Paleoseismology of the Rueisuei Segment of the Longitudinal Valley Fault, Eastern Taiwan
by I-Chin Yen, Wen-Shan Chen, Chih-Cheng Barry Yang, Neng-Wei Huang, and Chii-Wen Lin

Abstract Paleoseismic trench excavations in the Dafu area of eastern Taiwan have provided data on the rupture history of the Rueisuei segment of the Longitudinal Valley fault during the late Holocene. The 1951 Taitung earthquake ruptured the Dafu site, which is characterized by several terrace raises with late Holocene sediments uplifted by the westward thrust fault. Trenches across the northwest-facing fault scarp exposed fluvial and alluvial deposit sediments. Although nearly all of the 23 radiocarbon ages vary somewhat within each layer, the overall age determined for each layer is in good accord with the stratigraphic ordering of these layers. Based on stratigraphic ordering and a statistical comparison of radiocarbon dates using the OxCal program, we estimate that two pre-1951 earthquake surface ruptures at the Dafu site occurred in the periods A.D. 1736–1898 and A.D. 1564–1680. The same OxCal model constrains the past two recurrence intervals to about 165 and 140 yr, although with sizable uncertainties, 55–215 and 90–260 yr, respectively, which are 95% ranges. Through the correlation of three trenches across the Longitudinal Valley fault, we are able to identify evidence for at least three earthquakes with moment magnitudes of about 7.0–7.2 that occurred up to 390 yr prior to and during 1951. Furthermore, based on the radiocarbon dates, the mean recurrence interval is roughly 150 yr (uncertainty is indeterminate), with a minimum vertical uplift rate of 8.5–12.2 mm/yr.

Introduction

The island of Taiwan is the product of the ongoing collision between the Luzon arc and the Chinese continental margin (Chai, 1972; Biq, 1973; Bowin et al., 1978; Teng, 1996; Fig. 1a). The Taiwan orogeny induced by collision started about 4 Ma (Chi et al., 1981; Teng, 1990; Lee and Lawver, 1995). At present, the active collision process is responsible for the highly active seismicity (Wu, 1978; Yu and Tsai, 1982; Tsai, 1986) and rapid crustal movement within and around the area (Chen, 1974; Seno, 1977; Yu et al., 1997). Lying between the two opposing Ryukyu and Luzon arcs, and based on its high level of seismicity, the Longitudinal Valley in eastern Taiwan is considered to be the suture zone of the active collision between the Luzon arc and the Chinese continental margin (Yu and Tsai, 1982; Kao et al., 1998; Rau and Wu, 1998; Chen and Rau, 2002; Kuochen et al., 2005).

The 150-km-long and approximately 4-km-wide Longitudinal Valley of eastern Taiwan lies between the Central Range and the Coastal Range, running from Hualien to Taitung (Fig. 2). The Longitudinal Valley fault is a blind fault under the Longitudinal Valley that dips eastward and separates the Chinese continental margin (the Central Range) to the west and the northernmost segment of the Luzon arc (the Coastal Range) to the east. Based on retriangulation undertaken between A.D. 1909 and 1942 (Chen, 1974) and the retriangulation and collection of leveling data carried out between A.D. 1983 and 1986 (Yu and Liu, 1989), shortening across the Longitudinal Valley fault was estimated to be 2 cm/yr. Several large earthquake ruptures on this fault occurred in 1951 (Hsu, 1962; Bonilla, 1975; York, 1976; Bonilla, 1977; Cheng et al., 1996).

On 24 November 1951, the Taitung earthquake took place, composed of two shocks that occurred at 18:47 and 18:50 UTC. The Yuli and Chihshang faults experienced surface ruptures during these earthquakes. The Yuli fault rupture extended about 43 km, strikes N20°E, and featured oblique left-lateral strike-slip movement. The maximum horizontal displacement was 163 cm, and the eastern block was uplifted 130 cm. The Chihshang fault is also an oblique left-lateral strike-slip fault 5 km away from the Yuli fault, with a rupture length of about 10 km and a strike of N20°E (Hsu, 1962; Bonilla, 1977). Because the surface ruptures were located in remote areas, there was no immediate investigation or detailed mapping of the rupture. The only map of the Taitung earthquake surface ruptures was published more than 10 yr after the earthquake, at a scale of approximately 1:2,000,000.
Figure 1. (a) Map showing the tectonic setting surrounding Taiwan. Taiwan orogen is located at the plate boundary between the Philippine Sea plate and the Eurasian plate; LVF: Longitudinal Valley fault. Current velocity vector of the Philippine Sea plate refers to Yu et al. (1997). (b) Geological map of the Coastal Range modified from Wang and Chen (1993).
More detailed maps of the active structures of the Longitudinal Valley have subsequently been produced (Shyu et al., 2005, 2007). Taiwan has experienced many destructive earthquakes during the past century (Bonilla, 1975, 1977; Cheng and Yeh, 1989). The 1951 earthquake events occurred within the locality with the highest level of seismicity in Taiwan. These events revealed the fault activity of the suture zone and illustrated the seismic potential of the Longitudinal Valley fault. Before the 1951 Taitung earthquake, there was no direct evidence of surface rupture in the Longitudinal Valley. Our goal is to obtain more information about the behavior of the Longitudinal Valley fault by conducting a paleoseismological study of the rupture zones. In the study reported herein, we excavated four trenches between the towns of Guangfu and Ruesuei, along the central part of the Longitudinal Valley fault, to determine the magnitudes of past earthquakes and the fault’s earthquake recurrence time.

**Geological Setting of the Longitudinal Valley**

The Longitudinal Valley is located between the Coastal Range and the Central Range in eastern Taiwan (Figs. 1 and 2). The Coastal Range is an assemblage of volcanic and siliciclastic rocks accreted within the Luzon arc-trench system (Chen, 1988; Fig. 1b). The Central Range is composed of low-grade metamorphic rock formed in the Mesozoic to Paleogene ages (Ho, 1988). Coarse clastic fluvial sediment (with a thickness of more than 1 km) from the late Quaternary age fills the Longitudinal Valley (e.g., Chen et al., 1974; Chen, 1976).

The east-dipping Longitudinal Valley fault is the dominant neotectonic element in eastern Taiwan. It follows the eastern edge of the valley and accommodates the rapid uplift of the Coastal Range on its hanging-wall block (Hsu, 1954; Hsu et al., 2003). Several large earthquakes occurred in 1951, causing surface ruptures along the fault (Hsu, 1962; Bonilla, 1975; York, 1976; Cheng et al., 1996). According to Angelier et al. (1997) and Lee et al. (2003), one part of the Longitudinal Valley fault is creeping aseismically at a high rate. Geodetic results indicate that the net horizontal motion across the Longitudinal Valley changes from 34 mm/yr along a section with a trend of 314° at Taitung to 25 mm/yr along the north–south section at Hualien (Yu et al., 1990). Creepmeter measurements reveal that the Longitudinal Valley fault zone is creeping at a rate of about 20 mm/yr near the town of Chihshang (Lee et al., 2001, 2003). Inversion of Global Positioning System (GPS) data across Taiwan also indicates that the Longitudinal Valley fault is a major active structure (Hsu et al., 2003).

In the central Longitudinal Valley, Quaternary alluvial fans and river terraces are well developed and preserved. The principal sources for the Quaternary deposits found within the valley are conglomerates from the Coastal Range and metamorphic rock from the Central Range. Surface ruptures along the Longitudinal Valley fault during the 1951 earthquake series (Hsu, 1962; Shyu et al., 2007) extend approximately 40 km from south of Guangfu to north of Fuli (Fig. 2), with 1.63 m of left-lateral offset and 1.3 m of vertical offset around the Ruesuei area (Hsu, 1955; Shyu et al., 2007). The seismic rupture displaced terraces from Guangfu to Ruesuei. A dense GPS network surveyed from 1996 to 1999 revealed a velocity of 13.3–20.4 mm/yr along a direction varying between 309° and 314° in this area (Yu and Kuo, 2001).
The 1951 Earthquake

Two major shocks occurred at 02:47 and 02:50 (local time) on 25 November 1951 (Taiwan Weather Bureau, 1952) on the Yuli and Chihshang faults, respectively. Cheng et al. (1996) used the S-P times reported by the Taiwan Weather Bureau to relocate the epicenter using a Monte Carlo algorithm. The length of the surface fault rupture and the maximum ground-motion amplitudes were applied to reevaluate the magnitude of these two events. They placed the hypocenter of the first shock at 23.100°N and 121.225°E, with a depth of 16 km and a magnitude of $M_w 6.2$. The hypocenter of the second shock was located at 23.175°N and 121.350°E at a depth of 36 km, with a magnitude of $M_w 7.0$. They also derived focal mechanisms by combining the first P motion reported by the Taiwan Weather Bureau (1952) with geological data recorded in Hsu’s (1962) map. They conclude that the first shock was a thrust fault with a left-lateral strike-slip component (strike, N32°E; dip, 70° SE; and rake, 70°) and that the second shock was a left-lateral strike slip with a thrust fault component (strike, N25°E; dip, 70° SE; and rake, 40°). These two shocks caused 17 fatalities and seriously injured 326, while destroying 1016 houses and partly damaging 582 others from the village of Wulou (3.8 km north of Rueisuei) to Chihshang.

Shyu et al. (2007) reevaluated the 1951 earthquake ruptures by analyzing published documents, relevant reports, and photographs and by interviewing more than 40 elderly local residents who experienced the earthquakes. Based on this reevaluation, they divided the surface ruptures into three sections from south to north—the Chihshang, Yuli, and...
Rueisuei sections. The Chihshang section is approximately 30 km long and probably ruptured during the first shock of the 1951 earthquake series. The length of the Yuli rupture is about 20 km, and the Rueisuei rupture is about 15 km long; both ruptures were probably produced by the second shock of the 1951 series. They concluded that the Chihshang rupture, which produced the first shock, probably triggered the subsequent failure of the Yuli and Rueisuei ruptures. They also consider that the northern end of the Rueisuei rupture is near the Tzu-Chiang Prison (about 10 km south of the town of Kuangfu) and that the southern end is near the village of Hekang (about 2 km east of the town of Rueisuei), extending about 15 km along the western foothills of the Coastal Range. Along the rupture, most of the rupture scarps are still visible, allowing us to select places to trench.

**Geomorphic Framework of the Trench Area**

Fuyuan stream is the largest stream in the study area that flows from the Coastal Range (Fig. 3). From Dafu Farm to Daduhwa village, the stream formed Holocene alluvial fans 5 km in length and 1 km in width in the central area of the Longitudinal Valley. Daduhwa stream flows from the Coastal Range and merges with the Fuyuan stream southwest of Daduhwa village. Aside from these two streams, a few intermittent streams also supply sediments to the alluvial fan. Several uplifted stream terraces, which are about 2–3 m higher that the alluvial fan, run along the mountain streams and cross the fans with a distinct fault scarp running in a north-northeast–south-southwest direction.

We reinvestigated the reported 1951 rupture and mapped the surface rupture in greater detail. We found that the 1951 earthquake rupture was along the reported north-northeast–south-southwest trending fault scarp and recorded about 1.2 m of height in this area. However, we also found a surface rupture that had not previously been mapped. This newly discovered surface rupture displaces the eastern terrace rise by about 2 m (Fig. 4). At this location, we excavated four trenches across and perpendicular to the surface rupture trace.

**Radiocarbon Dating**

We collected detrital charcoal in the trenches. Samples for radiocarbon dating were analyzed by Beta Analytic, Inc. (Miami, Florida). A total of 23 charcoal fragment samples were dated by accelerator mass spectrometry (Table 1). All samples are detrital, so they represent the maximum ages for the sedimentary layers from which they were collected, because the samples may have already had a significant radiocarbon age at the time they were deposited. These analyses suggest that the composite stratigraphic record at the Dafu site extended from at least A.D. 1500 to the present.

### Table 1

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<th>Sample Number</th>
<th>Laboratory Number</th>
<th>Stratigraphic Unit</th>
<th>Description</th>
<th>Radiocarbon Age* (yr B.P.)</th>
<th>Calendar Date</th>
<th>Calibrated Age† (yr A.D. 2σ)</th>
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<td>310 ± 40</td>
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</table>

*Radiocarbon ages were measured using accelerator mass spectrometry by Beta Analytic, Inc.

†Calendar age dendrochronologically calibrated by method A from the program of Reimer et al. (2004), with 2 standard deviation uncertainty.

‡Calibrated using OxCal Program 4.0.5 (Ramsey, 2007).
We assume that the charcoal incorporated into each deposit was derived from the ground surface or near-surface soil directly uphill from the depositional site and that the $2\sigma$ range in calibrated age adequately reflects the maximum deposit age. Therefore, the youngest radiocarbon date from each unit should best represent the maximum deposit age.

Based on this approach, a total of 23 samples yielded representative ages (Fig. 5), and these dates were used in the OxCal calibration and analysis program (Ramsey, 1995, 2001, 2007) to help interpret the ages of the deposits and timing of earthquake events at the Dafu site. This program uses stratigraphic relations among deposits and Bayesian statistics applied to deposit ages to develop probability density functions for the ages of interdeposit events. The laboratory ages of these deposits were calibrated to the tree-ring record using the OxCal program (version 4.0.5; Ramsey, 2007) and were then used to construct an analytical model that consists of four separate depositional phases encompassing the three earthquake events.

**Paleoseismology Analysis**

**Sequence of Events and Rupture Displacement**

We excavated four trenches, each about 20 m long, 6 m deep, and 8 m wide (DF-1, DF-2, DF-3, and DF-4) across the fault scarp at the Dafu site (Fig. 4b). The Longitudinal Valley fault at the margin of the Coastal Range displaces the Pleistocene conglomerate and Holocene alluvial deposits. The trench walls showed intense folding in the hanging wall, related to four reverse fault strands (Fc1, Fc2, Fc3, and Fc4). The exposed sediment is predominately composed of alluvial and colluvial deposits and two organic-rich silty layers (units O2 and O1; Fig. 6). The lower units G1 and G2 are stratified gravels with lenticular sand layers of alluvial deposits. The matrix of unit G1 is muddier than unit G2, and the gravel deposits of unit G1 are larger than those of unit G2. Unit S2 consists of matrix-supported gravels deposited as colluvium on the fault scarp. Unit S1 consists of planar laminated fine sand, interpreted to be a fluvisol deposit, forming a flood plain on the fault scarp.

On the basis of cross-cutting relations, event E1 along faults Fc1 and Fc4 occurred after deposition of unit S2 but before unit T. The displacement of fault Fc1 is thus interpreted to have been caused by the 1951 earthquake (Fig. 6). The vertical displacement of Fc1 in trench DF-4 is about 1.5 m (Fig. 6b). The vertical displacement of fault Fc1 in the northern wall of trench DF-2 is 1.7 m as defined by the offset of unit S2 (Fig. 6d, A to A'), whereas the bottom of unit O1 displays a vertical displacement of at least 3 m across the same fault (Fig. 6c, B to B'). These observations indicate that fault Fc1 has been subject to at least two events, which we refer to as the E1 event (the 1951 earthquake) and the Ena event (older). The restoration of the offset of the 1951 earthquake still gives a vertical displacement for fault Fc1 of 1.3 m, and unit G2 retains warping and overlapping.
on unit O2, which indicates that the Ena event occurred after the deposition of unit O2. We propose that fault Fc1 represents slippage from two events: 1.7 m in 1951 and 1.3 m from an older event (Ena).

The E2 event was preserved by a deformation event. Unit O1 between Fc3 and Fc1 in the north wall of DF-2 was deformed and covered by the undeformed unit S2, the deformation causing a 0.3-m vertical displacement of unit

Figure 6. (a) Map of the southern wall of trench 1. (b) Map of the northern wall of trench 1. (c) Map of the southern wall of trench 2. (d) Map of the northern wall of trench 2. The inset, d', is a detailed map of event E2 of the northern wall of trench 2. (e) Map of the southern wall of trench 3. (f) Map of the northern wall of trench 3. (g) Map of the southern wall of trench 4. (h) Map of the northern wall of trench 4. The dates indicate the 2σ calendrical age range for each sample, based upon accelerator mass spectrometry radiocarbon analyses (Table 1). (Continued)
O2 (Fig. 6d and the inset d'). Thus, the E2 event must have occurred after the deposition of unit O2 and before the deposition of unit S2.

The E3 event was responsible for the displacement of unit G1 along fault Fc3 and is also covered by the undeformed unit O1 (Fig. 6c–6f). The average vertical displacement of unit O2 across fault Fc3 is 0.6 m (Fig. 6d, D to D'). Unit G2 in the trenches DF-2 and DF-3 appears to have been displaced by fault Fc2 in the hanging wall (Fig. 6g), and the fault tip is covered by the undeformed unit S2 (Fig. 6c,
Thus, the Enb event must have occurred after the deposition of unit G2 and before the deposition of unit S2 by fault Fc2. The average vertical displacement of unit G2 across the fault Fc2 is 1 m (Fig. 6d, C to C′).

The stratigraphic relationships show the E2 and Ena displacements to have occurred after the deposition of unit O2, but there is no way to distinguish between the two events. On the assumption that each event was similar in terms of vertical displacement, we believe the two deformations probably occurred during the same episode of faulting and can determine that the extent of vertical displacement that occurred as a result of the E2 event was 1.6 m. Here, we also believe that the E3 event and the Enb event occurred at the same time. Hence, the E3 event caused a vertical displacement of 1.6 m.

Consequently, the evolution model of the fault active in the Dafu trench site is as shown in Figure 7. First, unit G1 was deposited after unit O2 and unit G2. The E3 event occurred after unit G1 was deposited with fault strands Fc2 and Fc3 and caused a vertical displacement of 1.6 m. After the E3 event, unit O1 was deposited following an erosion process. Immediately thereafter, the fault strand Fc1 was cut through O1 and caused the deformation in front of fault strand Fc1 during the E2 event, resulting in a total vertical displacement of 1.6 m. Finally, the 1951 event (E1) occurred after the unit S2 deposit on the erosion surface and was covered by unit T.

**Paleoearthquake Timing**

Based on radiocarbon dates estimated using the Bayesian approach and the paleoseismological event sequence, we propose the paleoearthquake timing for this fault segment. Assuming that the three stratigraphically consistent radiocarbon ages of the detrital charcoal samples (CLKN07, CLKN18, and CLKN101) represent the depositional ages of unit O2, we interpret the depositional age of unit O2 to be A.D. 1524–1660. Based on the 11 detrital charcoal sam-
we calculate the depositional age for unit O1 to be A.D. 1619–1854. Based on the seven detrital charcoal samples (CLK011, CLK035, CLK037, CLK056, CLK066, CLKN017, and CLKN089), the depositional age of unit S1 is A.D. 1762–1950. Finally, based on two detrital charcoal samples (DAF36 and DAF74), the depositional age of unit T, the youngest unit, is later than A.D. 1951. The E1 event is the 1951 earthquake. The E2 event must have occurred after the deposition of unit O1 and before the deposition of unit S2, that is, between A.D. 1736 and 1898, based on the Bayesian approach. The E3 event was responsible for the displacement of unit G1, yet is covered by undeformed unit O1, which indicates the E3 event occurred between the deposition of unit G1 and unit O1. The lack of dates for unit G2 prevents us from defining the upper chronological limit, but using the dates calculated under the Bayesian approach, we estimate that the E3 event occurred between A.D. 1564 and 1680.

Recurrence Time

Based on the chronological constraints in each trench for the paleoearthquakes, we attempted to correlate events between these four trenches (Fig. 7). At least three earthquake
events have occurred in the past 390 yr. The most recent event is the 1951 earthquake observed in all four trenches. The earliest event is E3, which probably occurred between A.D. 1564 and 1680 (95% confidence range). E2 probably occurred between A.D. 1736 and 1898 (95% confidence range). Using OxCal, we calculate the earlier recurrence interval to be 91–158 yr (95% confidence range) and the later interval to be 56–216 yr. The mean recurrence interval for the past 390 yr is about 150 yr (Table 2), but error statistics for the mean were not resolvable in OxCal, probably because there are only two intervals and the errors of each are relatively large.

Vertical Uplift Rate

In Figure 8, the solid line shows the vertical offset of each event in the vertical dimension and represents the age constraints of the events with 2σ uncertainties in the horizontal dimension. According to the estimated displacement and the calculated occurrence interval, we can delineate the average yearly vertical uplift rate as the slope of dashed lines, which is between 8.5 and 12.2 mm/yr during the past 390 yr.

### Discussion

#### Slip Rate Estimation

We were unable to determine the fault slip direction from the trenches. However, through a combination of the fault dipping angle and the vertical uplift rate, we can calculate a more accurate fault slip rate using trigonometry. Based on the 30° dipping angle of the fault and a vertical uplift rate of between 8.5 and 12.2 mm/yr, we obtain a slip rate of 17.0–24.4 mm/yr. This slip rate is very similar to the longer term slip rate of the Longitudinal Valley fault (22.7 mm/yr) obtained from the Holocene uplift rate of terraces along the Hsiukuluan River (Shyu et al., 2006). Therefore, we propose that the interseismic stress accumulation is totally released by a coseismic rupture. The Longitudinal Valley fault at this segment seems to be locked during interseismic periods.

#### Magnitude of the Paleoearthquakes

The magnitude of a paleoearthquake can be estimated from fault displacement. Wells and Coppersmith (1994) obtained relationships of average displacement to moment magnitude from published reports of documented historical surface ruptures. Using data from all types of faults, they found that moment magnitude (M) and average displacement (AD) are related as follows:

\[
M = (6.93 \pm 0.05) + (0.82 \pm 0.10) \times \log(AD).
\]

The average displacement of the 1951 earthquake (E1) was 1.7 m, which corresponds to a moment magnitude, M, of 7.1 ± 0.1. The average displacements of the E2 and E3 events were both 1.6 m, which corresponds to a moment magnitude (M) of 7.1 ± 0.1. Thus, the moment magnitudes of the paleoearthquakes at the Dafu site were about 7.0–7.2.
Conclusions

From the paleoseismological record of the Longitudinal Valley fault at the Dafu site, four reverse fault strands with three paleoearthquake ruptures occurred in A.D. 1951 and in the periods A.D. 1736–1898 and A.D. 1564–1680. The mean occurrence interval for the past 390 yr at the Dafu site is approximately 150 yr, and the slip rate is 17.0–24.4 mm/yr. Based on the empirical relationships of magnitude and surface displacement, the moment magnitudes of the paleoearthquakes were about 7.0–7.2.

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