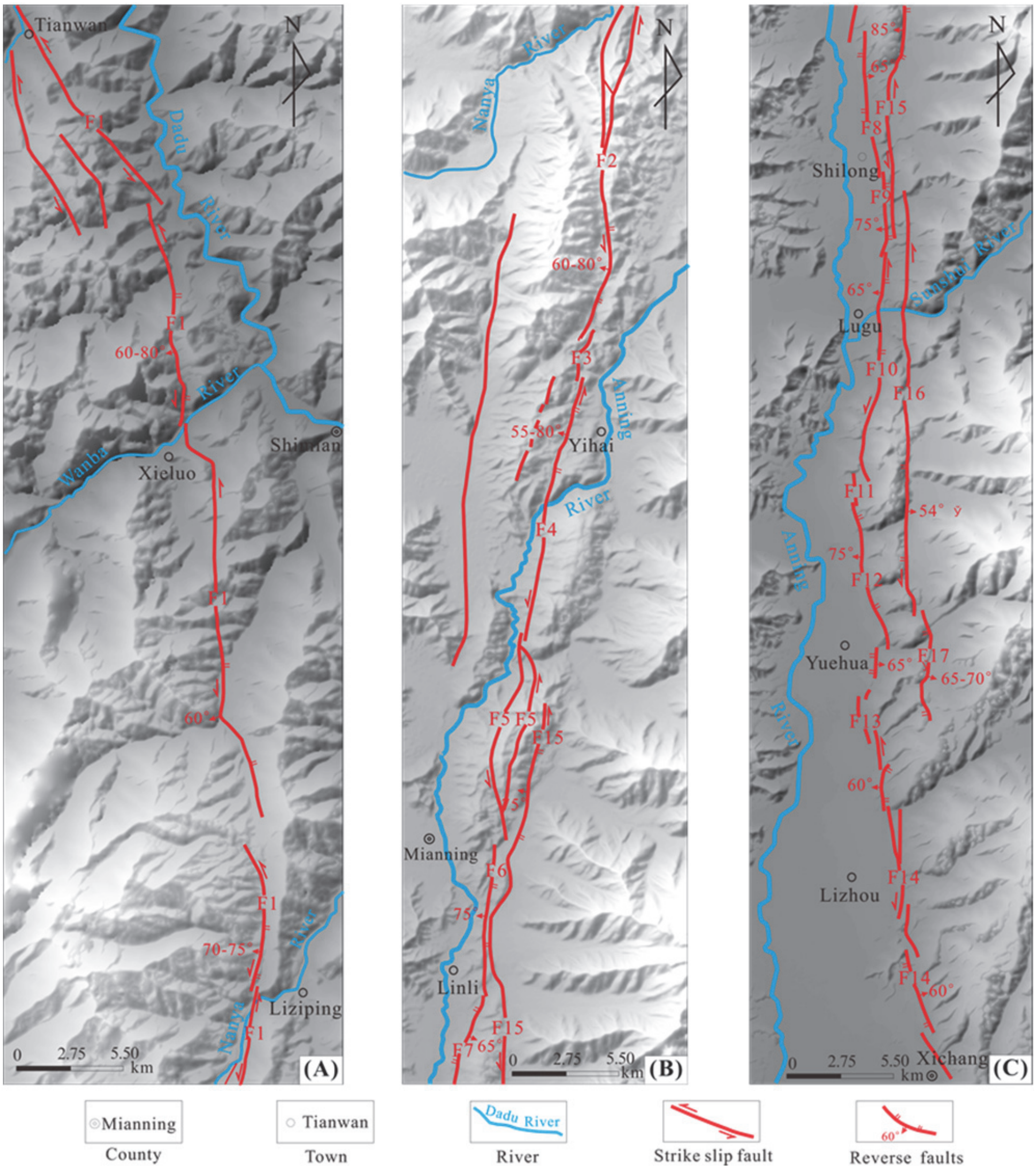

Fig. 2 Spatial distribution of the active part of the Anninghe fault zone: (a) The northern section of the active part of the Anninghe fault, (b) middle section of the active part of the Anninghe fault, and (c) southern section of the active part of the Anninghe fault (F1 - Zimakua fault, F2 - Paisigedi fault, F3 - Yejidong fault, F4 - Yihai fault, F5 - Mixiluogou fault, F6 - Shawan fault, F7 - Linlicun fault, F8 - Shilong fault, F9 - Shaguoshu fault, F10 - Lugu fault, F11 - Yijiahaizi fault, F12 - Yangfushan fault, F13 - Shejiluo fault, F14 - Hongshanzui fault, F15 - Shayema fault, F16 - Dapingzi fault, and F17 - Luji fault).

Coupled with the slow deformation of the active fault zone, a dense joint pattern developed in the slope rock mass near the fault zone, and the rock structure was thus damaged (Fig. 4). These actions led to deterioration of the mechanical properties of the slope rock mass and caused slope stability to decrease and even directly predisposed the zone to geological hazards, e.g., landslides.

3.2 Effect on slope stress field

Stress concentration levels are always high at fault intersections due to the mutual compression of the blocks on both sides of fault zones. With displacement along faults, the stress is suddenly released, and earthquakes may occur due to the sudden stress release. From a macroscopic view, regional faults affect and control the magnitudes and distributions of regional tectonic stress fields (Xie et al. 1993). From a microscopic view, stress fields in fault zones usually undergo significant changes, and a

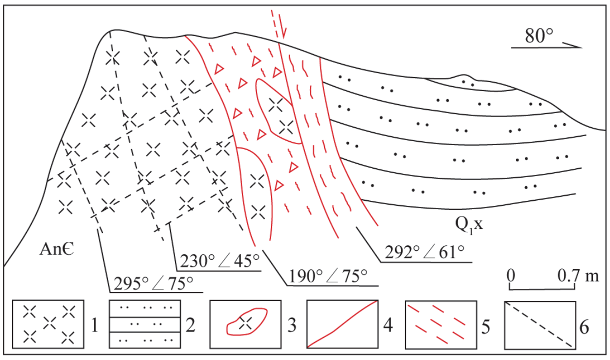

Fig. 3 Sketch map of the Shayemahaizi fault (1-Rhyolite, 2-Siltstone, 3-Fault lens, 4-Fault, 5-Cleavage zone, and 6-Shear joint).

Fig. 4 Fault-induced rock mass fragmentation.

local stress field is formed in which the magnitude and direction are inconsistent with the regional stress field. Changes in the local stress field, especially local stress concentrations or substantial stress reductions, have a crucial influence on the formation of geological hazards due to weathering and unloading changes and mechanical property degradation of the slope rock mass. Consequently, tectonic movements, especially those due to active faults, have an important impact on the evolution and formation of large-scale landslides. They are one of the main internal factors that cause large-scale landslides under endogenic and exogenic dynamic coupling effects (Li et al. 2008; Hovius and Meunier 2012).

Zhang et al. (2016) and Zhou et al. (2017) pointed out that fault properties and deformation feartures have a controlling role in the distribution of the plastic zone of the slope and indirectly affect slope stability. According to our study of the Mogangling landslide in the Dadu River area, the fault zone exerts an obvious influence on the shear stress of the slope rock mass. A finite element calculation model was established by using phase software, in which the strike was 150° and the dip was 60° for the west branch of the Detuo fault, while the width was 10 m. The initial stresses that were applied at the boundary of the finite element calculation model were σ_1 = 7 MPa, σ_2 = 5 MPa and σ_3 = 3 MPa (Fig. 5). The materials in the calculation model were granite and the fault zone (Table 1). The stress field distributions of the slope rock mass in the ten phases of incising the Dadu River were analyzed.

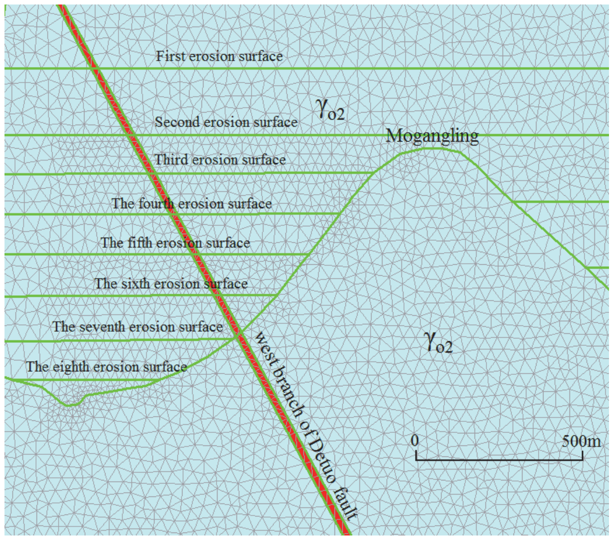

Fig. 5 FEM model of simulated Dadu River undercutting (planation surface altitude 2,300 m).

The results show that the west branch of the Detou fault at the front of the slope affected the local stress field during the process of Dadu River undercutting and slope evolution. The high shear stress zone in the Detuo fault on the superficial slope rock mass (Fig. 6) caused the rock mass in the fault zone to exhibit an obvious dilatancy phenomenon (Deng 2020), which reduced the shear strength of the potential sliding surface and caused the slope to fail

Table 1 Calculation parameters for the FEM model

Material	ρ (g/cm³)	E (GPa)	μ	φ (°)	c (MPa)	σ_t (MPa)
γ_{o2}	2.69	20.0	0.23	51.92	2.52	1.11
Fault	2.21	1.8	0.33	26.85	0.08	0.00

Note: ρ, Density; E, Deformation modulus; μ, Poisson's ratio; φ, Internal friction angle; c, Cohesion; σ_t, Tensile strength.

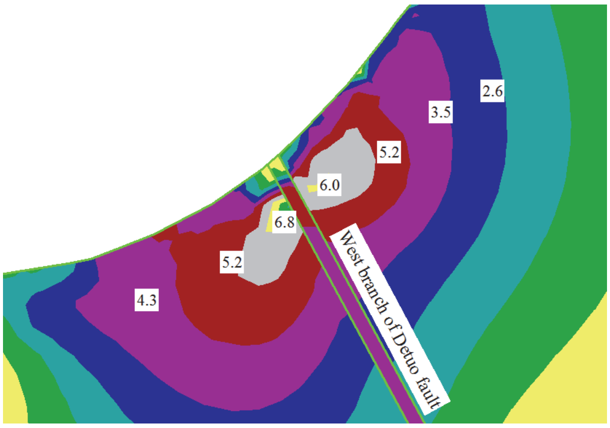

Fig. 6 High shear stress zone in the Detuo fault on the superficial slope rock mass (unit: MPa)

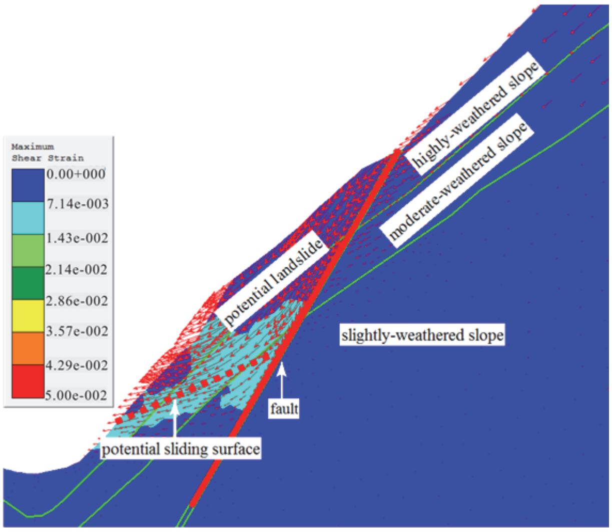

Fig. 7 Maximum shear-strain zone in the middle and lower parts of the slope that is controlled by steep faults.

rapidly during the 1786 Ms 7.75 Moxi earthquake.

During the geological survey period, we also determined that there were shear planes in the middle and lower parts of the slope due to steep faults. This phenomenon is more obvious in the highly-weathered slope rock mass because the high level of weathering has led to widespread tensile deformation of the slope rock mass, which reduced the strength and integrity of the rock mass and was conducive to the formation of the landslide body. The numerical analysis results also demonstrated that the maximum shear strain occurred in the middle and lower parts of the slope near the fault (Fig. 7), which is detrimental to the overall stability of the slope. The slope may fail along the fault zone and maximum shear strain zone under exterior disturbances, and continuous shear creep deformation may trigger a large-scale landslide disaster. Consequently, the fault has different degrees of influence on the magnitude and distribution of the regional stress field, which directly or indirectly promote slope damage to cause an avalanche disaster. The landslide effects of fault zones are an important research topic.

3.3 Effect on landslide distribution

The results of remote sensing and field surveys within 20 km of the Anninghe fault zone show that the impact and control of the Anninghe fault zone on landslides have distinct segmentation and concentration characteristics. The distribution features of landslides are analyzed in the area from Fuxi town to Xichang city and in the area from Xichang city to Dechang County. The relationship between the landslide distribution and the Anninghe fault zone is shown below.

(1) A total of 147 landslides are present from Fuxin Town to Xichang city, including one giant landslide, two super large landslides, 34 large landslides, 56 medium landslides, and 54 small landslides (Fig. 8a). Statistics results show that 86 landslides are distributed in the zone that is influenced by the eastern branch of the Anninghe fault (less than 2 km), which account for 58.5% (Fig. 9a), 26 landslides are distributed in the zone that is influenced by the Hongmo fault, which account for 17.69%, and only 35 landslides are distributed in the remaining areas, which account for 23.81%. The relationship between the distance (D) to the east branch of the Anninghe fault and the number of landslides (N) is given in Eq. (1).

$$\ln(N) = 3.66 - 1.63 \times \ln(D), (R=0.73) \quad (1)$$

These results indicate that the eastern branch of the Anninghe fault and the Hongmo fault exerts clear influence and control on the landslide distribution in the study area. The farther the distance from the fault, the lower the number of landslides.

(2) Different from the landslide distribution in the section from Fuxing town to Xichang city, the landslides in the section from Xichang city to Dechang County are concentrated west of the Mopanshan fault zone and are located on the left bank of the Yalong River (Fig. 8b). These landslides are impacted and controlled by the zone of influence of the Mopanshan-Jiuxitou fault. These faults strike nearly NS and do not belong to the Anninghe fault zone. The influence of the Anninghe fault zone on

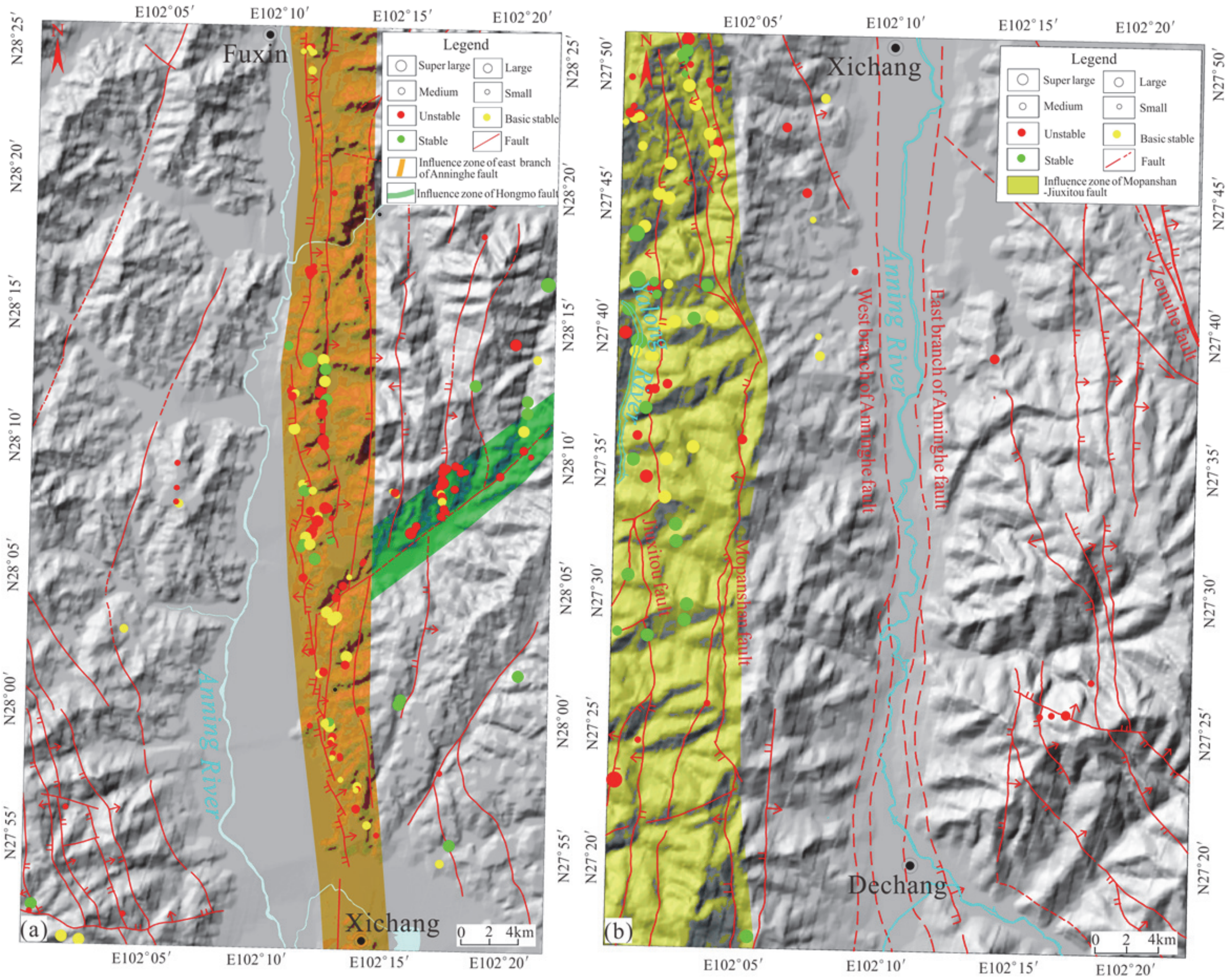

Fig. 8 Fault and landslide distribution from Fuxin town to Dechang County, Sichuan Province, China, (a) Fuxin town to Xichang city section; (b) Xichang city to Dechang County section.

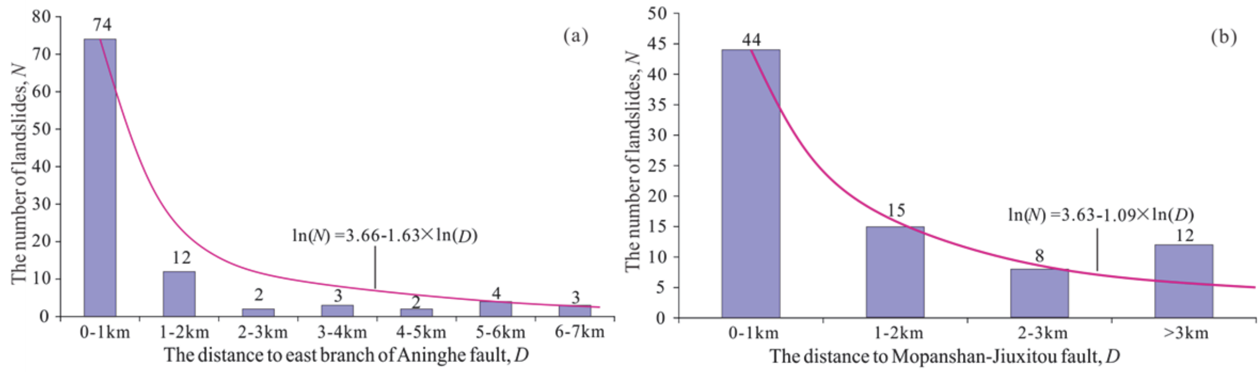

Fig. 9 The relationship between landslide numbers and distance to fault zone, (a) to the east branch of Anninghe fault; (b) to the Mopanshan-Jiuxitou fault.

these faults is relatively slight. There are 79 landslides in this section, including four superlarge landslides, 32 large landslides, 26 medium landslides, and 17 small landslides. The relationship between the distance (D) to the Mopanshan-Jiuxitou fault and the number of landslides (N) is given in Eq. (2).

$$\ln(N) = 3.63 - 1.09 \times \ln(D)\ (R=0.81) \tag{2}$$

Among them, 67 landslides are developed in the influenced zone of the Mopanshan-Jiuxitou fault (less than 3 km), which account for 84.81% (Fig. 9b), and only 12 landslides are developed in the remaining areas, which account for 15.19%. This is because the eastern and western branches of the Anninghe fault zone pass through the Anning River Valley in a concealed form south of Xichang city but do not pass through the slopes on either side of the river valley. Accordingly, the Anninghe fault zone has a slight influence on the slope stability on both sides of the Anning River Valley.

(3) The investigation shows that more than 80% of all landslides are distributed within 2-3 km of the fault rupture zone, which illustrates that fault zones play an important role in landslide distributions. This relationship does not adequately explain or assess indicators such as terrain landforms, rainfall, slope structures, human activities and historical earthquakes. The only reasonable and scientific explanation is that the active fault zone can lead to a decrease in rock mass strength and thus exacerbate slope instability and failure. It can reflect the distinctive characteristics of the landslide distribution along the active fault zone.

3.4 Effect on debris flow

The influence of fault zones on debris flows is related to the strikes of fault zones and gullies and the intersection angles of fault zones and gullies (Liu et al. 2020). Fault zones control the formation and evolution of gullies. The characteristics of the longitudinal gradient are also controlled by the fault zone when the strike of a fault zone is close to that of a gully. The displacement along the fault zone may affect the planar shape of the valley if the fault zone intersects the gully at a large angle. The strike of the Anninghe fault zone is generally in the SN direction, and the strike of most gullies is E-W in this area.

Clearly, the intersection angles of the Anninghe fault zone with most gullies are large. The slope rock masses on both sides of the valley are fragmented, and fragmented materials can accumulate in trenches because the fault zone passes through valleys. These accumulations provide abundant substance for debris flows. Taking the Dianzi village group debris flow as an example, the Yihai fault passes through a series of gullies with an EW strike (Fig. 10). There are large numbers of landslides with poor stability that are close to the fault zone. These landslides accumulated at the foot of the slope and formed the main source of

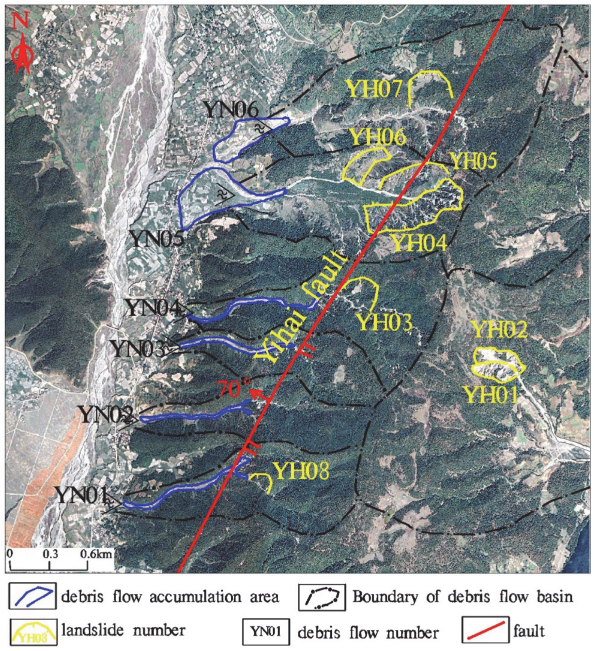

Fig. 10 Fault and debris flow group in Dianzi village, Mianning County, China.

debris flows. Furthermore, the fault fracture zone continuously flows into the gully due to slope erosion and further supplements the material source of debris flows and thereby forms a group of debris flows.

Another example is Chulu gully on the right bank of the Dadu River in the northern section of the Anninghe fault zone. The length of the gully is 20.81 km, and the area of the basin is 76.3 km². The elevations of the top and bottom of the gully are 4,580 m and 955 m, respectively. The average longitudinal gradient is 174.2‰. In the basin, the Anshunchang fault, Jiziping fault, Xiyoufang fault, Moxi fault and Wanba fault are present. These faults strike nearly NS or NNW and intersect the main gully at large angles. The slope rock masses on both sides of the gully have been fragmented due to the fault zone, and many landslides have developed.

A large amount of fault zone material has accumulated in the gully from long-term slope erosion. The loose materials are mainly distributed in the middle and lower reaches of the gully, and the locations of the loose materials show a good correspondence with the fault zone locations (Fig. 11). The total volume of solid material in the gully is approximately 22.90×10^6 m³, while the total volume of loose materials is 2.10×10^6 m³. Several large-scale mudslides occurred in the gully in 1952, 2003 and 2007, which resulted in direct economic losses of

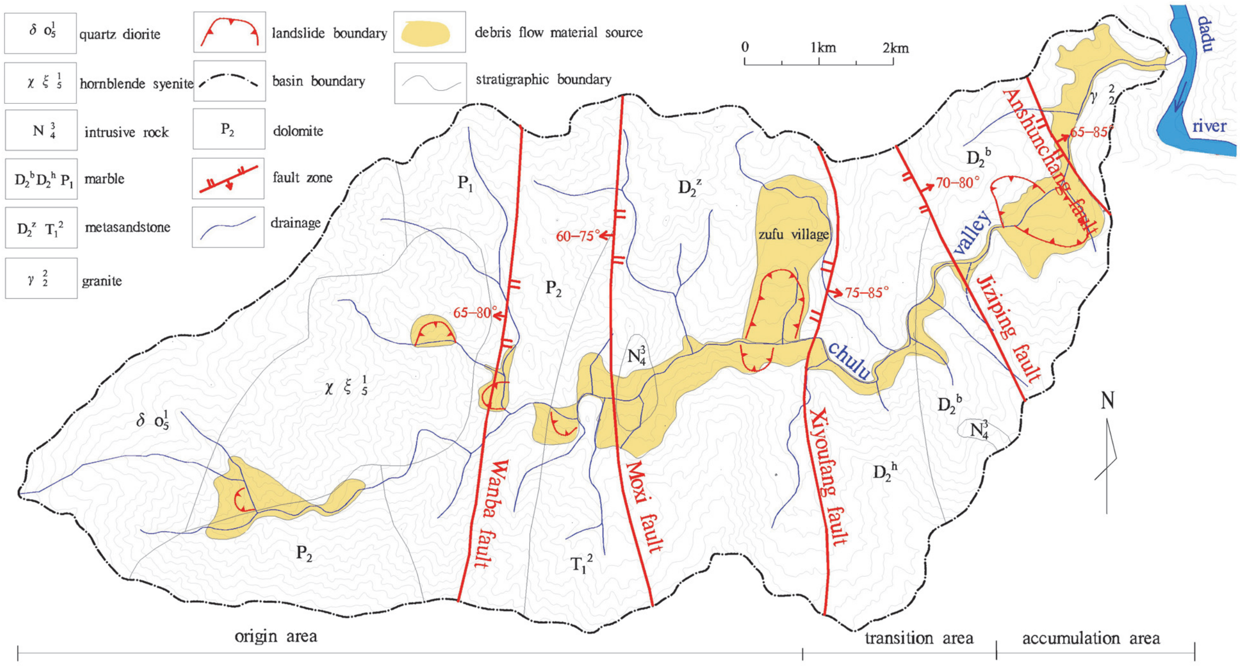

Fig. 11 Fault and loose debris flow materials around the Chulu Gully in the northern section of the Anninghe fault zone.

more than tens of millions of yuan. In recent years, many small- and medium-scale mudslides have occurred and have posed serious threats to residents' safety, farmland and roads on both sides of the gully.

4 Sliding Mode Controlled by the Fault Zone

According to the previous analysis, the Anninghe fault zone exerts significant influence and control on the formation, evolution and distribution of landslides. Based on a broad regional perspective, the landslides are distributed linearly along the fault zone, which coincide with the fault strike and spatial distribution (He 2017; Yao et al. 2017). From the perspective of small areas and individual cases, the influences of fault zones on specific landslides are different (Zhang et al. 2016). Based on the field survey, the slide- control models of the Anninghe fault are summarized.

4.1 Fault rupture zone rock mass constituting the landslide body

The width of the Anninghe fault rupture zone is large and is hundreds of meters wide in some sections (Zhang 2014). When favorable terrain and free-face

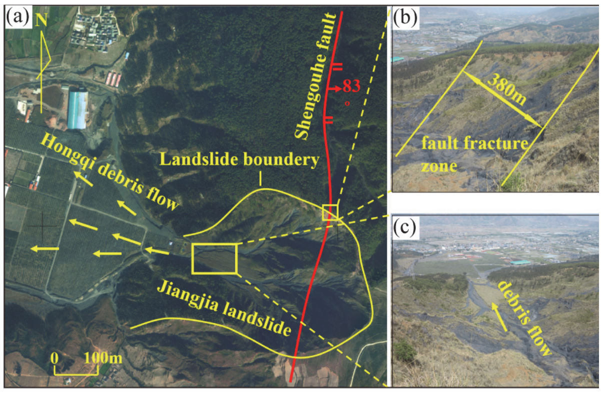

Fig. 12 Disaster chain pattern that was induced by the Jiangjia landslide to Hongqi debris flow (a) Panorama of remote sensing image; (b) fault fracture zone; (c) Hongqi debris flow.

conditions are present, the rock mass in the fault rupture zone directly constitutes a large-scale landslide, e.g., the Jiangjia landslide (Fig. 12a). The Shengouhe fault strikes NS and passes through the middle and bottom of the slope, which is consistent with the slope strike. The slope has favorable free-face conditions. Researchers have measured the width of the fracture zone in situ and have proposed that its width is approximately 380 m (Fig. 12b). Due to the slow movement of the fault fracture zone, the rock mass in the fracture zone gradually breaks up and disintegrates into small rock masses with diameters less than 10 cm. In the rainy season, collapses often occur in the fault fracture zone. Runoff transports large quantities of loose materials and forms debris flows (Fig. 12c). Thus, a typical fault fracture zone-landslide-gully source-debris flow disaster chain forms.

4.2 Fault controlling the sliding boundary of landslide

The Yangcaigou landslide, which is located in Hedong Village, Mianning County, is a typical sliding boundary landslide that is controlled by faults. The overall landform of the landslide is high in the north and low in the south, with a topographic slope of 17°-25° and trend of 200°. The slope crest elevation is 1,850-1,900 m, and the toe elevation is 1,795-1,815 m. The landslide is 140-330 m long and 300-350 m wide, with a total volume of approximately 0.262×10^6 m^3. According to geological survey and exploration data, the Yangcaigou landslide can be divided into landslides #Ⅰ, #Ⅱ and #Ⅲ; landslide #Ⅰ is mainly developed in the Biziyida fault fracture zone. The boundary on both sides of the landslide is controlled by the Biziyida fault zone (Fig. 13). The landslide extends to both sides along the fracture zone under the combined action of washing against the fault fracture zone at the west side of the Yangcai valley and that of the east, which gradually forms the current Yangcaigou landslide.

4.3 Fault controlling the crown of landslide

The Mixiluogou fault passes through the middle of the slope and controls the crown of the landslide in Mixiluo Valley, Mianning County. An old landslide and two new landslides developed between the fault and foot of the slope (Fig. 14a). High-precision GPS monitoring data demonstrate that the strike-slip rates of the Mixiluogou fault are 8-10 mm per year, which has a strong traction effect on the landslide and hastens the overall creep sliding of the landslide.

4.4 Fault constituting the toe of landslide

Conventional studies suggest that faults have a slight influence on the stability of slopes when faults pass through the foot of slopes. However, this conventional view is not always correct. In our field investigation, we found that faults passing through the foot of the slope and being consistent with the

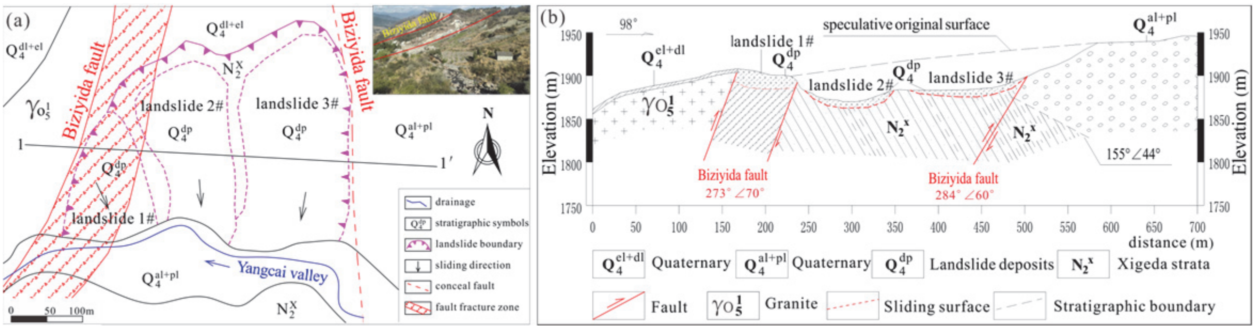

Fig. 13 Typical example of lateral landslide boundaries controlled by faults, (a) Engineering geological plan of the Yangcaigou landslide; (b) Section map of the Yangcaigou landslide.

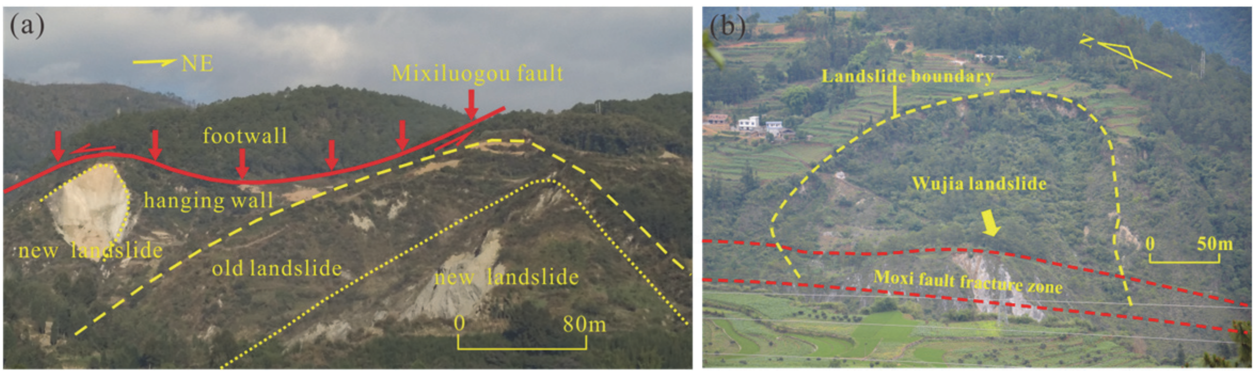

Fig. 14 The fault controlling the crown of the landslide and constituting the toe of the landslide, (a) Example of controlling a landslide crown by a fault; (b) Moxi fault crossing the toe of the Wujia landslide.

strike of the slope play an important role in influencing the stability of the slope and the formation and evolution of landslides. A typical example in our investigation is the Wujia landslide in Xianfeng town, Shimian County. The main sliding direction is EW-225°, and the sliding volume is approximately 0.15×10^6 m^3 (Fig. 14b). The bedrock of the landslide is Sinian granite. The Moxi fault zone, with a large size and poor stability, is developed at the foot of the slope. The strikes of the fault zone and slope are consistent. The rock masses at the foot of the slope in the fault zone gradually slide into the gully, and the rock masses at the back of the slope slide under the combined effects of rainfall and creep deformation. Thus, the Wujia landslide formed.

5 Discussion

(1) From Fuxin town to Xichang city, the Anninghe fault zone has a significant controlling effect on the development and distribution of landslides, while the controlling effect of the Anninghe fault zone is weak and the Mopanshan-Jiuxitou fault zone provides the main controlling effect from Xichang city to Dechang County. This is mainly related to the spatial distribution, scale and terrain landforms of the fault zone. Therefore, active faults and the influenced zones should not be directly designated as susceptible regions.

(2) The eastern edge of the Tibetan Plateau is a region with characteristics of greatest topographic steepness, strongest endogenic and exogenic geological processes, and extremely frequent climate changes. This region has experienced strong neotectonic movements, developed active faults, and has distributed substantial landslides and debris flows. Therefore, this region is a natural testing site and typical area for studying geological hazards. In the past, more attention was paid to studying the formation mechanisms and distributions of geological hazards from the perspective of exogenic geological action, and less attention was paid to studying the landslide-debris flow disaster chain and landslide effects from the perspective of active structures (Zhang et al. 2016, 2017). In recent years, scholars have noticed the influence and control of active faults on the development and distribution of landslides. However, research on landslides is still in a preliminary stage due to the extremely complicated geological conditions on the eastern edge of the Tibetan Plateau. There are still a host of engineering geological problems and disaster prevention topics that need further study, e.g., accurate recognition of high, concealed landslides, prevention of remote disaster chains, and endogenic and exogenic dynamic coupling effects and disaster-causing mechanisms in active fault zones.

(3) This paper only analyzes and explains the influence and control model of creep sliding on the landslides in the Anninghe fault zone but does not involve the disaster patterns of landslides that were triggered by historical earthquakes.

(4) It is suggested that the landslide distribution along the Anninghe fault zone should be considered in infrastructure planning and construction. In the Shimian-Xichang section, planned large-scale infrastructures should be more than 2 km away from the east branch of the Anninghe fault. In the Xichang-Dechang section of the Anninghe fault, planned large-scale infrastructures should be more than 1 km away from the Mopanshan-Jiuxitou fault zone. Planned infrastructures should avoid long distances that are parallel to the fault zone and cross the fault zone at large angles.

(5) This paper analyzes, from the perspective of the relationship between geological hazards and the fault zone, the landslide distribution and sliding mode controls along the Anninghe fault zone. In addition to the fact that the Anninghe fault zone contributes to the formation of landslides, other factors (e.g., topography, landforms, lithology, and groundwater) also play essential roles in predisposing portions of this area to landslides.

6 Conclusions

(1) At large scales, fault zones control the lithology distribution and tectonic stress field. At small scales, faults destroy the structure and integrity of slope rock masses and reduce their mechanical strength, which lead to stress concentrations or substantial reductions in local sections of slopes. Faults play a crucial role in the distributions of slope plastic zones and maximum shear strain, which are conducive to the formation and evolution of landslides.

(2) The influence and control of the Anninghe fault zone on the distribution of landslides exhibit

obvious segmentation characteristics. 80.3% of landslides are distributed within a 2-3 km distance from the east branch fault of Anninghe and the Hongmo fault zone in the section of Mianning County to Xichang City, and 83.5% of landslides are distributed within the Mopanshan-Jiuxitou fault influence zone.

(3) The fault zone controls the formation and evolution of gullies and the characteristics of the longitudinal gradient if the strike of the fault zone is basically the same or is close to the strike of a gully and provides erosional materials or uncovers materials that become part of debris flows. Unstable landslides often develop on both sides of the valley where the fault zone passes if the fault zone intersects the valley at a large angle. Unstable landslides provide abundant material for debris flows, which may even block gullies, which increases the destructive effects of debris flows.

(4) According to the field investigation and typical case analysis, four slide-controlling models are summarized on the basis of the creep deformation of the fault zone, e.g., the fault rupture zone rock mass directly constitutes a landslide, the fault controls the lateral boundary of the landslide, the fault controls the crown of the landslide, and the fault constitutes the toe of the landslide.

Acknowledgements

This research was supported by China Geological Survey Projects (Grant No. 20160272, 20211379), the Second Tibetan Plateau Scientific Expedition and Research Program (Grant No. 2019QZKK0904) and Sichuan Science and Technology Program of China (Grant No. 2020YFS0296).

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