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Yue-Gau Chen, Wen-Shan Chen, Yuan Wang, Po-Wen Lo, Tsung-Kwei Liu and Jian-Cheng Lee

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Geomorphic evidence for prior earthquakes: Lessons from the 1999 Chichi earthquake in central Taiwan

Yue-Gau Chen*
Wen-Shan Chen
Yuan Wang
Po-Wen Lo
Tsung-Kwei Liu
Department of Geosciences, National Taiwan University, 245 Choushan Road, Taipei 106, Taiwan, Republic of China
Jian-Cheng Lee Institute of Earth Science, Academia Sinica, P.O. Box 1-55, Nankang, Taipei, Taiwan, Republic of China

ABSTRACT

The September 21, 1999, M_w 7.6 Chichi earthquake destroyed several thousand buildings and caused more than 2000 fatalities in central Taiwan. The earthquake occurred along the Chelungpu fault, a thrust fault on the western flank of the Taiwan fold-and-thrust belt. The surface rupture was more than 90 km long, and vertical displacements ranged from 3 to 8 m. Although pre-existing scarps were identified along the Chelungpu fault, the fault had previously been categorized as a less important active fault, owing to the lack of geochronologic evidence and the failure to recognize fault-related geomorphic features. Identifying geomorphic features at active faults in Taiwan will permit the delineation of future surface ruptures and the determination of past magnitudes of past earthquakes, thus contributing to hazard assessment.

Keywords: earthquake, rupture, faults, fault scarps, terraces.

INTRODUCTION

The 1999 Chichi earthquake is one of the largest-magnitude reverse-slip events to have occurred in Asia during the twentieth century; its rupture length is surpassed only by the 1932 rupture along the Chang-Ma fault in northern China (Peltzer et al., 1988). The Chichi earthquake occurred in a densely populated region of central western Taiwan, where seismological and geodetic instrumentation is also relatively dense. Abundant geologic observations of surface ruptures and excellent geomorphic strain markers provide a unique opportunity to examine the prehistoric earthquake history of the Chelungpu fault. Moreover, the 1999 earthquake has raised fundamental questions about the recurrence of reverse-slip earthquakes in Taiwan. Prior to the 1999 Chichi earthquake, the Chelungpu fault was not clearly understood as a coseismic active fault. On geologic maps, the fault line was represented by a dashed line that connected limited outcrops (Chang, 1971; Chinese Petroleum Corporation, 1982a, 1982b). This paper presents geomorphic evidence for past surface ruptures along the Chelungpu fault. Documentation of prehistoric ruptures on this and other active faults and folds will help determine the size and frequency of earthquakes on thrust faults in Taiwan.

Active Tectonics

Taiwan is located at an active plate boundary between the Eurasian continent and the Philippine Sea plate, where an arc-continent collision has been ongoing since the late Miocene (Ho, 1988; Teng, 1987, 1990). The arc-continent collision has produced a fold-and-thrust belt with uplift rates ranging from a few to several tens of millimeters per year (Chen, 1984; Peng et al., 1977). Recent Global Positioning System data also demonstrate that the entire island is moving westward with respect to the Eurasian continental margin at ~10–12 mm/yr (Yu et al., 1999). In response to the deformation, a series of east-dipping thrust faults, the ages of which decrease to the west, has developed at the plate margin (Ho, 1988; Suppe, 1981, 1983). The Chelungpu fault, reactivated by the 1999 Chichi earthquake, is exposed immediately east of the frontal thrust fault that is marked by the concealed Changhua fault in central Taiwan (Fig. 1). Prior to the 1999 earthquake, the Changhau and Chelungpu faults were categorized as less important active faults (Chang, 1971; Bonilla, 1975, 1977; Hsu and Chang, 1979; Chang et al., 1998). One previous earthquake (M_L = 6.0 in 1917) has been tentatively attributed to the Chelungpu fault (Wu, 1978). A few recent geologic investigations indicate stream terrace offsets that may have resulted from Holocene fault movement, but these studies lacked age control (Yang, 1997; Chang et al., 1998). Not only was the Chelungpu fault's seismic history unknown, but its trace was also uncertain before the 1999 earthquake, because fault-associated geomorphic features had been overlooked.

1999 SURFACE RUPTURE

The surface rupture caused by the 1999 earthquake is complex and multisegmented. The surface rupture is more than 90 km long and generally follows the pre-existing Chelungpu fault trace (Ma et al., 1999). Along the northern segment, from Taichung City northward, the surface rupture does not coincide with the mapped Chelungpu fault (Fig. 1). To the east of Taichung City, the rupture continues to strike generally north, but turns northeastward and finally eastward at the northeast termination of the rupture (Fig. 1). It splays into a few disseminated branches, the maximum vertical displacement of which reaches 7–8 m at the bend near the city of Shihkang (Fig. 1). From Taichung City southward, the surface rupture trends north and generally follows the previously mapped trace of the Chelungpu fault (Fig. 1). Here, rupture is characterized by a single fault trace with left-lateral movement and an average vertical displacement of ~3 m. South of Tsaotun, the rupture closely follows the trace of the Chelungpu fault, with average vertical displacement of 2–3 m. Minor surface ruptures with offsets were documented near the towns of Tsaotun and Chushan.

Except for the southernmost and northernmost parts of the surface rupture, the 1999 surface rupture closely follows the mountain front (Fig. 1). Where it cuts through river valleys, the rupture follows the base of stream terraces. We focus on the relationships between the 1999 surface rupture and prior earthquake offsets, determined by stream-terrace scarps as offset markers.

TECTONIC GEOMORPHOLOGY

Relationships between active faulting and the offset of stream terraces have been successful for identifying active faults (Allen, 1975; Sieh and Jahns, 1984). This paper documents the coseismic offsets and evaluates the paleoevents at three sites, where stream terraces are well developed along the Chelungpu fault. Site 1 is near the city of Shihkang, where the surface rupture cut through a hill front in the south, as well as the active flood plain of the Tachia River in the north (Fig. 2), forming a spectacular waterfall. Here, the rupture deviates from a north trend to follow the previously mapped Chelungpu fault northeastward (Fig. 1). The hanging wall of the Chelungpu fault consists of

*E-mail: ygchen@ccms.ntu.edu.tw.

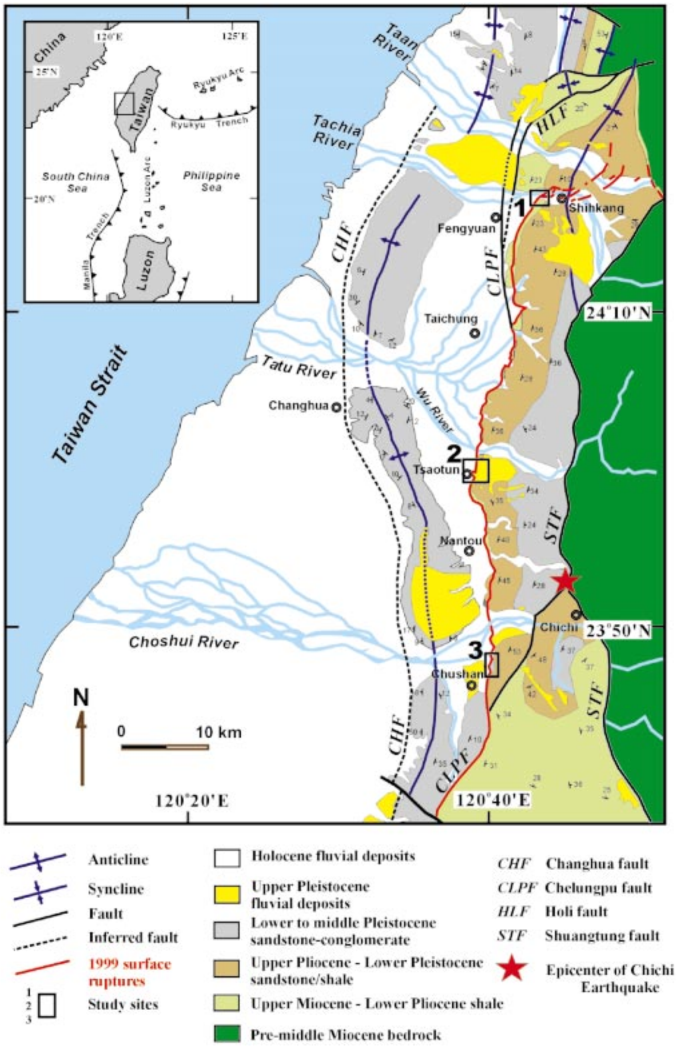


Figure 1. Geologic map of west-central Taiwan. Red line marks surface rupture associated with 1999 Chichi earthquake. Note that northern part of surface rupture cuts through hanging wall of pre-existing Chelungpu fault, and west of Shikang rupture is characterized by multiple discontinuous segments.

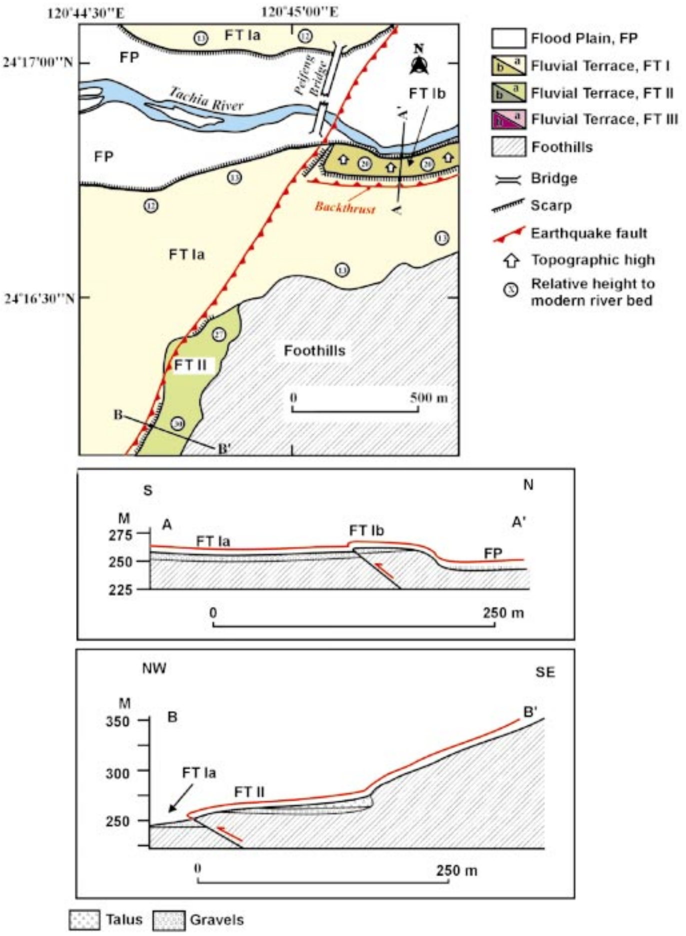


Figure 2. To east of city of Shihkang, three levels of strath terraces are identified as FT Ia, FT Ib, and FT II. Terrace 1a represents most extensive terrace level. Scarp that bounds FT II coincides with 1999 surface rupture. FT Ib scarps also coincide with 1999 rupture and backthrust fault that also broke in 1999. All relative heights labeled in map were measured before Chichi earthquake. Red lines on cross sections represent postearthquake topography.

Pliocene mudstone with intercalated sandstone, and the footwall consists of thick Pleistocene-Holocene gravel (Meng, 1963). The fault dips to the east, at ~35° with a vertical displacement of ~6.5 m. Uplift along the hanging wall created a waterfall that quickly cut down to form a new strath terrace (or rock-floored terrace of Ahnert, 1996, Fig. 2). To the south, the surface rupture is close to a pre-existing scarp that cuts fluvial terraces FT Ib and FT II, with a cumulative scarp height of 5–6 m. During the 1999 earthquake, FT Ib was further offset ~3 m by a minor backthrust along its southern edge (A–A′ in Fig. 2). Pre-existing fault scarps that offset FT Ib and II are the consequence of past earthquakes along the Chelungpu fault. If the 1999 offset of 5–6 m is assumed to be at the Tachia River location, the 14–17 m scarp between terrace FT Ia and FT II suggests the occurrence of at least three prior events. The 7 m scarp across the backthrust suggests the occurrence of at least two prior events.

Site 2 is located immediately east of the city of Tsaotun, where the surface rupture cuts the westward-flowing Ailiao Stream. Although the stream terraces had been documented previously (Lin, 1957; Shih et al., 1985), our work after the 1999 earthquake suggests the presence of four fluvial terraces (FT Ia, FT Ib, FT IIa, FT IIb), as shown in Figure 3. The four strath terraces are 8, 15, 20, and 36 m in height above the present Ailiao Stream bed. The western scarps that cut the terraces are all oriented north-south, perpendicular to the general direction of the east-west–oriented stream, suggesting that the scarps are tectonic features and not stream-terrace risers. In addition, the 1999 surface ruptures are located along the toe of the pre-existing scarps that face westward (FT Ia, FT Ib, and FT IIb in Fig. 3). To the south of the Ailiao Stream, the 1999 surface rupture branches into two strands. These two strands offset FT Ib and FT Ia. FT Ib is ~8 m higher than the modern Tsaotun flood plain and FT Ia is ~7 m higher than FT Ib. Although the highest terrace, FT IIa, was not cut by the 1999 rupture (Fig. 3), its western edge has been identified as a fault trace on the basis of outcrop investigation along the Ailiao Stream. This old fault trace was active before development of FT Ia and was offset 36–38 m in prior earthquakes (A–A′ in Fig. 3). Because the vertical displacement along the 1999 surface rupture is ~3–4 m, the elevation differences of 8 and 15 m from the Tsaotun flood plain to FT Ib and FT Ia may suggest the occurrence of 2–3 and 4–5 prior events, respectively, on the present trace. Furthermore, the 35–37 m offset of FT IIa corresponds to as many as 10 events. Some prior earthquakes occurred to the west of the 1999 surface rupture.

Site 3 is located north of Chushan along the Tungpuna Stream, a tributary of the Choshuichi River (Fig. 1). Here, a series of five stream terraces is exposed (FT Ia, FT Ib, FT II, FT IIIa, and FT IIIb in Fig. 4), wherein thin gravel beds unconformably overlie folded bedrock. The 1999 surface rupture extends along the base of the west-facing

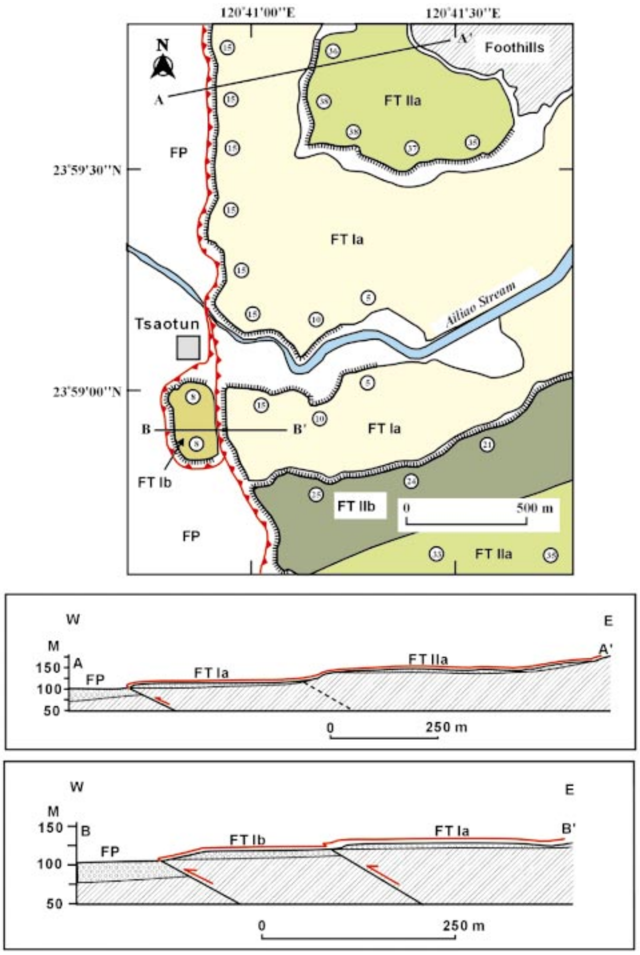


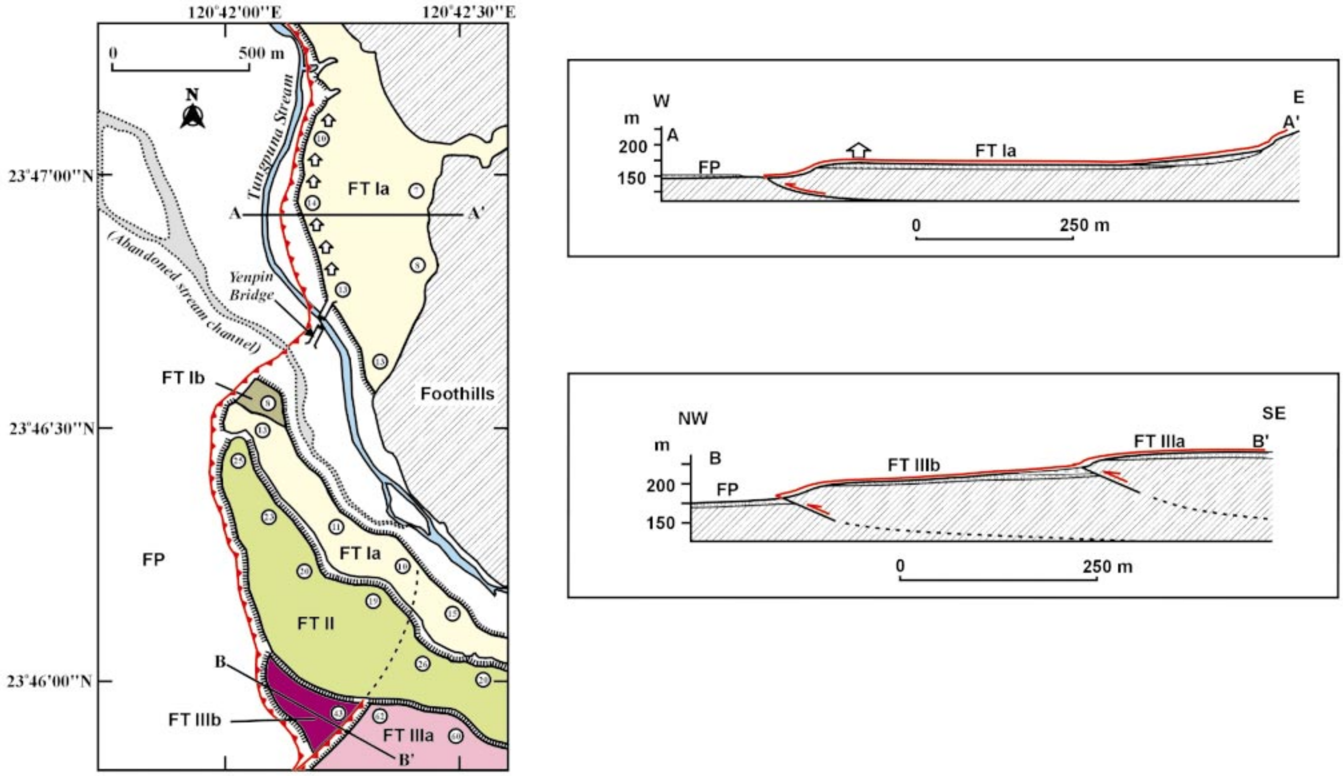
Figure 3. At city of Tsaotun, rupture extends along pre-existing scarps of FT Ia and FT Ib, which face west. Lowest relative height of FT Ib indicates that it is most recent scarp. No significant surface rupture was detected along scarp of FT II. For explanations, see Figure 2.

terrace scarps and corresponds to the previously mapped trace of the Chelungpu fault. An offset of ~3 m was produced along the thrust fault during the 1999 earthquake. Numerous strath terraces were formed by episodic displacement on the Chelungpu fault. In addition, the FT Ia (see A–A′ in Fig. 4) was tilted slightly southwestward, indicating a rotational component to the active deformation. If the slip during the 1999 earthquake is assumed to have been characteristic, the 43 m vertical offset between the FT IIIb and the modern flood plain suggests that more than 10 prior earthquakes have occurred on the trace of the 1999 surface rupture. Although a small northeast-running branch was also found along the base of FT IIIa (B–B′ in Fig. 4), no observable offset was found on lower terraces. Perhaps distributed deformation or site-specific ground shaking caused the concentrated property damage along the line of extension.

DISCUSSION AND CONCLUSIONS

Traditional geologic techniques, such as determining surface and subsurface bedrock geology by means of relative dating, have been used to document and classify active faults in Taiwan into three classes: class 1, class 2, and suspect active faults (Chang et al., 1998). Faults that are categorized as class 1 are those with historic ruptures (i.e.,

Figure 4. Map showing eastern area of Chushan. Scarps facing west coincide with 1999 surface rupture. Decrease in relative height from surface rupture eastward and terraces on southern stream bank developing northeastward indicate rotation on hanging wall. Eastward migration of stream channels is consistent with regional-scale tilting. For explanations, see Figure 2.



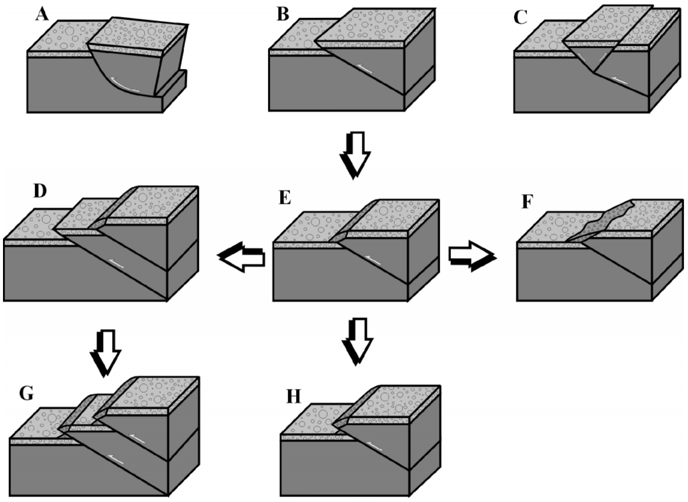


Figure 5. Block diagrams illustrating evolution of river-terrace deformation caused by coseismic offset. A–C: Fault scarp forms parallel to fault-line trace. D–E: During period of seismic quiescence, scarp will be modified and scarp-derived colluvium will be deposited adjacent to fault scarp. F: During long periods of quiescence, fault-line scarp will retreat substantially and become irregular. If recurrence interval is sufficiently short, fault-line scarp will be well preserved.

Meishan in 1906, Tuntzechiao and Shihtan in 1935, Hsinhua in 1946, and other earthquakes listed in Chang et al., 1998) or faults younger than 10 ka. The Chelungpu fault was not categorized as a class 1 fault because geomorphic criteria were not considered during the classification of the fault, despite the fact that its hanging wall overrides the youngest stream terrace (Yang, 1997).

It was not until after the 1999 Chichi earthquake that the significance of older fault scarps that flank numerous river terraces was recognized. Our work since the 1999 earthquake indicates that the modern stream channels were offset by as much as 3–8 m. The existence of a flight of stream terraces indicates that the flood plains have been repeatedly disrupted by fault offsets in the past. By analogy, it is almost certain that similar flights of terraces, common in western Taiwan, were formed by episodic faulting in the past. We have not been able to reconstruct the entire deformation history because of insufficient age data for the uplifted terraces. Nevertheless, our observations allow us to propose the following qualitative model for the evolution of river-terrace deformation in Taiwan (Fig. 5). The initial terraces form by coseismic vertical offsets along thrust (Fig. 5, A and B) and associated backthrust (Fig. 5C) faults. Tilted terrace surfaces form over listric faults (Fig. 5A). Fault scarps are well preserved when the earthquake recurrence interval is short enough, as is the case with the Chelungpu fault (Fig. 5, D and E). Substantial degradation of the scarp occurs during long periods of fault dormancy (Fig. 5F).

Geomorphic features are also useful in determining structural styles. For example, FT Ia and FT II in Figure 4 exhibit eastward tilting that was not documented in the northern part of the surface rupture. This tilting, which is associated with eastward migration of the Tungpuna Stream (Fig. 4), may be indicative of a change in the angle of dip of the fault plane.

Prior to the 1999 earthquake, study of the abundant geomorphic evidence would have indicated that the Chelungpu fault was active. The scarp heights combined with terrace ages could have helped us determine the slip rate along the Chelungpu fault. In addition, by identifying single event scarps that offset river terraces, the magnitude of slip from past earthquakes could have been determined. The failure to observe these geomorphic features contributed to the substantial losses during the 1999 earthquake. In order to decrease the human fatalities and material losses in future events, a critical evaluation of geomorphic features associated with the active fold-and-thrust belt of Taiwan is required. In particular, it is urgently needed in western Taiwan, an area that has been highly populated and industrialized.

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