Re-evaluation of the surface ruptures of the November 1951 earthquake series in eastern Taiwan, and its neotectonic implications

J. Bruce H. Shyu[1,*], Ling-Ho Chung[2], Yue-Gau Chen[2], Jian-Cheng Lee[3], Kerry Sieh[1]

1: Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA

2: Department of Geosciences, National Taiwan University, Taipei, Taiwan

3: Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan

* corresponding author, Phone: +1-626-395-6177. Fax: +1-626-683-0621.
E-mail: jbhs@gps.caltech.edu

Abstract

The earthquakes of November 1951 constitute the most destructive seismic episode in the recorded history of the Longitudinal Valley, eastern Taiwan. However, information about their source parameters is sparse. To understand the relationship between the 1951 ruptures and the new interpretations of the regional neotectonic architecture of the Longitudinal Valley, we re-evaluated the November 1951 ruptures by analyzing old documents, reports and photographs, and by interviewing local residents who experienced the earthquake. As a result, we have revised significantly the rupture map previously published. We divide the surface ruptures into Chihshang, Yuli, and Rueisuei sections. The first shock of the 1951 series probably resulted from the Chihshang rupture, and the second shock probably resulted from the Yuli and Rueisuei ruptures. The lengths of these ruptures indicate that the two shocks had similar magnitudes. The Chihshang and Rueisuei ruptures are along segments of the Longitudinal Valley fault, a left-lateral oblique fault along which the Coastal Range thrusts westward over the Longitudinal Valley. The Yuli rupture, on the other hand, appears to be part of a separate, left-lateral strike-slip Yuli fault, which traverses the middle of the Longitudinal Valley. The complex behavior of these structures and interaction between them are important in understanding the future seismic hazard of the area.

Introduction

The island of Taiwan occupies an awkward position along the boundary between the Eurasian and Philippine Sea plates, where subduction and collision are progressively consuming oceanic fragments of both the Eurasian and the Philippine Sea lithosphere (Fig. 1). In the brief century or so of recorded history, Taiwan has experienced several strong and destructive earthquakes (e.g., Bonilla, 1975, 1977; Hsu, 1980; Cheng and Yeh, 1989), the most recent of which was the disastrous 1999 Chi-Chi earthquake (see, e.g., Chen et al., 2001). These are the seismic manifestation of an orogeny that has been in progress for the past several million years (e.g., Ho, 1986; Teng, 1987, 1990, 1996). Along the suture marked by the narrow, north-south Longitudinal Valley in eastern Taiwan, the Luzon volcanic island arc is actively accreting to the metamorphic core of the island (Figs. 1 and 2). Almost half a century before the 1999 earthquake, an earthquake series there dramatized the important role the valley plays in the overall neotectonics of Taiwan. This series includes three magnitude 7 earthquakes centered near the northern end of the valley on October 22nd and two events on November 25th, which shook most severely the middle of the valley. Surface ruptures approximately 15 kilometers long at the northern end of the valley accompanied the October events, and more than 60 kilometers of surface rupture in the central part of the Longitudinal Valley accompanied the November events (e.g., Hsu, 1962; Yu, 1997). Together, the five earthquakes killed more than 80 people and destroyed thousands of houses (Hsu, 1980; Cheng and Yeh, 1989), thus constituting the most disastrous seismic event in eastern Taiwan in recorded history.

Despite their pre-eminence in Taiwan's seismic history, we know little about these earthquakes. The November doublet and its surface ruptures are particularly obscure. Although casualties were not as large as those from the October events, principally because they occurred in a rural part of the countryside, the surface ruptures were longer. However, the remoteness of the locality at that time hampered immediate investigation and detailed mapping of the ruptures. Thus, the only map of the November 1951 surface ruptures has been an approximately 1:2,000,000-scale figure published more than ten years after the earthquake (Hsu, 1962). There have been several subsequent attempts to investigate active faults in the Longitudinal Valley (e.g., Hsu and Chang, 1979; Shih et al., 1983; Yang, 1986; Chu and Yu, 1997; Chang et al., 1998; Lin et al., 2000). Nonetheless, most of these efforts either confused the 1951 ruptures with fault scarps that did not rupture in 1951, mapped only short segments of the 1951 rupture, or used erroneous information in compiling rupture locations. For example, some of these compilers considered the collapse of houses and bridges to indicate passage of a rupture underfoot. On other maps, landslides reported by local witnesses or visible in photographs taken after the earthquake appear as tectonic ruptures.

Recently, more detailed maps of the active structures of the Longitudinal Valley have been produced (e.g., Shyu et al., 2002; submitted). These new efforts have stimulated us to attempt compilation of a more detailed and accurate map of the 1951 ruptures, in order to gain a better understanding of their relationship to the active faults of the valley and their neotectonic roles. Thus, we have made an attempt to re-evaluate the evidence for surface ruptures during the November events. The most important question we attempt to address is whether the 1951 events were caused by the major structures of the Longitudinal Valley. If so, did it involve all or just a subset of these structures? The answer to this question has important implications for the evaluation of seismic hazard potential in the area.

In our attempt to re-evaluate the surface ruptures, our principle sources have been the published literature, vintage photographs and interviews of local residents. We have examined all available scientific and non-scientific reports on the earthquake, including a number of newspaper reports written after the earthquake. Also, we have examined many old photographs taken after the earthquake, searching for evidence of surface rupture. Some, but not all, of these photographs appeared in earlier reports (Taiwan Weather Bureau, 1952; Chu and Yu, 1997; Yu, 1997). We have made a considerable effort to determine the exact locations of the features in these photographs. Moreover, we conducted interviews with more than 40 old local residents who experienced the earthquake and had information about the location of surface ruptures and other aspects of the earthquakes. A complete compilation of these data appears in Chung (2003). In this brief paper, we present only a few examples of these data.

Although we have attempted to ensure the reliability of all of this information, some uncertainties remain. Many reports in the literature are, for example, too vague to determine whether or not they are reliable. Some photographs cannot be assigned a certain location, because of agricultural modifications in the 50 years after the earthquake or lack of distinctive landmarks. Also, some of the information we acquired in the interviews was vague, uncertain, or even contradictory. Nonetheless, by sifting all of the information, we have been able to improve significantly our understanding of the ruptures associated with the earthquake.

Tectonic background of the Longitudinal Valley

The Longitudinal Valley in eastern Taiwan is located between two major tectonic blocks (Fig. 2). To the east is the Coastal Range, an assemblage of Miocene through early Pliocene volcanic arc rocks and associated turbidite deposits, mélange, and fringing-reef limestones (Chen, 1988; Ho, 1988). These rocks are similar to rocks that constitute the remnant of the Luzon island arc immediately to the south and the sediments of the adjacent sea floor. Thus, the rocks of the Coastal Range appear to represent a highly shortened forearc basin and volcanic arc (e.g., Chang et al., 2001). On the western side of the Longitudinal Valley is the eastern flank of the Central Range, which is composed of Mesozoic to Paleogene low-grade metamorphic rocks, predominantly schists and slates (Ho, 1988). The contrast in the constitution of the two ranges demonstrates that the intervening long, linear Longitudinal Valley occupies a major tectonic suture (e.g., York, 1976; Teng, 1990). Coarse late

Quaternary clastic fluvial sediments fill the valley. The thickness of these sediments is unknown, but is likely more than a kilometer (e.g., Chen et al., 1974; Chen, 1976).

The dominant neotectonic element of this part of the island is the east-dipping Longitudinal Valley fault, which traverses the eastern edge of the valley (Fig. 3). It is characterized by high rates of sinistral reverse motion along its southern two-thirds and mostly sinistral motion along its northern one-third (Shyu et al., submitted). The geomorphic manifestation of this fault is clear along most of the valley, but it is rather complex, especially along its southern two-thirds. Distinctive tectonic landforms include discontinuous scarps that range up to several meters high along the range front and are lobate and irregular in plan view. These are associated commonly with west-tilted surfaces on the hanging wall block. Along most of the valley, these thrust-fault scarps are also accompanied by numerous secondary anticlines and synclines in the hanging-wall block.

Another major active structure along the southern two-thirds of the valley is a reverse fault that dips westward, beneath the eastern flank of the Central Range (Fig. 3). This fault, named the Central Range fault by Biq (1965), may be the major structure along which rapid uplift of the eastern flank of the Central Range is occurring (e.g., Shyu et al., submitted). Geomorphic evidence of this active fault includes a straight eastern flank of the Central Range along the southern two-thirds of the Longitudinal Valley and fluvial terraces that are perched tens to hundreds of meters above modern streambeds along a long segment of the range front. The most prominent feature among these is the Wuhe Tableland near the town Rueisuei in the middle of the valley (Shyu et al., 2002; submitted; Fig. 3).

Recent geodetic measurements show that the Longitudinal Valley is narrowing at a rate of about 40 mm yr-1 (e.g., Yu et al., 1997). Creepmeter measurements show that the Longitudinal Valley fault zone near the town Chihshang is creeping obliquely at a rate of about 25 mm yr-1 (Angelier et al., 1997; Lee et al., 2001). Inversions of GPS data across southern Taiwan also indicate that the Longitudinal Valley fault is a major active structure (e.g., Hsu et al., 2003). Contributions to strain accumulation by the Central Range fault, however, are not yet clear.

The November 1951 earthquake series

The major shocks of November 25th occurred at 02:47 and 02:50, local time (Taiwan Weather Bureau, 1952). Since they occurred just 3 minutes apart and not many seismic stations were operating in Taiwan at that time, widely disparate source parameters have been calculated and reported for the earthquakes (e.g., Taiwan Weather Bureau, 1952; Gutenberg and Richter, 1954; Lee et al., 1978; Hsu, 1980; Abe, 1981). The analyses by the Taiwan Weather Bureau (1952) and Hsu (1980) indicate the first one is larger of the two, whereas the catalog of Lee et al. (1978) indicates the opposite. In the catalogs of Gutenberg and Richter (1954) and Abe (1981), the two events appear as a single earthquake. Epicentral locations vary widely among these reports and are commonly very far from known faults of the Longitudinal Valley.

Recently, Cheng et al. (1996) used S-P times reported by the Taiwan Weather Bureau (1952), a Monte Carlo algorithm and information about the surface faults and maximum ground motion amplitudes to relocate the epicenters and calculate the magnitudes of the two events. They place the hypocenter of the first shock at 23.1°N and 121.225°E, at a depth of 16 km (Fig. 2). Their hypocenter for the second shock is at 23.275°N and 121.35°E, at a depth of 36 km. They also find that the magnitude of the second shock is larger than that of the first shock (M_w=7.0 vs. M_w=6.2). Moreover, they derived focal mechanisms using the first motions reported by the Taiwan Weather Bureau (1952) and Hsu's (1962) map of the surface ruptures. They conclude that the first shock was generated by a thrust fault with a subordinate left-lateral component, striking N32°E and dipping 70°S. From more limited first-motion information, they conclude that the second shock originated on a left-lateral strike-slip fault with a subordinate thrust component.

The surface ruptures of the earthquake have never been mapped in detail. The most widely accepted version is depicted in Fig. 2, which is from Hsu (1962). In this representation, the fault extends approximately 40 km from about 10 km south of Kuangfu to just north of Fuli (Fig. 2). Since this line runs through the town of Yuli, Hsu named it the Yuli fault and considered it to be the rupture that caused both of the November 1951 earthquakes. Also, on the same map he drew another line just south of the Yuli fault, extending about 20 km from around Fuli to near Kuanshan. He named this line the Chihshang fault and believed it to be an active fault, by virtue of its clear and young topographic appearance. However, Cheng et al. (1996) suggested that Hsu's Chihshang fault also ruptured in 1951. They suggest that the Chihshang fault ruptured during the first shock and that the Yuli fault ruptured during the second shock.

Several important questions arise from these earlier efforts. Did, in fact, the Chihshang fault rupture during the earthquake? If so, how far north did the rupture extend? And was the Chihshang rupture contiguous with the Yuli rupture? If both structures ruptured, are they parts of the same fault? If not, what is the relationship between them? And finally, what are the relationships between the Yuli and Chihshang ruptures and the Longitudinal Valley fault? Are they along two segments of the Longitudinal Valley fault? Or, are they ruptures of faults that are distinct from the Longitudinal Valley fault? What is the implication of the fact that the Yuli fault runs through the town of Yuli, very far from the western mountain front of the Coastal Range? In our attempt to re-evaluate the November 1951 ruptures, our main goal has been to answer these questions.

Re-evaluation of the November 1951 ruptures

We have been able to determine the location of the November 1951 ruptures in many places. Fig. 3 shows that our re-evaluation leads us to divide the ruptures into three separate strands, which we call the Chihshang, Yuli, and the Rueisuei ruptures. The Chihshang rupture is similar to the Chihshang fault first noted by Hsu (1962). The Yuli and Rueisuei ruptures are roughly coincident to his Yuli fault, but constitute two entirely different structures.

The Chihshang rupture

The southern end of the Chihshang rupture is approximately 4 km south of the town of Chihshang (Chung, 2003). The rupture extends northward from there along the western foothills of the Coastal Range for about 20 kilometers, to a point near the village of Tungli (Fig. 4a). It is difficult to determine confidently whether the rupture extended north of Tungli, because the evidence is very scattered. We suggest, however, that it may have reached the Yuli railroad bridge just east of Yuli. If this is the case, the total rupture length of the Chihshang rupture is close to 30 kilometers.

Although Hsu (1962) did not document surface ruptures near Chihshang during the November 1951 earthquakes, we have several reasons to believe that surface ruptures did occur there. First, when we interviewed local residents in villages around Chihshang, many of them said that they did witness surface ruptures along the western foothills of the Coastal Range. Second, the epicenter of the first shock in the November 1951 series is more than 10 km away from the southernmost point of Hsu's Yuli rupture. According to Cheng et al. (1996), the relocation of this epicenter is unlikely to be more than 10 km in error. Many recent large strike-slip earthquakes, such as the 1992 Landers, 1999 Izmit, and 1999 Hector Mine earthquakes, have epicenters on or very close to their surface ruptures (e.g., Sieh et al., 1993; Barka, 1999; Treiman et al., 2002). If surface ruptures accompanied the first shock, the nearest ones would probably not be farther than 10 km from the epicenter for an earthquake with a significant strike-slip component. And finally, after the earthquake, there were many local newspaper reports of damage and destruction around Chihshang (Yang, 1953; Chung, 2003).

From near Chihshang north to near Fuli, we found evidence for almost continuous rupture along the eastern edge of the Longitudinal Valley (Fig. 4a). Our interviews indicate that the largest vertical offset along this segment is about half a meter.

Around Fuli, the vertical offset was smaller, and the evidence for surface rupture is not as continuous as it is to the south. Near Fuli, the ruptures are characterized by *en echelon* cracking, with vertical displacements less than 0.2 meters, up on the east. Farther north, between Chutien and Tungli, vertical displacement is much larger, approximately 1 to 1.5 meters, and the ruptures appear to be continuous again. We have found an old photograph of a locality near the Yuli Convalescent Hospital, in which the rupture exhibits a scarp about 1.5 meters high (Fig. 4b). This scarp is only a meter high now, due to agricultural modifications (Fig. 4c).

North of Tungli, we did not find undisputable evidence for rupture in 1951. Based upon newspaper reports published shortly after the earthquake that the Yuli railroad bridge was offset and broken by the earthquake, Yu (1997) suggested that the rupture ran through the bridge about 200 meters west of the bridge's eastern end (Fig. 4a), with offsets about 0.1-0.3 meter vertically and 0.3-0.4 left-laterally. However, no other document confirms the existence of the rupture there. Yang (1953) mentioned that there were cracks in the Hsiukuluan River bed, but without photographs or eyewitness accounts, we are uncertain whether the cracks are in fact fault ruptures. The bridge did break during the earthquake, but this may have been due to seismic shaking rather than faulting underfoot. Since Yu (1997) was very confident about this location and he did provide detailed information about the offset, we favor his suggestion. Our interviews indicate that the rupture did not extend north of the Yuli railroad bridge (Fig. 4a). Although Cheng et al. (1996) maintain that their photograph on Plate I-3, which shows rupture of ~0.6 meter vertical offset, to be from a point north of the Yuli railroad bridge, the location of the photograph has been strongly questioned (e.g., Yu, 1997; Chung, 2003).

It is quite clear that the Chihshang rupture occupies a segment of the Longitudinal Valley fault. The fault has long been known to be an oblique-slip fault, with significant component of vertical movement (e.g., Hsu, 1962; Ho, 1986, 1988; Chen, 1988). The Chihshang rupture had a similar sense of oblique slip. Based upon geomorphic evidence, Shyu et al. (submitted) mapped the major strand of the

Longitudinal Valley fault along the eastern edge of the Longitudinal Valley. East of Chihshang, this strand follows a clear, almost linear scarp about 20 meters high. This is exactly coincident with surface ruptures of 1951. Along this reach, the fault has been rapidly creeping for at least 20 years (e.g., Yu and Liu, 1989; Angelier et al., 1997; Chow et al., 2001; Lee et al., 2001). Our discovery of 1951 ruptures here demonstrates that the fault fails by both creep and by seismic rupture.

North of Fuli, the hanging wall block of the Longitudinal Valley fault exibits a series of anticlinal hills and backthrusts (Yang, 1986; Chung, 2003; Shyu et al., submitted). The 1951 ruptures run along the westernmost edge of these hills, but we have no evidence that these folds and backthrusts moved during the earthquakes.

In summary, the Chihshang rupture of 1951 occurred along a 30 km length of the Longitudinal Valley fault. The ruptures were characterized by oblique offset, similar to the sense of slip along the fault depicted on geologic maps (e.g., Chen, 1988; Ho, 1988) and monitored during the past 20 years. Along most of its length, the vertical offset along the rupture was less than half a meter, but along the Tungli-Chutien section, it was as much as 1.5 meters. We are uncertain about the total length of this rupture, but it was at least 20 kilometers and no longer than 30 kilometers.

The Rueisuei rupture

The southern end of the Rueisuei rupture of 1951 is about 2 km east of the town of Rueisuei. From there, the rupture extended about 15 km north along the western foothills of the Coastal Range to the Tzu-Chiang Prison, about 10 km south of the town Kuangfu (Fig. 5a). We have found abundant evidence that rupture was almost continuous along this reach (Chung, 2003).

Like the Chihshang rupture, the Rueisuei rupture follows the western edge of the Coastal Range, along the eastern side of the Longitudinal Valley. Sense of slip on the rupture appears to be oblique, with significant amounts of vertical offset. For example, Hsu (1962) reported that at one location, the slickensides on the fault plane showed 1.63 meters of left-lateral offset and 1.3 meters of vertical offset. However, in most of the photographs we have found, there is no way to resolve a left-lateral component. Vertical offset, on the other hand, is usually clear and greater than 1 meter, with a maximum of 2.1 meters. Most of the rupture scarps are still visible, and a recent trench across one of them (Fig. 5b) revealed at least a half meter of vertical offset during the 1951 earthquake (W.-S. Chen, personal communication).

Our investigation indicates that the northern end of the Rueisuei rupture is near the Tzu-Chiang Prison, but its southern end is more difficult to determine. The southernmost location where we have found evidence for the rupture is near the village of Hekang (Fig. 5a). Although during the earthquake, the village of Rueimei was heavily damaged, with many collapses of houses, none of the local residents we interviewed recalled any surface rupture in or near the village. There were also widespread landslides south of Rueimei during the earthquake, but none are clearly related to fault rupture. Thus, it appears that the southern end of the Rueisuei rupture is approximately at Hekang.

The Rueisuei rupture is coincident with a topographic break at the western base of the Coastal Range, where, based upon geomorphic evidence, Shyu et al. (submitted) mapped the active strand of the Longitudinal Valley fault. Thus, as with the 1951 Chihshang rupture, the Rueisuei rupture of 1951 ran along a segment of the Longitudinal Valley fault. The oblique sense of offset along the Rueisuei rupture is similar to the sense of offset along the Chihshang rupture, and in both cases, the 1951 rupture has the same sense of slip as is indicated on geologic maps (e.g., Chen, 1988; Ho, 1988) of the Longitudinal Valley fault.

The Yuli rupture

The Yuli rupture of 1951 was best documented near the Yuli town center. Since Yuli was already a medium-sized town when the earthquake struck, we have found many photographs showing the actual ruptures and seismic destruction. Farther from the town center, the evidence is far more scattered (Chung, 2003).

Unlike the Chihshang and Rueisuei ruptures, which follow mostly the eastern edge of the Longitudinal Valley, the Yuli rupture lies on the valley floor, in places only a kilometer or so from the Central Range (Fig. 6a). The rupture's southern end is just south of Yuli, where it runs through the town center and destroyed many buildings in the town, including the former Yuli Elementary School (e.g., Hsu, 1962; Bonilla, 1975; Yu, 1997). North of the town center, the rupture probably extended along the Hsiukuluan River bed. Based upon local witnesses and old photographs, we suggest that it extended to a point about 5 km southeast of Rueisuei (Fig. 6a). The total length of the Yuli rupture is about 20 kilometers. Near Yuli, the Yuli rupture is nearly parallel to the Chihshang rupture and runs about 1.5 kilometers west of the Chihshang rupture.

In the town center of Yuli, all of the photographs we have found indicate that the rupture was almost purely strike-slip. Although some reports suggested a small vertical component of slip (e.g., Yu, 1997), no vertical offsets are visible in the photographs. One of the most thoroughly documented locations of the rupture was the former Yuli Elementary School (Fig. 6b). The classroom building at the school was offset left-laterally about 0.4 meters (Fig. 6c). However, a row of pebbles at the northern edge of the athletic field of the school was offset only about 0.16 meters (Bonilla, 1975; Fig. 6d). The amount of offset therefore varied significantly in a very short distance within the school grounds (Bonilla, 1975).

While no document reported the extension of the rupture north from the Yuli town center, we believe that it extended along the Hsiukuluan River bed to a point approximately 4 km southeast of Rueisuei, where there is a linear ridge about 200 meters long, rising 5 meters above a river terrace east of the Hsiukuluan River (Fig. 6a). The name of this ridge, Kuokailiang, means "the lid of a pot" (Figs. 6a and 7a). The landowner, who lives right next to the ridge, recalled ruptures along the eastern side of the ridge during the 1951 earthquake, which may have also extended southward more than 500 meters past the ridge (Yang, 1986). Since the long axis of the ridge trends toward the ruptures in Yuli, we wonder whether or not the surface ruptures were continuous between these two locations. In fact, we have found many photographs of ruptures in the riverbed between Yuli and Kuokailiang, near the village of Sanmin (Yu, 1997; Figs. 7a and 7b). Therefore, we believe the Yuli rupture may well have traversed the riverbed from Yuli to Kuokailiang ridge. A recent man-made outcrop in the ridge revealed multiple and complicated faults on its eastern side, suggesting that the ridge was formed by shear dilatation resulting from strike-slip movement in the river gravels (e.g., Chung, 2003).

North of Kuokailiang, there is no evidence for the Yuli rupture. Although the Yuli and Rueisuei ruptures were originally mapped by Hsu (1962) as a single Yuli fault, and most later investigations (e.g., Yu, 1997; Cheng et al., 1996; Lin et al, 2000) followed this interpretation, we found no evidence that the Yuli rupture was contiguous with the Rueisuei rupture. In fact, our mapping of tectonic landforms (Shyu et al., submitted) shows that the two ruptures occurred on two distinct faults. First, the Yuli rupture traverses the Longitudinal Valley floor, whereas the Rueisuei rupture runs along the western edge of the valley. Second, the Yuli rupture is somewhat discontinuous on the map, although this may be more a function of sparse documentation than actual discontinuity. In contrast, the Rueisuei rupture is very continuous. Finally, and most significantly, the style of offset on the two ruptures differs markedly. Yuli rupture offsets were almost pure left-lateral strike-slip, while offsets on the Rueisuei rupture were oblique-slip, with a distinct vertical component. This difference in style of offset may well be the reason why documentation is more sparse along the Yuli rupture; the moletracks and *en echelon* cracks of strike-slip ruptures are generally more subtle to the untrained eye than the scarps of dip-slip faults.

In summary, the Yuli and Rueisuei ruptures of 1951 are two distinctive features. Slip along the Yuli rupture was predominantly left-lateral strike-slip in nature, and we did not find clear evidence for any vertical offset during the earthquake. North of Yuli, the rupture appears to extend along the Hsiukuluan River bed to Kuokailiang, approximately 4 km southeast of Rueisuei. If this is the case, the total length of the Yuli segment is about 20 kilometers.

The Yuli rupture and the Longitudinal Valley fault

In contrast to conventional ideas, we believe that the Yuli rupture, unlike the Chihshang and Rueisuei ruptures, is not part of the Longitudinal Valley fault. Co-seismic offsets along both the Chihshang and Rueisuei ruptures are oblique-slip, as is the long-term movement along the Longitudinal Valley fault (e.g., Chen, 1988; Ho, 1988), whereas the Yuli rupture has predominantly left-lateral offset. Moreover, the Chihshang and Yuli ruptures are sub-parallel to each other near Yuli but not co-linear. Rather they are about 1.5 kilometers apart.

Based upon geomorphic evidence, Shyu et al. (submitted) have mapped the major active strand of the Longitudinal Valley fault between Yuli and Rueisuei. Just as to the south and to the north, this active strand runs approximately along the eastern side of the Longitudinal Valley, about 1.5 km east of the Yuli rupture. Although this active fault strand is obvious geomorphically, it did not break during the 1951 earthquake. We have found neither documents nor photographs showing rupture at any of the topographic scarps along this strand, and none of the residents we interviewed recalled any surface ruptures on this side of the Longitudinal Valley between Yuli and Rueisuei. The Yuli rupture clearly did not occur along this part of the Longitudinal Valley fault.

Instead, the Yuli rupture appears to have re-activated a pre-existing strike-slip fault, with clear evidence for prior strike slip. When mapping the active structures in the Longitudinal Valley, Shyu et al. (submitted) interpreted Kuokailiang ridge, at the northern end of the Yuli rupture, to be the product of a strike-slip fault west of the Longitudinal Valley fault. An outcrop in this “pressure” ridge reveals at least several meters of vertical separation along this fault (Chung, 2003; L.-H. Chung and J. B. H. Shyu, unpublished data). For a strike-slip dominated fault, this amount of total vertical offset suggests at least several tens of meters of cumulative left-lateral offset.

Discussion

The November 1951 earthquake series: a complex rupture event

The November 1951 earthquakes in the Longitudinal Valley constitute one of the most disastrous seismic episodes in the recorded history of eastern Taiwan. Although many kilometers of surface rupture were reported after the earthquake, no detailed map of the ruptures was produced. Most maps depicted the ruptures as occurring along a nearly straight line, with a discontinuity between Fuli and Yuli in some renditions (e.g., Hsu, 1962; Hsu and Chang, 1979; Cheng et al., 1996; Chu and Yu, 1997; Fig. 2). Our re-evaluation reveals that, in fact, the ruptures were more complicated than this. We divide the surface breaks into three separate ruptures — the Chihshang, Yuli, and Rueisuei ruptures, each with its own distinct characteristics. The Chihshang and Rueisuei ruptures occupied separate 30- and 15-km-long segments of the sinistral reverse Longitudinal Valley fault. The Yuli rupture did not occur along the Longitudinal Valley fault. Rather it occupied a left-lateral fault that traverses the valley floor more than a kilometer west of the Longitudinal Valley fault.

The recent relocation and parameterization of the sources of the two earthquakes by Cheng et al. (1996) are consistent with these rupture patterns. Their hypocenter for the first shock, at 02:47, is approximately at the southern end of the Chihshang rupture. Their hypocenter for the second shock, at 02:50, is near the northern end of the Chihshang rupture and the southern end of the Yuli rupture (Fig. 3). We suggest that the Chihshang rupture produced the first shock and induced the Yuli and Rueisuei ruptures, which produced the second, larger shock. The lengths of the ruptures help us calculate the moment magnitudes (M_w) of the two shocks, based upon published regressions of length against magnitude (e.g., Wells and Coppersmith, 1994). The first shock would have a moment magnitude (M_w) of 6.8, whereas the moment magnitude of the second shock would have been about 6.9. The similarity in magnitude of these two shocks is significantly different from that calculated by Cheng et al. (1996), because their calculation was based on the map of Hsu (1962), which shows a much greater difference in the lengths of the Chihshang and combined Yuli/Rueisuei ruptures. Similarity in magnitude of the two quakes is supported by the original earthquake report of the Taiwan Weather Bureau (1952), in which the intensity maps for the two shocks have similar peak intensities and areas.

It is well known that earthquakes can be triggered by changes in Coulomb failure stress that result from an earlier earthquake (e.g., Harris, 1998; Stein, 2003). This mechanism has been invoked, for example, to explain the progressive failure of the North Anatolian fault between 1939 and 1999 (e.g., Stein et al., 1997), and to calculate future seismic hazards along the fault (e.g., Hubert-Ferrari et al., 2000; Parsons et al., 2000). In general, after a major earthquake, areas where stress has increased are favored areas for aftershocks and/or subsequent mainshocks occur (Harris, 1998). In many cases, the areas where stress increases significantly are near the ends of the ruptures (e.g., Hubert-Ferrari et al., 2000; Anderson and Ji, 2003). Since the epicenter of the second shock of the 1951 earthquakes is near the northern end of the first rupture, it may well be in an area where the local Coulomb stress increased. The Yuli rupture of the second shock lies about 1.5 km west of the Chihshang rupture, which broke during the first shock. The reverse component of slip on the east-dipping Chihshang rupture might have well decreased the normal stress around the Yuli rupture, thus promoting the left-lateral rupture to occur. Such induced rupture events, with different modes of slip due to local stress field change, are exemplified by the Rainbow Mountain-Fairview Peak-Dixie Valley earthquake of 1954 (e.g., Hodgkinson et al., 1996). There, an M=7.2 oblique-slip event triggered failure of an adjacent normal fault in an M=6.7 earthquake.

The relationship between the Yuli and Rueisuei ruptures is also complex. There is a gap of approximately 5 km between these two ruptures (Figs. 5a and 6a). It is noteworthy, however, that the northern end of the Yuli rupture at Kuokailiang is very close to the unruptured strand of the Longitudinal Valley fault, and may well extend beneath the Longitudinal Valley fault further north (Fig. 3). Thus, it is plausible that the Yuli rupture triggered the Rueisuei rupture. This would be reminiscent of what happened during the Enggano, Sumatra, earthquake of June 2000. There, about 65% of the earthquake's moment was produced by strike-slip rupture on a fault in the downgoing oceanic slab. This was followed by failure of a patch of the overlying subduction interface (Abercrombie et al., 2003).

Another important result of this documentation of the 1951 rupture is that the Longitudinal Valley fault, a fault that is currently creeping at a high rate, previously failed seismically. The Chihshang rupture is along a portion of the fault that is well known for its rapid creep behavior (e.g., Yu and Liu, 1989; Angelier et al., 1997; Chow et al., 2001; Lee et al., 2001). Since the fault ruptured during the 1951 earthquake, one might well suspect that current creep is not releasing all strain accumulating in the blocks adjacent to the fault, and that creep should be viewed as retarding rather than eliminating the prospect of future seismic ruptures there. At this moment, we do not have enough information to determine whether or not this dual behavior also characterizes strands of the Longitudinal Valley fault further to the north or to the south. Preliminary geodetic measurements near Rueisuei indicate the fault may creep there, but much more slowly (Yu and Liu, 1989). Further investigation is needed to resolve these details of strain accumulation and release along the Longitudinal Valley fault.

What is the Yuli fault?

The Yuli fault was originally proposed by Hsu (1962) in describing the 1951 earthquake ruptures. His definition encompasses both our Yuli and Rueisuei ruptures. His idea was that since the Yuli fault ruptured in 1951, it is probably the main fault of the Longitudinal Valley. Later studies of the Longitudinal Valley, such as those by Chu and Yu (1997), Yu (1997), and Lin et al. (2000), all adopted this point of view, mapping the Longitudinal Valley fault through the town of Yuli. This, however, creates geometric problems. The town of Yuli is far from the western foothills of the Coastal Range, where the Longitudinal Valley fault runs. As a result, previous maps show a significant bend or *en echelon* step over of the fault south of Yuli. These maps ignore the geomorphic evidence that the Longitudinal Valley fault is a continuous oblique reverse fault along the western Coastal Range front.

In fact, there are three principal faults in the valley, and portions of two of these ruptured in 1951. No geomorphic or structural evidence supports the geometries of the earlier workers. The sinistral reverse Longitudinal Valley fault is clearly continuous along the entire eastern side of the valley between Taitung and Hualien (Shyu et al., submitted). It does not bend or step over toward the west except at Rueisuei, where the Coastal Range front itself bends.

Therefore, the "Yuli fault" of Hsu (1962) clearly encompasses two different structures. Its northern part, defined by the Rueisuei rupture, is actually a portion of the sinistral reverse Longitudinal Valley fault that is bringing Coastal Range rocks over the Longitudinal Valley. The southern part of Hsu's Yuli fault is the predominantly left-lateral Yuli rupture. Since the northern part of Hsu's (1962) Yuli fault is part of the Longitudinal Valley fault, we propose to retain Hsu's name only for the fault that broke along the Yuli rupture. Thus, we suggest that the term "Yuli fault" hereinafter only be used in reference to the Yuli rupture of the 1951 earthquakes. This fault is a sinistral fault that traverses the Longitudinal Valley, with negligible vertical movement.

We are unsure whether or not the Yuli fault dips eastward at depth. If so, it could be an integral part of the obliquely slipping Longitudinal Valley fault zone. However, its location, west of the east-dipping Longitudinal Valley fault and its predominance of strike-slip movement make such a geometry very unlikely. We believe the alternative — that it is a separate, steeply dipping, strike-slip fault that has developed within the sediments of the valley, structurally separate from the Longitudinal Valley fault system (Fig. 8).

Implications for seismic hazard assessment

Our re-evaluation of the November 1951 ruptures raises many important questions relevant to seismic hazard assessment in the Longitudinal Valley. For example, it is clear that between Yuli and Rueisuei, the Longitudinal Valley fault did not rupture during the 1951 earthquakes. Why did this happen? We have proposed that the stress loading on the Yuli fault by the failure of the Chihshang segment of the Longitudinal Valley fault promoted the failure on the Yuli fault. The stress loading should, in fact, have been even higher for the unruptured segment of the Longitudinal Valley fault between Yuli and Rueisuei, and have brought it closer to failure. A pre-1951 rupture along this segment may have shed so much stress from the adjacent crust that this segment could not be loaded to the point of failure by the rupture of adjoining segments to the north and south in 1951. Alternatively, it is conceivable that this segment fails entirely by creep. More detailed paleoseismic and geodetic investigations along this segment are needed to resolve this question.

The Chihshang and Rueisuei ruptures clearly represent seismic failure along segments of the Longitudinal Valley fault. However, the two segments are behaving quite differently at present. The Chihshang segment is creeping rapidly, whereas the Rueisuei segment is not. What does this imply about future seismic activity along these two segments? Does the Chihshang segment have a longer average recurrence interval than the Rueisuei segment, or does it just have smaller amounts of offset per earthquake? Again, paleoseismological and geodetic studies along these two segments could address these questions.

The Yuli fault may be the most poorly understood structure in the middle Longitudinal Valley. For example, we don’t know at this moment whether or not this fault extends further northward, beneath the Longitudinal Valley fault, or further southward beneath the Central Range fault. Although the Yuli fault appears to have moved previously, there is no constraint on its long-term slip rate. Furthermore, Bonilla (1975) suggested that the Yuli fault might be creeping, but more recent investigations suggest that it is not (e.g., Chung, 2003). A short-aperture geodetic array across this fault should reveal which is the case. Paleoseismic studies could reveal its seismic behavior.

Conclusions

In our attempt to re-evaluate the ruptures of the November 1951 earthquake series in the Longitudinal Valley, eastern Taiwan, we have analyzed all published documents, and relevant reports and photographs, and we have interviewed more than 40 elderly local residents who have experienced the earthquake. We divide the surface breaks into three separate ruptures from south to north — the Chihshang, Yuli, and Rueisuei ruptures. The Chihshang rupture was approximately 30 kilometers long and probably ruptured during the first shock of the 1951 earthquake series. The length of the Yuli rupture was about 20 kilometers, and the Rueisuei rupture was about 15 kilometers long. Consideration of epicentral locations and focal mechanisms suggests that the Yuli and Rueisuei ruptures produced the second shock of the 1951 series. The Chihshang and Rueisuei ruptures occurred along widely separate lengths of the Longitudinal Valley fault, and both experienced oblique-slip movement during the earthquake. The sense of slip along the Yuli rupture, on the other hand, was left-lateral, and the rupture occurred on a fault that traverses the middle of the valley floor and is distinct from the Longitudinal Valley fault. The failure of the Chihshang rupture, which produced the first shock of the November 1951 earthquakes, probably triggered the subsequent failure of the Yuli and Rueisuei ruptures. The active structures in this middle section of Taiwan's Longitudinal Valley are complex — mountain ranges to the east and west are converging on the valley on two opposing reverse faults. The 1951 earthquakes involved partial rupture of just one of these and a strike-slip fault breaks the valley sediments in between.

Acknowledgments

We thank Y. Wang and T.-C. Lin for their assistance with the field work. We are also grateful for valuable discussions with Profs. J.-P. Avouac, H.-T. Chu, J.-C. Hu, and J.-C. Lin. Many old photographs and documents were kindly provided by Profs. T.L. Hsu, M.-S. Lin, and S.-N. Cheng. The help of many local residents in eastern Taiwan, especially Mr. S.-H. Chang, K.-C. Chiang, L.-P. Tseng, and C.-S. Chang, are greatly appreciated. This work was supported by both the National Science Foundation and the National Science Council.

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Figure captions

Figure 1. Taiwan is experiencing a transitory tandem suturing of a volcanic arc and a sliver of continental crust to the Asian continental margin. The 1951 earthquakes in the Longitudinal Valley resulted from failure of faults along the eastern of the two sutures. This suture is developing by the oblique collision of the Luzon volcanic arc into a narrow strip of continental crust. Current velocity vector of the Philippine Sea plate adapted from Yu et al. (1997). DF: deformation front; LCF: Lishan-Chaochou fault; LVF: Longitudinal Valley fault; WF: Western Foothills; CeR: Central Range; CoR: Costal Range.

Figure 2. Shaded relief map shows the middle part of the Longitudinal Valley, between the Central and Coastal Ranges, published epicenters of the November 1951 earthquakes (Cheng et al., 1996), and associated ruptures (Hsu, 1962). Hsu (1962) concluded that the Yuli fault is the source of the 1951 earthquakes, but the Chihshang fault is an active fault that did not rupture in 1951. Cheng et al. (1996), on the other hand, suggest that sinistral reverse slip on the Chihshang fault produced the first of the two earthquakes and that similar slip on the Yuli fault produced the second event.

Figure 3. Our estimate of the extent of the November 1951 ruptures (red). Blue lines are major active reverse faults and flexures bounding the Longitudinal Valley that did not rupture in 1951. Modified from Shyu et al. (2002, submitted) and unpublished results of J. B. H. Shyu and L.-H. Chung. Ch: Chihshang rupture; Yu: Yuli rupture; Rs: Rueisuei rupture. Dashed faults are inferred.

Figure 4. The Chihshang rupture. (a) Map of the Chihshang rupture. Red lines are the ruptures, and blue lines are active structures not ruptured in 1951. Modified from Shyu et al. (submitted) and unpublished results of J. B. H. Shyu and L.-H. Chung. YRB: Yuli railroad bridge. (b) An old photograph of the rupture at point A,

between Chutien and Tungli, shows approximately 1.5 meters vertical offset that occurred during the earthquake. The photograph was taken by T. L. Hsu, looking toward the east, and was provided by M.-S. Lin. (c) A recent photograph taken at the same location, also looking toward the east. The scarp is only 1 meter high at present due to modifications associated with agriculture.

Figure 5. The Rueisuei rupture. (a) Map of the Rueisuei rupture. Modified from Shyu et al. (2002, submitted) and unpublished results of J. B. H. Shyu and L.-H. Chung. (b) A photograph taken at point K in Fig. 5a, showing the scarp produced in 1951. View is toward the south. A recent trench opened at this location revealed at least 0.5 meters of vertical offset during the 1951 event (W.-S. Chen, personal communication).

Figure 6. The Yuli rupture. (a) Map of the Yuli rupture. Modified from Shyu et al. (submitted) and unpublished results of J. B. H. Shyu and L.-H. Chung. Note that near Yuli, the Yuli and Chihshang ruptures are sub-parallel and about 1.5 kilometers apart. YRB: Yuli railroad bridge. (b) Detailed map showing the Yuli rupture at the Yuli Elementary School, modified from Bonilla (1975) and Yu (1997). (c) Offset in 1951 of about 0.4 meters near the classrooms in the Yuli Elementary School, at point X in Fig. 6b. View is toward the east. Modified from Taiwan Weather Bureau (1952). (d) Offset in 1951 of about 0.16 meters at the edge of the athletic field in the Yuli Elementary School, at point Y in Fig. 6b. View is toward the east. Modified from Bonilla (1975).

Figure 7. The Yuli rupture of 1951 north of Yuli. (a) Ruptures in the riverbed, perhaps near the village of Sanmin. View is toward northeast. From Yu (1997). (b) Another photograph of ruptures in the riverbed north of Yuli. The photograph was taken by T. L. Hsu and provided by M.-S. Lin. (c) Kuokailiang ridge, about 4 kilometers southeast of Rueisuei, is a linear ridge about 200 meters long and 5 meters

high above a river terrace. The 1951 ruptures ran along the near (eastern) side of the ridge.

Figure 8. A schematic tectonic east-west cross section of the Longitudinal Valley at the latitude of the Wuhe Tableland. The west-dipping Central Range fault crops out along the eastern edge of the Central Range and the Wuhe Tableland, but did not ruptured during the 1951 earthquakes. The steeply dipping Yuli fault and sections of the east-dipping Longitudinal Valley fault, on the other hand, ruptured. The Longitudinal Valley fault crops out along the eastern side of the Longitudinal Valley and accommodates uplift and deformation of the terraces along the western flank of the Coastal Range. The Yuli fault is a separate, discontinuous strike-slip fault developed in the sediments of the valley, structurally separate from the Longitudinal Valley fault system. Black: inactive fault in basement rocks; Blue: active fault not ruptured in 1951; Red: ruptures of 1951.

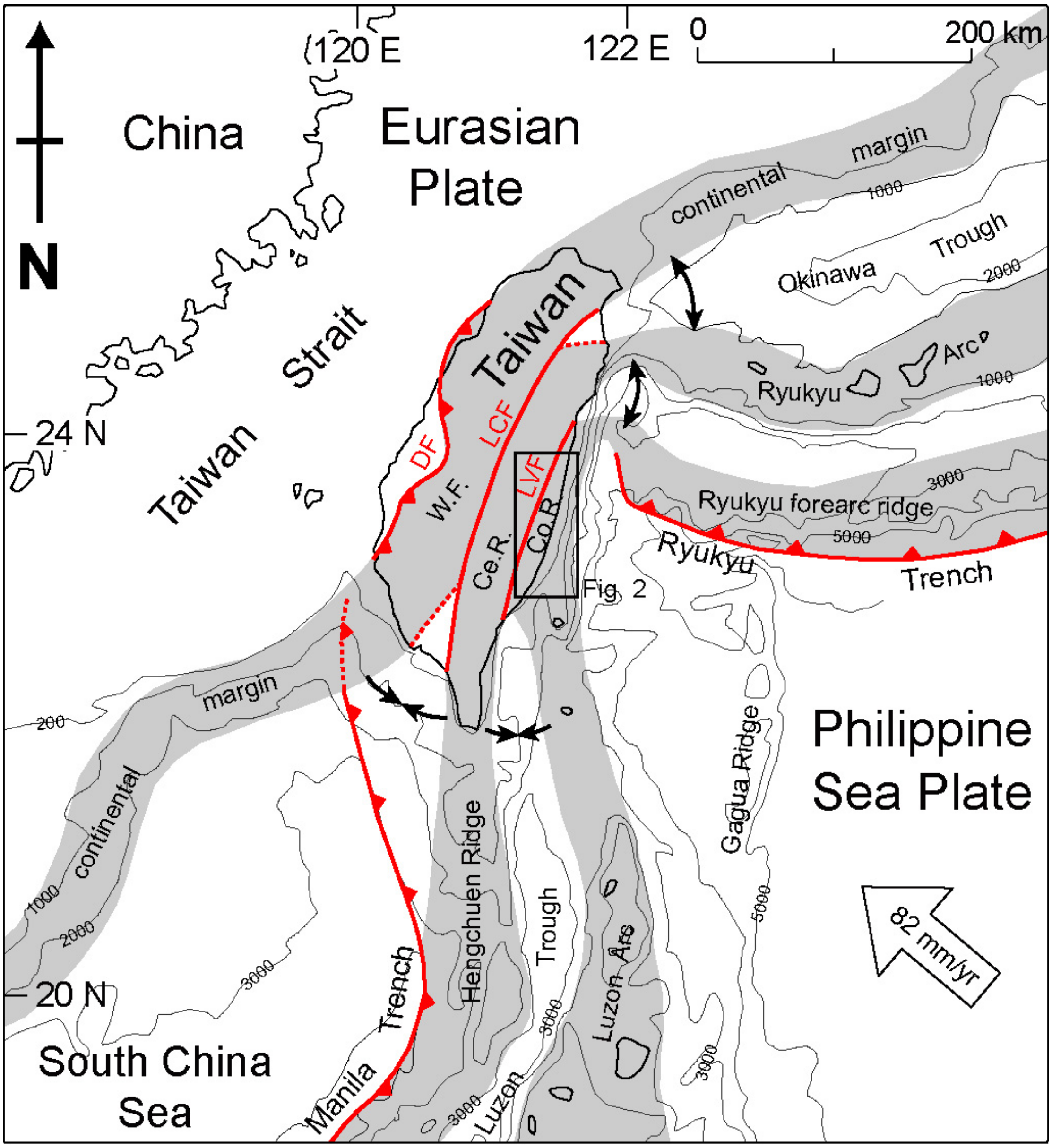

120 E
122 E
0
200 km
N
China
Eurasian Plate
continental margin
1000
Okinawa Trough
2000
Taiwan
Taiwan Strait
Ryukyu Arc
24 N
LCF
DF
LVF
W.F.
Ce.R.
Co.R.
Fig. 2
Ryukyu forearc ridge
3000
5000
Ryukyu Trench
margin
200
continental
Philippine Sea Plate
Gagua Ridge
Hengchuen Ridge
Trough
Luzon Arc
Luzon
82 mm/yr
20 N
South China Sea
Manila Trench

Figure 1

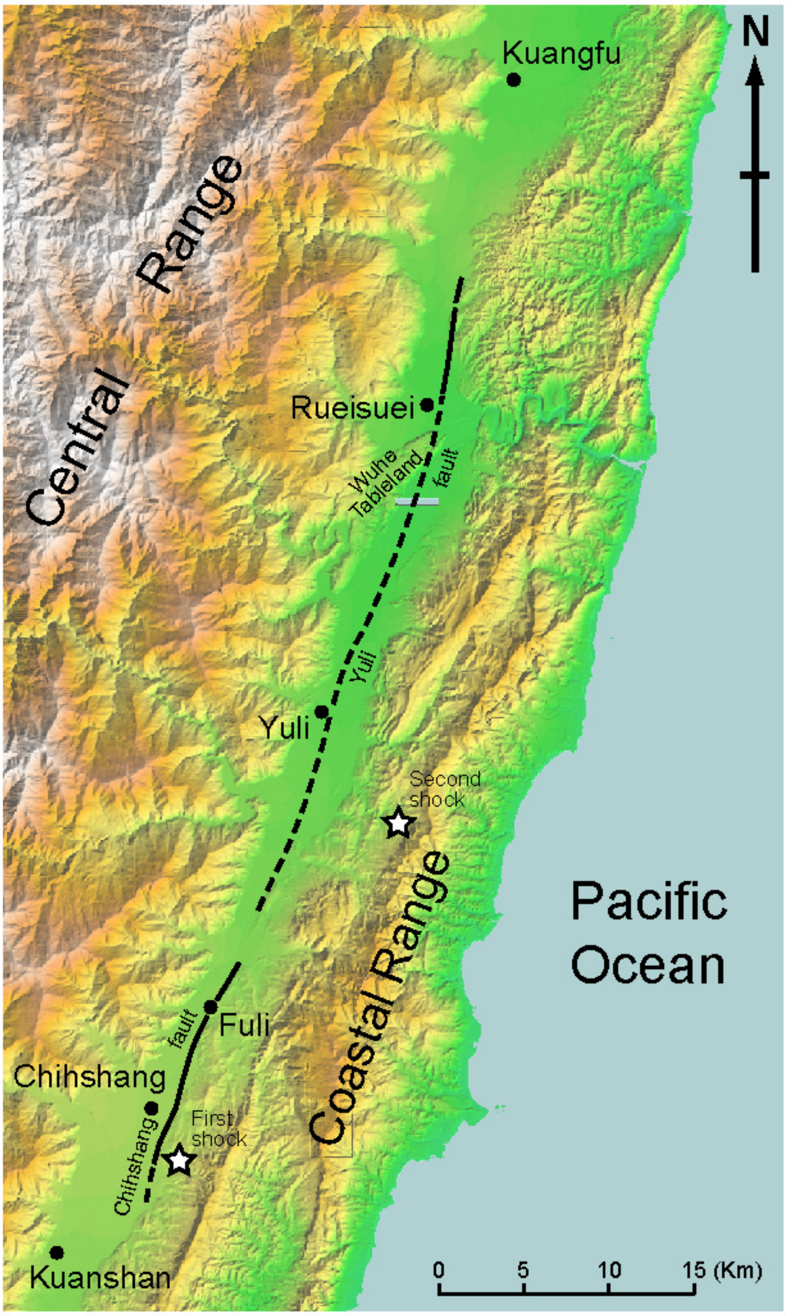

N
Kuangfu
Central Range
Rueisuei
Wuhe Tableland
fault
Yuli
Yuli
Second shock
Pacific Ocean
Coastal Range
Fuli
fault
Chihshang
Chihshang
First shock
Kuanshan
0 5 10 15 (Km)

Figure 2

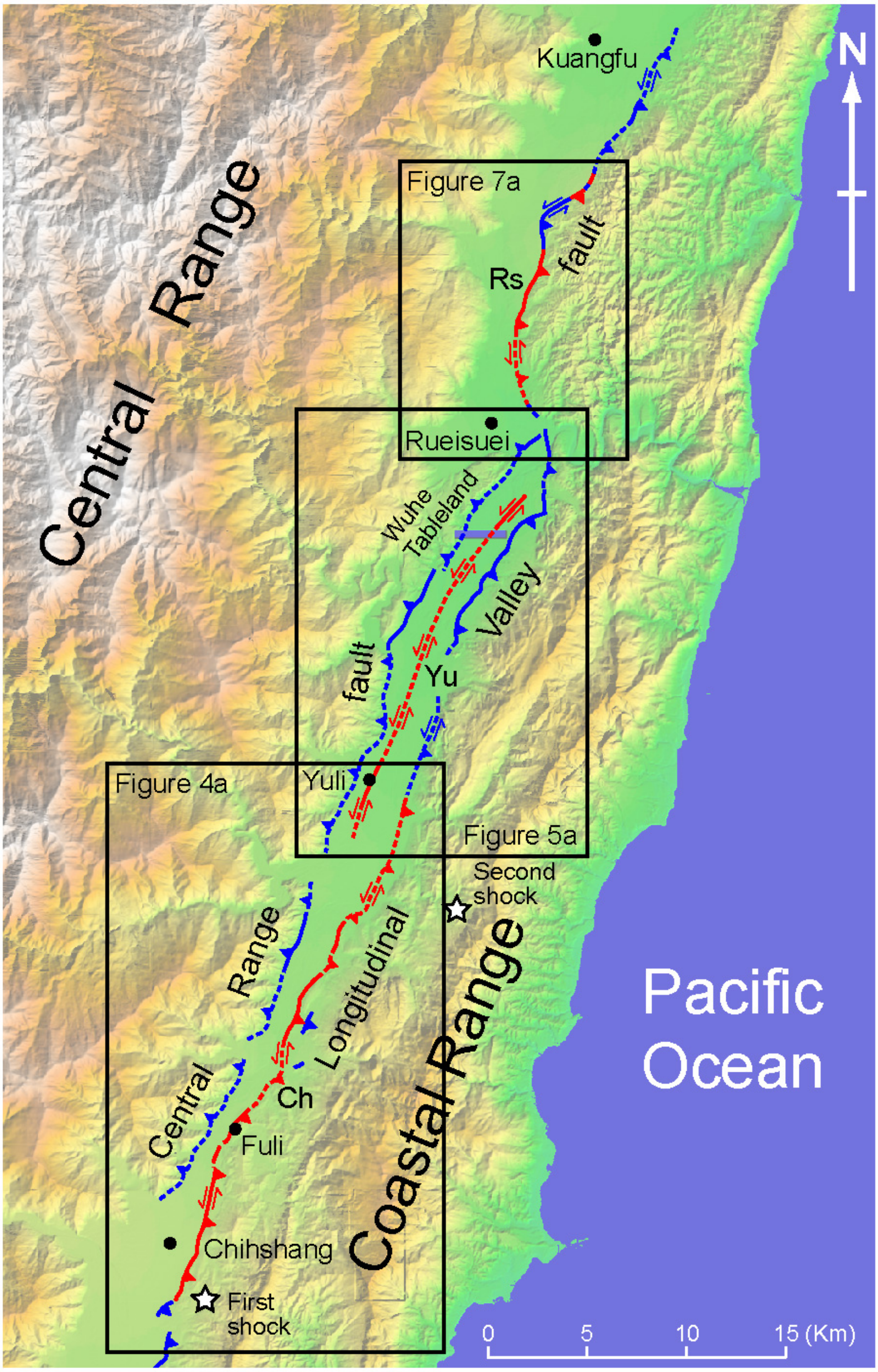

Kuangfu
N
Figure 7a
fault
Rs
Central
Range
Rueisuei
Wuhe
Tableland
Valley
fault
Yu
Figure 4a
Yuli
Figure 5a
Second
shock
Range
Longitudinal
Coastal Range
Pacific
Ocean
Central
Ch
Fuli
Chihshang
First
shock
0
5
10
15 (Km)

Figure 3

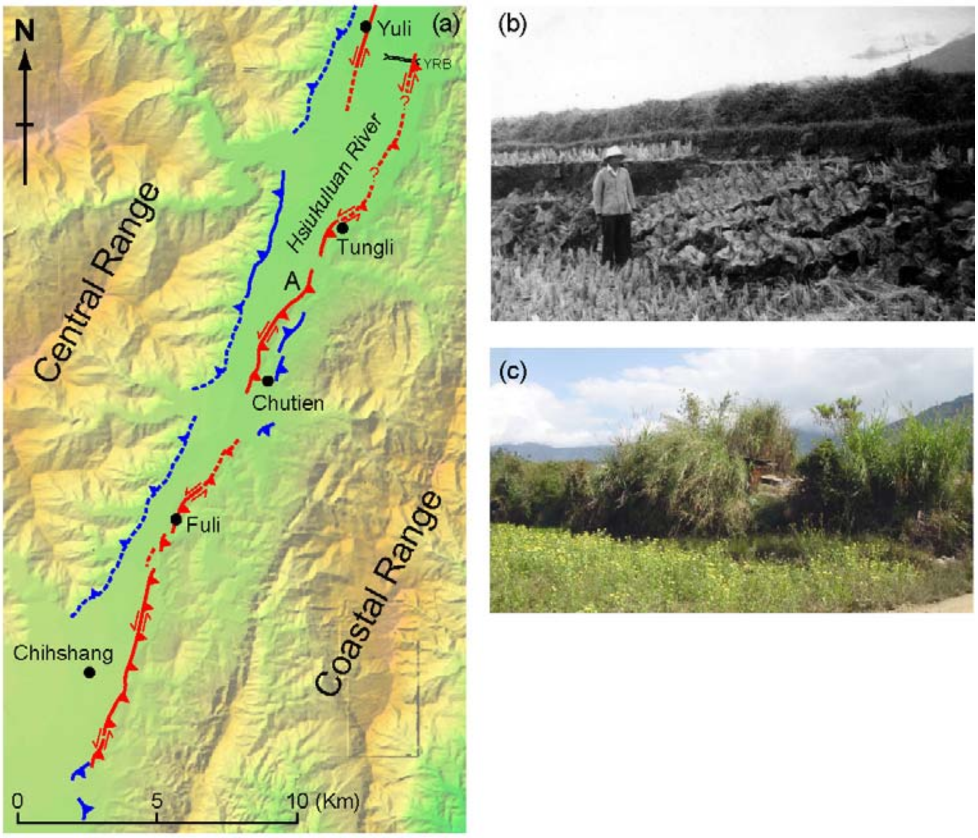
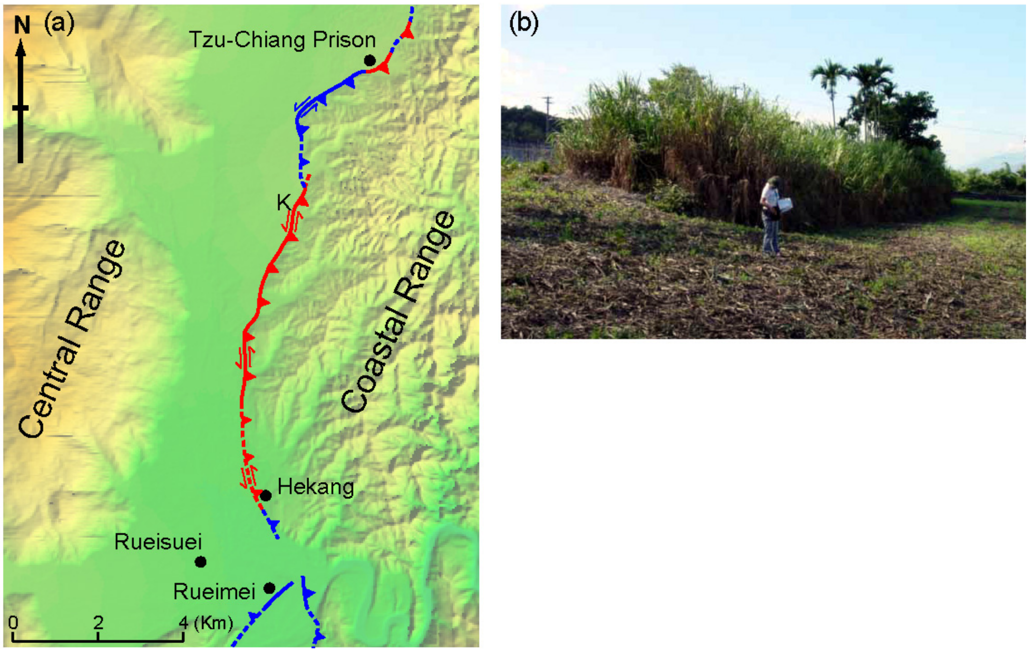

N
(a)
Yuli
YRB
Hsiukuluan River
Central Range
Tungli
A
Chutien
Fuli
Coastal Range
Chihshang
0
5
10 (Km)
(b)
(c)

Figure 4



N
(a)
Tzu-Chiang Prison
K
Central Range
Coastal Range
Hekang
Rueisuei
Rueimei
0
2
4 (Km)
(b)

Figure 5

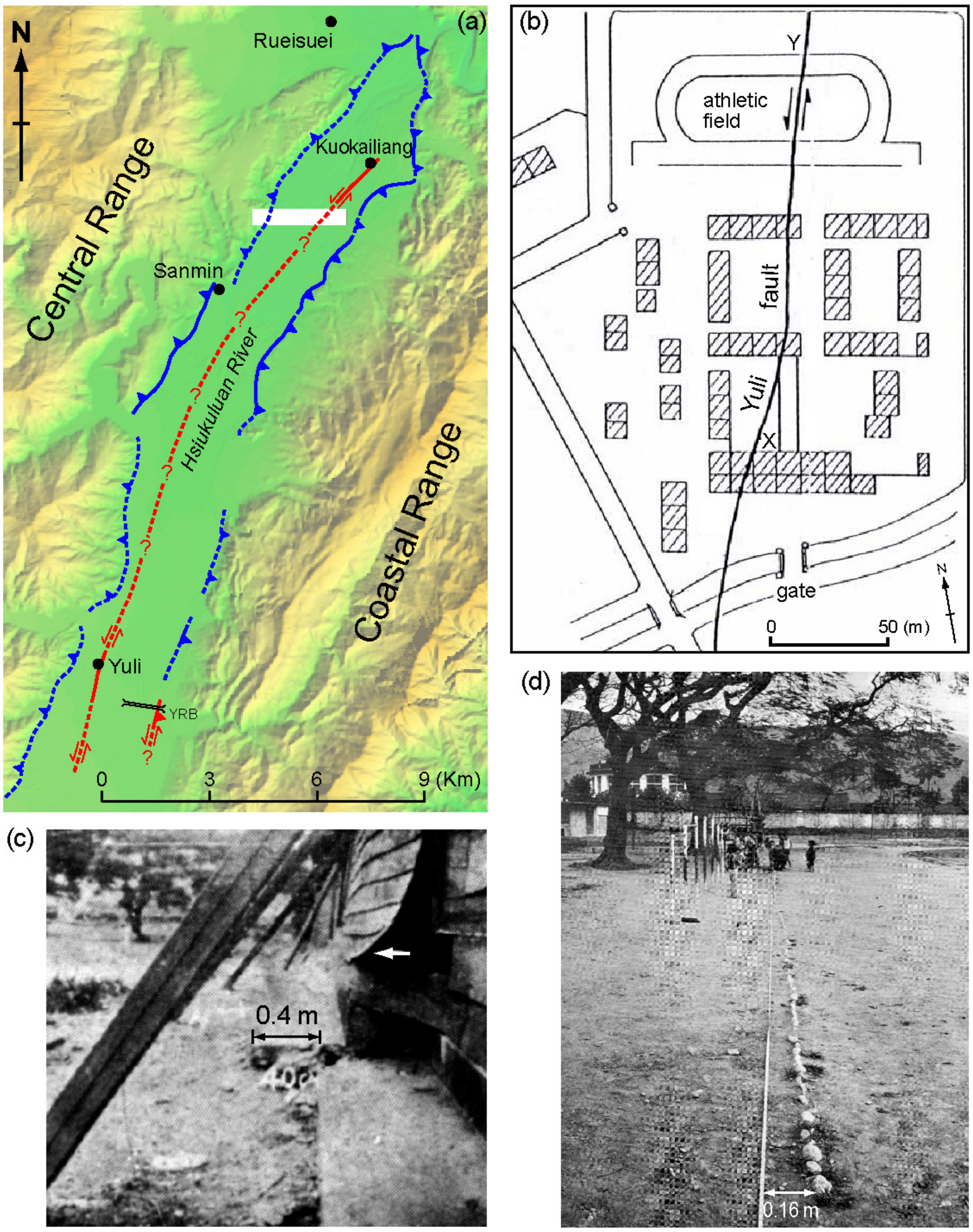

(a)
N
Rueisuei
Kuokailiang
Central Range
Sanmin
Hsiukuluan River
Coastal Range
Yuli
YRB
0
3
6
9 (Km)
(b)
Y
athletic field
fault
Yuli
X
gate
N
0
50 (m)
(c)
0.4 m
(d)
0.16 m

Figure 6

Figure 7

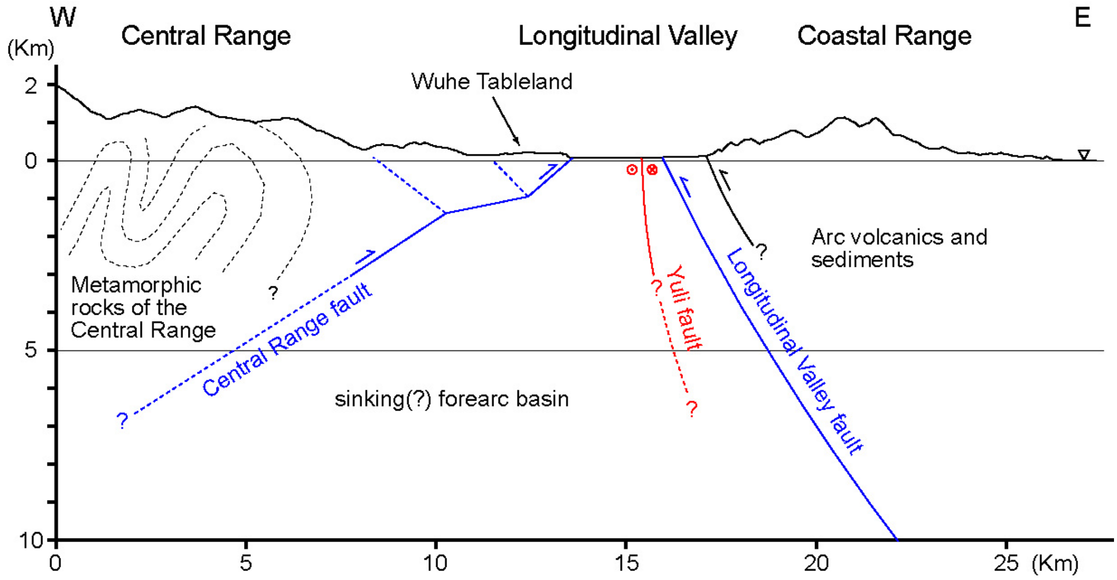

W
E
(Km)
Central Range
Longitudinal Valley
Coastal Range
Wuhe Tableland
Metamorphic rocks of the Central Range
Arc volcanics and sediments
Central Range fault
Yuli fault
Longitudinal Valley fault
sinking(?) forearc basin
2
0
5
10
0
5
10
15
20
25 (Km)

Figure 8