## **ORIGINAL ARTICLE**





# Investigating the structure under the Pingting Terrace from the co-seismic surface rupture of the 2022 Guanshan earthquake

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## Abstract

On September 17th and 18th, 2022, shallow earthquakes with magnitudes of 6.6 (M<sub>L</sub>) and 6.8 (M<sub>L</sub>) occurred in the eastern Taiwan Longitudinal Valley, which marks the collision zone between the Philippine Sea plate and the Eurasian plate, and led to noticeable surface deformation and ruptures within 70 km. This study primarily focuses on the southernmost section of the rupture zone—the Pingting Terrace. Surface rupture locations and behaviors correspond to changes in topography, providing mutual confirmation that the deformation behavior of Pingting Terrace is complex. Based on the distribution of surface ruptures and topography changes, this study roughly divides the Pingting Terrace into northern and southern segments, using the central concave feature as a boundary. The Riedel shear model analysis results show that the principal shear directions in the northern and southern segments are N–S trending and azimuth 20°, respectively. The maximum principal stress orientations are around 135° for the northern and 155° for the southern segments. These findings align with the fault mechanical investigation of the Lichi Mélange in the northern Muken River area of the Pingting Terrace. This suggests spatial changes in shear zone orientations within the Lichi Mélange, which contribute to developing pressure ridges due to transpressional forces. As a result, the Pingting Terrace experiences rapid uplift, causing the Luliao River to migrate southward into the Beinan River, while the eastern Beinan River turns to the eastward edge of the Pingting Terrace.

## **Key points**

- 1. Co-seismic surface rupture analysis using Riedel shear model.
- 2. Flower structure of the Pingting Terrace.
- 3. Relationship between the River channel change and the tectonic activity.

Keywords 2022 Guanshan earthquake, Co-seismic surface rupture, Pingting Terrace, Lichi Mélange, Flower structure

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#### **1** Introduction

On September 17th and 18th, 2022, two shallow earthquakes occurred in Guanshan and Chihshang, measuring magnitudes 6.6 ( $M_L$ ) and 6.8 ( $M_L$ ), respectively (Fig. 1). The seismic events resulted in strong shaking observed from Guangfu to Guanshan, even extending to the Luye area, and were followed by thousands of aftershocks. Based on the seismic moment tensor solution and the distribution of aftershocks, as reported by the Central Weather Administration (CWA), these earthquakes were predominantly characterized by strike-slip motion along a fault striking 190° and dipping to the west, with the compression axis oriented along NW–SE (Fig. 1; data sourced from CWA Seismological Center's catalog, as of November 30, 2022). This seismogenic fault is consistent with the proposed Central Range Fault (Biq 1965; Hsu 1976a; Angelier et al. 2000; Shyu et al. 2005, 2006; Hsu 2019).

Large shallow earthquakes typically result in surface ruptures and co-seismic deformation. This deformation not only reflects the surface trace of the seismogenic fault but also provides valuable insights into the structural characteristics of the fault at depth, while also being influenced by pre-existing tectonic environments (e.g., King 1986; Lin et al. 2001, 2003, 2009a, b, 2011; Huang et al. 2016; Wen et al. 2017; Yen et al. 2019; Hsu et al.



Fig. 1 Maps of 2022 Guanshan- Chihshang Earthquake sequence and aftershocks (data from the earthquake catalog of Central Weather Administration and as of November 30, 2022)

2019). In the case of this specific earthquake event, the surface rupture and co-seismic deformation are widely distributed in the Longitudinal Valley, covering a distance of over 70 km from Hualien to Taitung. GPS and DInSAR data reveal co-seismic displacements, indicating that the Guanshan Earthquake led to surface deformation in the Chihshang-Luye area. The energy released by the Chihshang Earthquake primarily propagated northward, inducing surface deformation in the Rueisuei-Chihshang area (Tang et al. 2023). Besides the significant deformation near the epicenter, there is also evident deformation and severe rupture along the Yuli Fault and the Chihshang Fault. These observations indicate that existing active faults were crucial in controlling the co-seismic deformation during this earthquake, which occurred near the surface and triggered fault activity.

This study focuses mainly on the Pingting Terrace in the Luye area, Taitung, which is a river terrace characterized by significant tectonic activity. This region is particularly noteworthy due to the overlapping area of the Chihshang Fault and the Lichi Fault. Interestingly, to the north of the Pingting Terrace, the Beinan River initially follows the Longitudinal Valley Fault at the front of the Coastal Range. However, within the Pingting Terrace, the river takes an eastward shift, entering the hanging block of the Longitudinal Valley Fault, highlighting the unique tectonic activity of the Pingting Terrace. During the 2022 Guanshan Earthquakes, the Pingting Terrace exhibited extensive surface rupture, offering valuable insights into the activity characteristics of underground structures. Our objective is to investigate the influence of pre-existing active faults, specifically the Chihshang Fault and the Lichi Fault, on these surface ruptures. Through this research, we have a unique opportunity to observe how earthquake-induced stress affects pre-existing structures and to gain insights into the underlying structural and movement patterns beneath the Pingting Terrace by analyzing co-seismic surface ruptures.

Additionally, this study aims to explore the deformation mechanism of the Pingting Terrace. Our field investigations have revealed that the distribution of surface rupture areas extends not only along the existing active faults but also on the front and back edges of the terrace. Moreover, the fractures include both compressional and shear failure, suggesting a more complex deformation behavior than the previous models, necessitating a reevaluation of the structural model of the Pingting Terrace. We utilized the Riedel shear model to analyze the co-seismic rupture, which enabled us to consider both compressional and shear ruptures. The analysis results indicate that the Pingting Terrace is located at the bend of the left-lateral shear zone, exhibiting a distinctive pressure ridge resembling a flower-shaped structure. This, in turn, led to the rapid uplift of the Pingting Terrace, impacting the channel evolution of the Beinan River.

This research holds immense significance in the fields of seismology and tectonics, offering a valuable opportunity to explore the forming mechanisms and kinematics of co-seismic Riedel shear structures. By investigating the relationships between seismic events, pre-existing fault systems, and surface ruptures, we gain a better understanding of the intricate processes that shape the Earth's crust during earthquakes. The findings from studying the tectonic activity of the Pingting Terrace and the specific behavior exhibited during the 2022 Guanshan Earthquakes are crucial for advancing our comprehension of regional seismic hazards and improving risk assessments.

#### 2 Geological background

The 2022 Guanshan-Chihshang Earthquake occurred within the Longitudinal Valley, located at the collision boundary between the Philippine Sea Plate and the Eurasian Plate (Fig. 1a). Historical records indicate that numerous catastrophic earthquakes have occurred within the longitudinal valley, suggesting significant fault activity within. On the eastern side of the Longitudinal Valley, there is a prominent active fault known as the Longitudinal Valley Fault. This fault is well-exposed and exhibits distinct topographical features. It experiences frequent seismic activity and measurable deformation. Researchers have conducted extensive works on the Longitudinal Valley Fault over the past few decades (e.g., Lee et al. 2001, 2003; Hsu et al. 2003; Lin 2004; Kuo-Chen et al. 2004; Shyu et al. 2005, 2006). Seismic data reveals that the fault is a high-angle east-dipping reverse fault with a leftlateral component. Geodetic monitoring has indicated a velocity difference of about 30 mm/year across the fault during the inter-seismic period (1993-1999) relative to the Penghu-Baisha station, reflecting energy accumulation along the Longitudinal Valley Fault (Hsu et al. 2009). Based on geological conditions and fault activity characteristics, the fault can be divided into four segments from north to south: Lingding Fault, Rueisuei Fault, Chihshang Fault, and Lichi Fault (Lin et al. 2009a, b, 2021; Chen et al. 2008a). On the western side of the Longitudinal Valley lies the Central Range Fault (Biq 1965; Hsu 1976a; Angelier et al. 2000; Shyu et al. 2005, 2006; Chen et al. 2008b; Hsu 2019), which is also the causative fault for the 2022 Guanshan-Chihshang Earthquake. Previous research and recent seismic events have indicated that the Central Range Fault is a high-angle reverse fault dipping to the west, with a left-lateral component. It also exhibits clear segmentation characteristics, consisting of the Hualien-Rueisuei segment, Yuli-Chihshang segment, and Chihshang-Taitung segment (Wu et al. 2006; Chuang et al. 2014; Wen 2018; Kuo-Chen et al. 2019; Hsu 2019;

Huang and Wang 2022). The 2022 Guanshan-Chihshang Earthquake first occurred in the Chihshang-Taitung segment, followed by the Yuli-Rueisuei segment the next day (Hsu et al. 2023). It also triggered the Yuli Fault within the Longitudinal Valley, as well as the Chihshang Fault and Lichi Fault within the eastern side of the Longitudinal Valley (Lee et al. 2023).

The Pingting Terrace is located in the southern segment of the Longitudinal Valley, with the Luliao River to the south and the Beinan River to the east (Fig. 2a). From a topographical perspective, the Pingting Terrace exhibits two-floor terraces thus it's also referred to as the Ercengping ("two-floor terrace" in Chinese). Actually, it can be separated into the "Lower Terrace" and the "Higher Terrace" obviously (Fig. 2b). The eastern side is characterized by high and steep cliffs formed by erosion from the Beinan River, while the western side consists of the alluvial fan of the Luliao River. Beneath the Pingting Terrace primarily lies the Lichi Mélange, overlain by the river terrace conglomerates of the Luliao River and Beinan River (Tong et al. 2006; Chi 2007; Shyu et al. 2008). The Lichi Mélange is extensively distributed on the southwestern side of the Coastal Range and mainly comprises strongly sheared mudstone with occasional interbedded foreign rock fragments of varying lithologies (Hsu 1976b; Teng 1981; Chen 1991, 1997; Chang et al. 2000, 2001; Huang et al. 2008). In this area, the Longitudinal Valley Fault is divided into two widely separated fault systems with distinct characteristics: the Chihshang Fault and the Lichi Fault. Based on topographical features and surface geological surveys, these two faults trend approximately north-northeast and are reverse faults dipping to the east. The Lichi Fault passes through the Xinliang Terrace at the front edge of the Lower Terrace, while the Chihshang Fault location is situated on the western edge of the Higher Terrace (Fig. 2b). The inclination angle of the Lichi Fault is estimated to be around 70° based on drilling data from Xinliang (Chi 2007).

The Pingting Terrace can be subdivided into six terrace levels (Fig. 2c). The easternmost part of the Pingting Terrace is the T1 formed by erosion from the Beinan River. In the northern segment, the Lower Terrace of the Pingting Terrace is T2. However, the southern segment of the terraces is influenced by tectonic activity, allowing further division into T3 and T4. The Higher Terrace of the Pingting Terrace can be divided into T5 and T6 due to a lower valley in the middle (Fig. 2c; Shyu et al. 2008). Furthermore, extending southward from the Lower Terrace, a feature known as the Xinliang Lineament can be delineated. Obsequent fault-line scarp on both the Lower and Higher Terrace, indicating complex tectonic activity in the Pingting Terrace (Fig. 2c; Shen et al. 2006; Jiang 2007; Lin et al. 2009a, b; Jiang et al. 2012; National Taipei University of Technology 2011). According to GPS velocity data from 2001 to 2003, the Pingting Terrace is moving at an approximate rate of 28.6 mm/year in the northwest direction (ERPN station). There's a significant velocity difference on both sides of the fault (approximately 16.9 mm/year), suggesting a slight left-lateral oblique motion (Chuang et al. 2012). The MT-InSAR results from ALOS images taken between 2007 and 2010 show a reverse slip velocity of about 7 mm/year for the Lichi Fault (PTF1) in the LOS direction, while the Chihshang Fault (PTF2) of the Higher Terrace has a reverse activity rate of 20 mm/year in the LOS direction (Deffontaines et al. 2017). Considering the topographic features and variations in fault activity rates, it is believed proposed that the Lichi Fault (PTF1) is a creeping reverse fault with a gentler angle, whereas the Chihshang Fault (PTF2) has a steeper inclination angle but is locked at the surface, causing deep-seated activity to result in folding of the overlying strata.

Based on the comprehensive research presented above, the Pingting Terrace can be considered a structural terrace formed by two reverse fault systems. However, when considering high-resolution terrain data and the co-seismic surface rupture patterns and distribution range generated by the earthquake in the Pingting terrace (Fig. 2b), it becomes evident that the subsurface structure of the Pingting terrace may be more complex.

#### 3 Method and results

## 3.1 Investigations of surface ruptures and geomorphological analysis

The co-seismic surface rupture on the Pingting Terrace was primarily triggered by the earthquake event that occurred on September 17th, 2022. Field investigations indicate that the co-seismic surface rupture is predominantly aligned with the scarp of Lower Terrace and the Xinliang Terrace, which follow the path of the Lichi Fault.

(See figure on next page.)

**Fig. 2** a Geological Map of the Southern Longitudinal Valley (adapted after geological maps of Taiwan 1/50,000, Geological Survey and Mining Management Agency, MOEA 2018). The black box indicates the location of the Pingting Terrace. **b** Terrain Map and Rupture Distribution of the Pingting Terrace. The red lines indicate active faults, including the Chihshang Fault and the Lichi Fault. The yellow dots represent the surface rupture locations of the September 17th, 2022 earthquake. **c** Structural and Terrain Map of the Pingting Terrace. The red lines represent surface structural lines identified from high-resolution digital elevation data. The terrace subdivisions were modified after Shyu et al. 2008. The gray lines depict 10-m contour lines



Fig. 2 (See legend on previous page.)

Some ruptures are situated at the leading edge of the fault and above the scarp of Higher Terrace (corresponding to the location of the Chihshang Fault) and behind the terrace (as illustrated in Fig. 2b). The rupture pattern is primarily characterized by compression, with occasional lateral displacement. Our focus is analyzing the rupture pattern, complemented by topographic features, to explore subsurface tectonic activity beneath the Pingting Terrace. Considering the distinct geomorphic attributes in the northern and southern portions of the Pingting Terrace, as well as the differing structural patterns on the eastern and western sides, we have divided the study area into three districts: the northern segment, the southern segment, and the eastern side (as depicted in Fig. 2b).

Within the northern segment of the Pingting Terrace (see Fig. 3), the surface rupture is concentrated on the scarp and terraced surfaces of the Lower Terrace. Nonetheless, surface rupture or building damage can also be observed at the forefront of the Pingting Terrace and on the Higher Terrace. The dominant rupture pattern is characterized by compression texture, occasionally accompanied by lateral shearing (as shown in Fig. 3a). Along the access road at the northernmost part of the Pingting Terrace, it is evident that bridges have undergone uplift deformation due to compression (Fig. 3b), with a rupture direction of approximately 120°. Despite the absence of significant terrain variations at the leading edge of the Pingting Terrace, surface rupture is still apparent on roads and buildings. At the labeled location 'c' (Fig. 3c), an observable compressional ridge with a direction of about 240° can be seen, along with a leftslip fracture oriented at 220°. Further to the south, at Ercengping Bridge, a noticeable right-slip fracture with a direction of 060° is present, accompanied by approximately 30 cm of displacement (Fig. 3d). Along the roads of the Lower Terrace, a series of surface damages are observable, including left-slip fractures with compression textures at around 170° (Fig. 3e). Beneath the road, the retaining wall is visible as a thrusting with a rightlateral, the orientation is 170°, 70°W (Fig. 3f). Continuing southward of the Lower Terrace, a distinct reverse scarp terrain becomes evident. Alongside this reverse scarp, the road and landscaped features display compression textures with directions ranging from 040° to 070°, resulting in 20 cm of uplift on the western side. The rupture extends along the reverse scarp (Fig. 3g). Due to the slope effects on the Lower Terrace, intermittent subsidence phenomena can occur on the road surface. The fissures' orientations parallel the slope direction, roughly aligned north-south. Adjacent to the road, retaining walls also show displacements ranging from 4 to 15 cm due to the earthquake's impact, with both left-slip and right-slip fractures observable (Fig. 3h). Approaching the scarp of Lower Terrace, the road displays compression texture with a direction of 030° (Fig. 3i). On the Higher Terrace, surface rupture is relatively limited. Along the road of the Higher Terrace, thrusting rupture with an orientation of 130°, 30°S occurs (Fig. 3j). In the middle section of the Pingting Terrace, distinctive topographic features of small channels come into view. The drainage facilities within these channels exhibit characteristics of compression texture, with the cement at the bottom experiencing compression in a trend of 065° (Fig. 3k).

In the southern segment of the Pingting Terrace, the surface rupture appears to be more scattered (Fig. 4). Ruptures are concentrated at the forefront of the Xinliang Terrace, and Lower Terrace. However, no surface rupture is observed on the Higher Terrace (Fig. 4a). On the Lower Terrace surface, left-lateral ruptures are observable with 015° and 010° trends, resulting in a displacement of around 5 cm (Fig. 4b). On the road of the reverse scarp, a noticeable compression texture with a direction of 010° is present (Fig. 4c). On the road of the Xinliang Terrace, continuous variations of compression texture are evident, with directions ranging from 030° to 055°, rotating to 070°. On the ditch wall beside the road, thrusting with a left-slip fracture at 055°, 40°S is observable (Fig. 4d). As one moves eastward to the scarp slope of the Lower Terrace, the direction of compression texture changes to 355° (Fig. 4e). The rupture trend on Xinliang Terrace continues to extend southward. On the cement wall of the fields, reverse damage with an orientation of 175°, 23°E is observed, resulting in a vertical displacement of approximately 9 cm (Fig. 4f). On the road, a left-slip fracture with a direction of 040, accompanied by compression texture, is visible, extending into the interior of the adjacent factory (Fig. 4g). On the surface of the Lower Terrace, compression texture with an orientation of 065°, 45°N is observed beside the distinct arc-shaped scarp, with the rupture pattern aligning with the terrain features (Fig. 4h). South of the Xinliang Terrace, at the foot of the hill, the cistern in front of the building displays left-slip with compression texture in a trend of 050° (Fig. 4i). On the western side of the Xinliang Wetland, a series of compression textures are still evident on roads and drainage ditches, with directions ranging from 070° to 085° (Fig. 4j). A concave terrain is observable at the southernmost part of the Higher Terrace of the Pingting Terrace. On the adjacent road, a continuous north-south left-slip fracture can be observed, accompanied by the collapse of the road slope (Fig. 4k).

Although active fault traces do not traverse the eastern side of the Pingting Terrace, surface ruptures are still observable in the aftermath of this earthquake in Houhu and on the access road of the Beinan River (Fig. 5). On the northeastern side of the Higher Terrace,



**Fig. 3** Fracture pattern of the co-seismic surface ruptures in the northern segment of the west side of Pingting Terrace, as indicated in Fig. 2b. **a** Fracture pattern of the co-seismic surface ruptures on a 1 m resolution DEM. **b** The access road on the northern side and the bridge have undergone deformation due to compression, with fractures trending at about 120°. **c** At the edge of the terraces, the road and drainage ditches show compression ridges trending at 240°, and left-slip fractures trending at 220° with a displacement of about 5 cm. **d** The Ercengping Bridge on the front edge of the terraces shows a right-slip fracture trending at 060°, with a sliding displacement of about 30 cm. **e** At Road of Lower Terrace, a left-slip fracture with a trend of 170°. **f** A retaining wall shows a right-lateral reverse thrust fracture trending at 170°, 70°W. **g** On the reverse slope of the Lower Terrace with a western side uplift of about 20 cm, trending from 040° to 070° from the road. **h** On the road slope of the Lower Terrace, there is a subsidence with fractures trending at about 020°. The retaining wall at the roadside shows left-slip fractures ranging from about 4 to 15 cm. **i** On the scarp road of the Lower Terrace, compression texture with a trend of 030°. **j** The road on the Higher Terrace slope has a left-slip with compression fractures at 130°, 30°S trending. **k** At the edge of the Higher Terrace scarp, compression texture within the drainage channel, the fracture trend of 065°

a series of left-slip fractures are observable on the access road, with rupture directions ranging from 005° to 025° (Fig. 5b–d). Right-slip fractures with a direction of 145° can also be observed along the roadside, and surface damage is accompanied by an approximate 3 cm subsidence (Fig. 5e). At the northernmost part of the Higher



**Fig. 4** Fracture pattern of the co-seismic surface ruptures in the southern segment of the west side of Pingting Terrace, as indicated in Fig. 2b. **a** Fracture pattern of the co-seismic surface ruptures on a 1 m resolution DEM. **b** On the Lower Terrace, left-slip fractures with trends of 015° and 010°, resulting in a displacement of approximately 5 cm. **c** On the road of the reverse slope on the Lower Terrace, compression texture with a trend of 010°. **d** Next to the cliff road of Xinliang Terrace, the thrust with left-slip fractures with trends of 055°, 40°S on the canal wall. **e** Compression texture with a trend of 355° on the Lower Terrace scarp. **f** On the cement wall of the Xinliang terrace, thrust fractures with trends of 175°, 23°E, with a vertical displacement of about 9 cm. **g** On the road of the Xinliang terrace, left-slip fractures with a trend of 040°, accompanied by compressive destruction, extending to the adjacent interior of the factory. **h** A distinct arc-shaped reverse slope on the Lower Terrace with compression texture of trending 065°, 45°N. **i** Under the hill of the Xinliang terrace, left-slip with compression fractures of 050° trending. **j** In the Xinliang Wetland, a series of compression textures with trends ranging from 070° to 085°. **k** In the southern depression of the Higher Terrace, continuous N–S left-slip fractures, accompanied by the collapse of road slopes

Terrace, continuous compression texture is observed on the retaining walls along the road. Notably, these compression textures were not caused by this earthquake and were previously documented in existing investigation reports, demonstrating deformation of the retaining walls (Fig. 5f; Shyu et al. 2008; Jiang et al. 2012). At the back slope of the Pingting Terrace, drainage ditches and slope exhibit compression texture, with an orientation of 140°,



**Fig. 5** Fracture pattern of the co-seismic surface ruptures on the east side of Pingting Terrace, the site as indicated in Fig. 2b. **a** Fracture pattern of the co-seismic surface ruptures on a 1 m resolution DEM. **b**–**d** Along the flood prevention road, a series of left-slip displacements can be observed with a trend of 005° to 025°. **e** Adjacent to the access road on the eastern side of the terrace, a right-slip fracture with a trend of 145°, accompanied by approximately 3 cm of subsidence. **f** In the northernmost section of the Higher Terrace, fractures are generated by compression in the retaining wall (old). **g** On the back slope of the Pingting Terrace, there are reverse thrusts and compressions with trends of 140°, 50°S. **h**, **i** On the eastern access road, compression texture with a trend of 010°–030°

50°S (Fig. 5g). On the access road at the easternmost side, compression texture with directions ranging from 010° to 030° trends is observable on the cement road (Fig. 5h, i).

Through surface rupture investigations, it is evident that fracture slip patterns and distribution locations correspond to the topographic features of the Pingting Terrace (Fig. 6a). Compression structures accompanied by left-slip fractures are observable on the slope, while strike-slip damage systems can be seen on the step surface. The sole rupture on the western edge of the terrace lacks distinct topographic variation. We carried out three E-W trending cross profiles across the Pingting Terrace, one N–S trending profile along with longitudinal structural, and marked the surface rupture



Fig. 6 The distribution of the co-seismic surface ruptures and geomorphic features in Pingting Terraces. **a** Surface rupture distribution. The base map is drawn from 1 m resolution DEM. **b** Structural profile combining terrain cross-section of Pingting Terraces with surface rupture patterns

patterns at their respective positions on the profiles (Fig. 6b). The results demonstrate active recent tectonic processes within the Pingting Terrace. Aside from two east-dipping reverse fault systems with evident leftslip fractures, several west-dipping thrust faults are also apparent. Surface rupture observations suggest fault activities behind the Pingting Terrace (east side), along the slopes, and on the present river terraces, indicating potential newly developed structures. Two sets of east-moving back-thrust faults have formed on the Lower Terrace. The primary reverse fault on the Higher Terrace bifurcates into two branches, resulting in the emergence of secondary terraces. In the southern segment of the Pingting Terrace, fault activity is more pronounced at the forefront of the Xinliang Terrace than the Lower Terrace, while surface ruptures are nearly absent on the Higher Terrace. Left-slip fracture can be observed on the northern and southern ends of the Higher Terrace, consistent with tectonic. It can be inferred that the Houhu lineament of the Pingting Terrace features a prominent left-lateral and back-thrust fault system. From the longitudinal profile (profile IV), a depression in the middle of the Pingting Terrace is evident, likely formed by an ancient river channel. Considering the compression structures at the northern and southern ends of the terrace, combined with the topographic characteristics, it is deduced that the reverse system bends to encompass the northern and southern ends of the Pingting Terrace (Fig. 6b).

#### 3.2 Riedel shear structure analysis

After conducting on-Site investigations into the direction, patterns, and distribution of surface ruptures, it becomes evident that the tectonic activity within the Pingting Terrace is not solely attributed to simple reverse fault systems. Strike-slip components are also observed in the fault activity. Previous studies have also indicated the presence of strike-slip components within the Pingting Terrace based on topographic features and geodetic monitoring (Shyu et al. 2008; Chuang et al. 2012). Accordingly, our research team employed the Riedel shear structures model to analyze the geometric relationships, regional stress, and principal shear directions of the surface ruptures within the Pingting Terrace. The concept of Riedel shear structures originated from clay-cake deformation experiments conducted by Cloos (1928) and Riedel (1929). In previous studies, Riedel shear structures have been identified across various scales of strike-slip fault zones, including map-scale, outcrop-scale, and even micro-scale (e.g., Bestmann et al. 2000; Davis et al. 2000; Ahlgren 2001; Lin et al. 2001; Angelier and Bergerat 2002; Katz et al. 2004; Scholz et al. 2010; Zhang et al. 2010). Geometrically, Riedel shear structures consist of a series of fractures, encompassing

compressional textures, R and R' conjugate shear structures, tension fractures, and P shear structures. The orientations of these structures are correlated with the trend of the principal displacement zone (PDZ) at specific angles. The conjugate R and R' shear structures are oriented at  $\Phi/2$  and 90° –  $\Phi/2$  with respect to the principal shear direction, respectively, where  $\Phi$  represents the internal friction angle of the fractured rock or structure (Riedel 1929; Tchalenko 1968; Bartlett et al. 1981; Christie-Blick and Biddle 1985; Woodcock and Schubert 1994; Davis et al. 2000; Qu 2019). Tension fractures and compressional structures are oriented at 45° to the principal shear direction, perpendicular to each other. Both R and P shear structures are symmetrical and share the same sliding direction with the PDZ (Fig. 7a). The angular relationships among various fractures are adjusted in actual shear zones due to geological conditions, structural considerations, and strain rates during faulting (Katz et al. 2004). While artificial structures and varying mechanical properties of pavements could potentially influence the angles of shear structures, this study conducts a comprehensive analysis of diverse rupture patterns backed by a substantial amount of measured data.

As a result, the analysis of co-seismic rupture data collected from the surface can accurately represent the nature of fault activity within the Pingting Terrace. Based on the survey results, a total of 75 surface rupture data points were collected across the study area. The dominant rupture types within the Pingting Terrace feature compressional structures, left-lateral ruptures, and occasional right-lateral ruptures. Upon considering the correlations among these rupture types, it is inferred that left-lateral ruptures in this area correspond more closely to P-structures rather than R-structures.

Due to the divergent terrain and structural characteristics between the northern and southern segments of the study area, separate statistical analyses were carried out. The outcomes suggest that in this earthquakeinduced surface ruptures, the northern segment displays larger slip and compression amounts, broader rupture distribution, and greater consistency in rupture orientations. Conversely, the southern segment witnesses a concentration of ruptures primarily on the newly developed Xinliang Terrace, characterized by relatively smaller slip amounts and greater variation in rupture orientations (Fig. 7b, c). Applying the Riedel shear model analysis method to these segments yields the principal PDZ and maximum principal stress ( $\sigma_1$ ) directions for each region, as depicted in Fig. 7. In the northern segment, the PDZ direction aligns closely with the N–S trend (azimuth 0°), whereas the  $\sigma_1$  direction is oriented NW–SE. In contrast, in the further southern segments, the PDZ direction rotates to a near NNE-SSW trend (azimuth 20°), with the azimuth of the  $\sigma_1$  direction at 155° (Fig. 7d).

#### 4 Discussion

## 4.1 Investigation of Riedel shear structures in the Pingting terrace

In natural shear zone systems, specific angular relationships between individual shear structural features are observed, particularly the angles between R, R', and P structures, as well as their angles with the main slip zone. These angular relationships are influenced by various factors, such as regional geological conditions, pre-existing structures, rock strength (expressed as the coefficient of internal friction), strain rate during fault activity, and stress state (Dresen 1991; Ahlgren 2001; Lin and Nishikawa 2011).

Based on the research findings, the shear structures within the Pingting Terrace are identified as R' and P structures. The angle between the P structure and the principal displacement zone (PDZ) can provide insights into the local bedrock characteristics. In both the northern and southern sections, the angles between P structures and the PDZ are approximately 20°, implying an inferred coefficient of internal friction angle of around 40° for the underlying rocks. According to previous survey data, the footwall of the Pingting Terrace is composed of conglomerate alluvium, and the hanging wall is the Lichi Mélange with an overlying conglomerate layer (Tong et al. 2006; Chi 2007). Additionally, our oN-Site investigation has confirmed that the shallow layer of the Pingting Terrace is primarily covered with conglomerates. Previous studies suggest that the coefficient of internal friction angle for conglomerates is approximately 35°-40° (Barton and Choubey 1977; Lin et al. 2014). The friction angle for mudstone is around 26° (Spears and Taylor 1972; Taylor and Spears 1981). After weathering, the friction angle can decrease to 20° (Skempton 1970). When the mechanical properties of Lichi Mélange contain a moisture content exceeding 10%, the friction angle is approximately 10°-18° (Fang 2002). Based on this information, it is inferred that the shallow conglomerate influences the surface rupture characteristics in the region.

In this study, during the statistical analysis of shear structural features, not only the orientations of R' and P shear structures but also the orientations of compression structures are considered. This approach aims to mitigate factors that may introduce angular errors into the analysis. This seismic surface rupture analysis is believed to effectively reveal the activity characteristics of the faults beneath the Pingting Terrace by utilizing a substantial amount of measured data.



**Fig. 7** Riedel shear analysis results of the Pingting Terrace. **a** Geometrical Characteristics of Riedel Shear Model Fractures. **b** Further differentiation into northern and southern segments based on the terrain structural features and surface rupture trends of the Pingting Terrace. **c** Statistical chart of rupture directions for the northern and southern segments of the Pingting Terrace. **d** Analysis results of Riedel shear for the northern and southern segments of the Pingting Terrace.

#### 4.2 The stress in Lichi Mélange

The outcomes of the Riedel shear model analysis reveal the orientations of maximum principal stresses within the region: the northern segment aligns with an NW-SE direction (135°), while the southern segment is oriented at 155° (Fig. 7d). The change in stress field orientation may be attributed to the geometry of the fault. According to previous studies, stress deflection can occur due to lateral density/strength contrasts, flexural stresses, or the presence of geological structures such as faults (Sonder 1990; Bell and McCallum 1990; Zoback 1992, 2007; Yale et al. 1994; Zoback and Richardson 1996; Kastrup et al. 2004; Yaghoubi et al. 2023) and salt diapirs (Dusseault et al. 2004). When a fault is present, it acts as a stress guide, influencing the orientation and magnitude of stress in its vicinity. The stress state within the Pingting Terrace can be further compared with the fault activity characteristics observed within the Lichi Mélange. Chang et al. (2001) conducted comprehensive field investigations along the Muken River on the northern side of the Pingting Terrace (refer to Fig. 2a for the Muken River's location). The Lichi Mélange within the Muken River is composed of intensely sheared mudstone. By extensively measuring the slickenside information from fault surfaces, it becomes possible to deduce the maximum principal stress direction within the Lichi Mélange. Through segmented statistical analysis, the variability of the maximum principal stress is found to range between 135° and 170°. In addition to measuring the reverse displacement components, many strike-slip components are also measured. This indicates that the shear zones and stress conditions within the Lichi Mélange are intricate and encompass both strike-slip and thrust components, and also confirms that the fault strike can be changed. The stress directions recorded in the field align with the phenomenon of maximum principal stress as observed in the co-seismic surface rupture analysis conducted in this study.

#### 4.3 The flower structure in Lichi Mélange

Previous research has proposed that the Pingting Terrace is a tectonic terrace formed by two faults, the Chihshang Fault and Lichi Fault, both exhibit characteristics of reverse faults with a left-lateral component (Shyu et al. 2008 and Chuang et al. 2012). However, in the course of mountain building, it is plausible that the entire fault zone does not consistently move in a fixed direction at the same rate. Uplift and left-lateral movements occasionally dominate in different scenarios, as discerned from the slickensides recorded in the Lichi Mélange (Chang et al. 2001). Regardless of high-resolution topographic data, it has become apparent that the Pingting Terrace hosts many intricate structural linear features. Furthermore, examining co-seismic surface rupture resulting from the 2022 Guanshan earthquake has revealed the presence of multiple strike-slip fracture systems within the Pingting Terrace. The compression texture systems are distributed along the frontal edge of the terrace and behind the terrace. This suggests that the existing structural models no longer adequately account for the complete deformation behavior of the Pingting Terrace.

Considering the terrain, structural patterns, and surface ruptures in the Pingting Terrace, it can be classified into two distinct structural units: the northern and southern segments. The results of the Riedel shear model analysis of the co-seismic surface rupture unveil that the primary shear zone in the northern segment trends in a north-south direction, whereas in the southern segment, it alters its direction to approximately 020° (Fig. 7d). In strike-slip fault zones, the stress state and geometry will change along the fault zone when a fault undergoes bending. If the fault's directional change introduces a significant vertical stress component, it can induce the uplift of a central block, giving rise to flower-like pop-up structures (Woodcock and Fischer 1986; Harding 1985, 1990; Hinsch et al. 2005; Dewey et al. 1998; Davis et al. 1996). Positioned within a left-lateral fault system, as the fault's trend curves to the left, a transpressive regime emerges at the center, forming flower structures and resulting in rapid uplift of the Pingting Terrace (Fig. 8). In accordance with the flower structure model, signs of reverse fault compression deformation are noticeable on the eastern and western sides of the Pingting Terrace (Figs. 3, 4, 5). Moreover, within the terraces, multiple sets of reverse faults and backthrust systems can be observed (Figs. 3, 4). In the middle of the terraces, there is clear evidence of left-slip fractures (Fig. 5).

The phenomenon of strike-slip fault bending appears to align with the distinctions in trend between the Chihshang Fault's southernmost segment and the Lichi Fault's northernmost segment. The Chihshang Fault and Lichi Fault are developed within the Lichi Mélange (Lin et al. 2009a, b) and constitute the primary shear zones. Upon their individual developments, they intersect within the Pingting Terrace. The divergence in fault trend at this intersection forces the Pingting Terrace to a transpressional regime, fostering the formation of flower structures. This observation also corresponds to the fact that the Longitudinal Valley Fault in this region bifurcates into two widely separated fault systems exhibiting distinct characteristics.

#### 4.4 The diversion of Luliao and the Beinan rivers

The Pingting Terrace is adjacent to the alluvial fans of the Luliao River and the Beinan River. The terrace surface consists of riverbed gravel, indicating that sediment is



Fig. 8 The underground structural model of the Pingting Terrace. Based on the analysis results of the Riedel shear model, it is inferred that the Pingting Terrace is a flower structure formed by the turning of a strike-slip fault

transported and deposited by the Luliao or Beinan Rivers. Based on previous dating data, the deposition age is estimated to be around 1530-1690 years ago (Shyu et al. 2008). The Luliao River alluvial fan has a radius of around 5.8 km and reaches a height of 140 m at its highest point. It extends toward the western base of the Coastal Range. Considering the present position of the Luliao River, the alluvial fan has an asymmetrical shape with a larger northern area and a narrower southern section (Kou et al. 1985; Chang et al. 1994). To the north of the Pingting Terrace, the Beinan River originally followed the Longitudinal Valley Fault which is at the frontal of the Coastal Range. However, within the Pingting Terrace, the Beinan River shifts to the east and enters the hanging block of the Longitudinal Valley Fault. This river diversion led to the rapid formation of a new riverbed (Shyu et al. 2008).

Observing the topography of the Pingting Terrace, a relatively lower terrace is visible above the middle of the Higher Terrace. This lower terrace may correspond to an ancient riverbed of the Luliao River, potentially formed and carved before the terrace uplift. The course change of the Luliao River after the terrace uplift left behind a depression atop the terrace. Previous researchers have identified traces of ancient water flow heading southeast in the southern part of the Higher Terrace of the Pingting Terrace (Shyu et al. 2008). Furthermore, the narrowest segment area of this terrace aligns with the axis of an anticline, indicating that the structural activity of

the Pingting Terrace influenced the ancient water flow. Additionally, the growth rate of the anticline surpassed the rate of incision by the small water channel. A geomorphologic evolution model of this area is proposed in Fig. 9.

These observations present an evolutionary process of the Luliao River, Beinan River, and Pingting Terrace (Fig. 9). In the initial stage (Stage I), before the formation of the Pingting Terrace, the terrace apex was situated at the tail end of the Luliao River alluvial fan. The fault was active along the Coastal Range, and during this period, the Beinan River followed the fault (Fig. 9a). In stage II, the Pingting Terrace experienced an uplift due to the bending of the strike-slip fault. During this phase, the Luliao River continued to flow across the terrace, but the development of an anticline caused the river to gradually narrow. The Beinan River started to shift eastward due to the terrace uplift (Fig. 9b). As the terrace elevation continued to rise in stage III, the Luliao River altered its course to the south, expanding the Luliao River alluvial fan. The Beinan River also curved increasingly due to the terrace uplift (Fig. 9c). Approaching the recent stage (Stage IV), the Pingting Terrace displayed a dual-level terrace feature, and ongoing fault activity contributed to the formation of the Xinliang Terrace at the terrace's leading edge. The Luliao River persisted in its southern course change, resulting in the wide-narrow distribution of the Luliao River alluvial fan. The Beinan River meandered closer to the Coastal Range and established



**Fig. 9** Illustrations of the evolution of Pingting Terrace, Luliao River, and Beinan River over time. **a** In the early stages, almost 1600 years ago, Pingting Terrace was located at the toe of the alluvial fan of the Luliao River, and the faults were developed along the front of the Coastal Range. **b** Due to the overlapping of two faults with different strikes, the Pingting Terrace began to uplift, consequently influencing the course of the Beinan River, which changed direction. The Luliao River, however, maintains its course across the terrace, leaving behind discernible remnants of its past path. **c** The Pingting Terrace continued to uplift, causing the Luliao River to divert to the south, the alluvial fan to extend southward, and the Beinan River to curve even more. **d** The Pingting Terrace developed into a two-tiered terrace feature, with the Beinan River forming a new floodplain within the curved region, and the Luliao River continuing its southward course, merging with the Beinan River

new accumulation terraces behind the Pingting Terrace (Fig. 9d).

### **5** Conclusions

Through the analysis of co-seismic surface ruptures caused by the 2022 Guanshan Earthquake in the Pingting Terrace area, the following conclusions can be derived:

1. The co-seismic surface ruptures brought about by the 2022 Guanshan Earthquake correspond to the topo-

graphic features of the Pingting Terrace, thereby confirming the connection between surface ruptures and underlying structures.

2. Co-seismic surface ruptures within the Pingting Terrace encompass compression texture, left-slip, and right-slip fractures. The Riedel shear structure analysis indicates the presence of P structures, R' structures, and compressional structures in these surface ruptures. According to the geometric relationship between the fractures, it can be deduced that a principal displacement zone in the N–S orientation (azimuth 0°) on the northern segment and approximately 020° on the southern segment.

- 3. In the Pingting Terrace, the angle between the P structure and the principal displacement zone is approximately 20°. This angle can be inferred that the internal friction angle of the terrace material is about 40°, reflecting that the surface rupture characteristics are affected by the conglomerate in the shallow layer.
- 4. The maximum horizontal stress orientations from the co-seismic surface rupture analysis are approximately 135° for the northern segment and 155° for the southern segment. These findings align with the fault inversion results of the Lichi Mélange in Muken River near the northern side of Pingting Terrace.
- 5. The Riedel shear model analysis shows that the Pingting Terrace rests upon a bent left-lateral fault system. As this fault system undergoes directional changes, a transpressive environment characterized by lateral compression emerges, resulting in the development of a flower structure and the swift uplift of the Pingting Terrace.
- 6. The rapid uplift of the Pingting Terrace plays a pivotal role in the eastward deviation of the Beinan River, leading to the relocation of the Luliao River's channel and forming an alluvial fan wider in the north and narrower in the south.

Our results show that the co-seismic surface rupture analysis of this earthquake can clearly reflect the tectonic activity of the Pingting Terrace. When the shear zone undergoes bending within the Lichi Mélange, transpressive stress at these bends can lead to the formation of pressure ridge structures. Additionally, the structural evolution of the Pingting Terrace has played a pivotal role in altering the courses of both the Beinan and Luliao Rivers.

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#### Author contributions

YH: Primary investigation work, compilation, and analysis of field data, structural model interpretation, and article writing. CC: Structural model interpretation, article content discussion, and proofreading assistance. IY: Assistance in field investigation work and participation in discussions. SH: Assistance in field investigation work and participation in discussions. JY: Organization of the field investigation team, assistance in fieldwork, and provision of suggestions.

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#### Data availability

This study is primarily based on field investigations, with the majority of data consisting of survey photographs. Additionally, structural data have been

annotated on the images. There is no geophysical observation data available to provide.

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