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Surface Rupture of 1999 Chi-Chi Earthquake Yields Insights on Active Tectonics of Central Taiwan

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Abstract The 1999 Chi-Chi earthquake was caused by rupture of the Chelungpu fault, one of the most prominent active thrust faults of Taiwan. This largest of Taiwan's historical fault ruptures broke the surface for over 90 km at the western base of the rugged mountain range. A short right-lateral tear extended southwestward from the southern end of the Chelungpu fault, and a complex assemblage of shallow folds and faults ran northeastward from the northern end. Vertical offsets averaged about 2 m along the southern half of the Chelungpu fault and about 4 m along the northern half, and offsets of 5 to 7 m were typical along the northern part of the major thrust. The sinuous nature of the surface trace is consistent with seismographic data that indicate a dip of about 30°. The 1999 rupture draws attention to the fact that this active fault system is highly segmented and that this segmentation influences the characteristics of seismic ruptures. Active faults to the south, north, and west of the Chelungpu fault have distinctly different characteristics. Faults to the south and north broke the surface during earthquakes in 1906 and 1935. The active Changhua fault to the west, a blind thrust similar in length to the Chelungpu, has not ruptured in the historical period and should be considered a prime candidate for generating a future earthquake.

Introduction

Taiwan exists because of a complexity in the collision of the oceanic Philippine Sea plate and the Eurasian plate. To the south, an oceanic part of the Eurasian plate is subducting beneath the Philippine Sea plate, along the Manila trench (Fig. 1a). At the latitude of southern Taiwan, the Philippine Sea plate is riding up over the continental shelf of the South China Sea. The result is the bulldozing both westward and upward of shelf sediments. This has created the island of Taiwan in the past 5 million years (Ho, 1988; Teng, 1987, 1990). Since Taiwan is such a young tectonic entity, recent crustal movements are inevitable, and active structures are widely distributed (Bonilla, 1975, 1977; Peng *et al.,* 1977; Chen, 1984; Yu *et al.,* 1997, 1999; Chang *et al.,* 1998).

The 1999 rupture is the most recent manifestation of the rapidly evolving neotectonic setting of Taiwan along the plate boundary and the resulting southeast-to-northwest obduction of shelf sediments of the South China Sea onto the shelf (Ho, 1988; Teng, 1987, 1990). Although Taiwan is only 400 km by 200 km in dimension, it is one of the more seismically active regions on Earth. More than 50 active faults were previously reported (Bonilla, 1975, 1977; Chang *et al.,* 1998). During the twentieth century more than 180 earthquakes equal to or larger than M_L 6.0 and 40 equal to or greater than M_L 7.0 have occurred (Cheng *et al.,* 1999). About 30 of these have caused loss of life or property. However, surface rupture has accompanied only four of these earthquakes. Even globally, well-documented ruptures of thrust faults are quite rare (Rubin, 1996). Thus, the occurrence of surface rupture during the 1999 earthquake provides an unusual opportunity to observe directly an active thrust fault and to clarify its role in the rapidly evolving neotectonic story of Taiwan.

Neotectonics of Central Taiwan

The neotectonics of northern Taiwan results from a very different geometry and polarity of subduction. There the Philippine Sea plate is subducting beneath the Eurasian plate, and back-arc spreading is occurring along the Okinawa trough (Fig. 1a). Suppe has explained kinematically how the flipping of subduction polarity is migrating southward across the island (Suppe, 1984). Currently, the line of flipping is about 20 km north of the region of the 1999 rupture. Thus, the 1999 rupture occurred in the neotectonic context of northwestward obduction of shelf sediment onto the Eurasian continent.

Looking at central Taiwan, the 1999 rupture was the latest increment of slip to occur along a north–south–striking

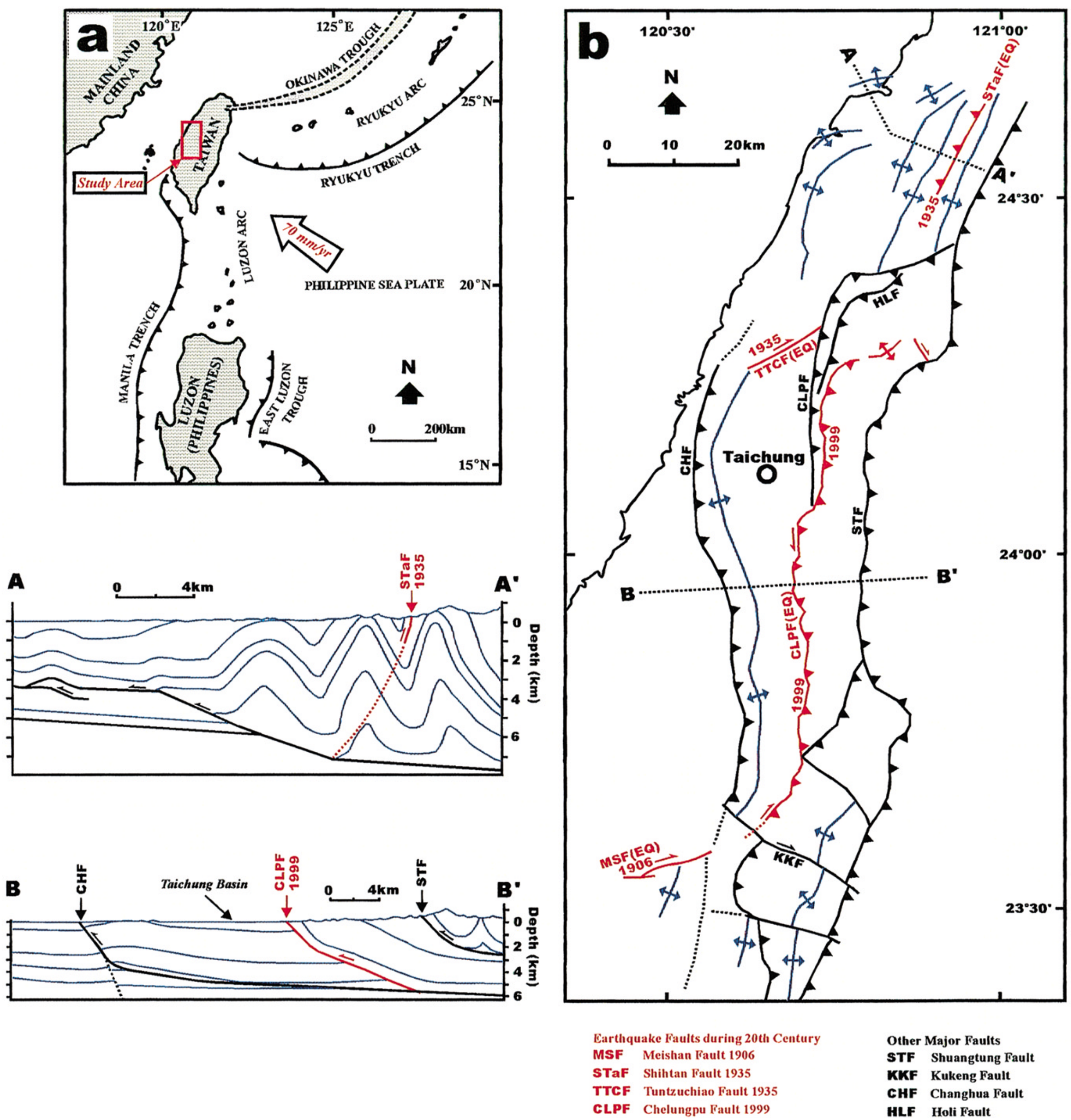

Figure 1. (a) Modern tectonic environment around Taiwan region, where the collision is still ongoing while the Philippine sea plate is moving northwestward with a speed of 70 mm/yr (Ho, 1988; Teng, 1987, 1990). (b) Detailed structure map of Taichung and Miaoli areas (CPC, 1982). The relevant twentieth century ruptures are marked in red. The other major faults are in black, and major anticlines are in blue. Cross sections show that the Miaoli area (AA′) is composed of a chain of folds, which is distinguishable to Taichung area where crustal slices bounded by major thrust faults (Bonilla, 1975, 1977; Namson, 1981, 1983, 1984). To the south, the CHF and its associated anticline are truncated by MSF and the southernmost extension of 1999 rupture.

thrust fault. This fault—the Chelungpu fault (CLPF)—had been well characterized before the earthquake (Meng, 1963; Chang, 1971). It is one of three major east-dipping thrust faults along which the mountain ranges have been rising at this latitude (Fig. 1b, cross section BB′). The thrust faults in the west initiated more recently in the east than in the west (Chen *et al.,* 2000a), a sequencing that is consistent with snowplow theory (Suppe, 1981, 1983; Davis *et al.,* 1983). The CLPF was initiated only about 0.7 million years ago (Chen *et al.,* 2000a, 2001)—it cuts Pleistocene footwall strata at an angle of about 30°, but it is parallel to Pliocene hanging-wall strata (Meng, 1963; Chang, 1971). Thus it is a thrust ramp in the shallow crust that must become a bedding-parallel decollement at depth (Davis *et al.,* 1983). From these relationships one can infer that total throw exceeds 12 km and that the average slip rate for the past 0.7 million years is greater than or equal to 17.1 mm/yr. Geodetic Global Positioning System (GPS) vectors show that contraction across the entire island is about 56 to 82 mm/yr, whereas 3.9 to 12.7 mm/yr was obtained for fold and thrust belt at the latitude of the CLPF (Yu *et al.,* 1997, 1999).

Faulting of young strata had shown the CLPF to be a young fault (Chang *et al.,* 1998; Yang, 1997). But its clear geomorphic expression had not been widely appreciated prior to the earthquake. Therefore, its surface trace was depicted on maps as a dashed line connecting limited outcrops (Meng, 1963; Chang, 1971; CPC, 1982), and its northern half had been mapped not along the mountain front, but beneath the sediments of the Taichung basin (Fig. 2). Scientists categorized the CLPF fault as a second class active fault, which means that evidence in support of Holocene activity was not compelling (Chang *et al.,* 1998).

Surface Rupture of 1999

The 1999 rupture of the CLPF crops out primarily along the western base of the mountain front (Central Geological Survey [CGS], 1999; Ma *et al.,* 1999; Bilham and Yu, 2000) (Figs. 2 and 3). The southern part follows its previously mapped fault trace; however, the northern part migrates eastward into an original hanging wall and exhibits a curvature in Tachia river valley. As is common for thrust faults, the trace of the fault rupture is highly sinuous, and so local dextral and sinistral components of slip vary greatly over short distances. Where modern floodplains cross the mountain front, geomorphic evidence of previous faulting is eroded or buried. Elsewhere, the rupture faithfully added to the height of older scarps cutting alluvial and colluvial deposits (Fig. 3e, g).

To first order, the rupture trace is continuous and not geometrically disjunct. However, the nature of slip along the rupture does suggest division of the rupture into four distinct domains (Fig. 2). Segments II and III represent the principal rupture (Fig. 3c–i), whereas segments I and IV are the southernmost and northernmost portions (Fig. 3a, j). Segments II and III are separated at Wufeng by a 4-km jog in the range front and the rupture. Slip along segment II is nearly pure thrust, and vertical offset ranges from 1 to 4 m (Figs. 2, 3b–i). The regional left-lateral component of slip is less than 0.5 m. Vertical offsets along segment III are commonly 3.5–6 m, and near Shihkang over 8 m (Fig. 4b). Sinistral components of offset along segment III range from 2 to 5 m (CGS, 1999; Lin *et al.,* 2000).

The vertical offsets are a basis for estimating the magnitudes of dip slip on the fault plane if one can establish the dip of the fault plane. The observed dips are consistent with the 20° to 30° dips estimated from hypocentral depth and seismographic inversions (Ma *et al.,* 1999; Kao and Chen, 2000). In general, as shown in Figure 2, the slip in the north is higher than in the south, indicating that the CLPF must be segmented and recurs with various spatial and temporal recurrence intervals as reported along the San Andreas fault in the United States (e.g., Sieh, 1978).

Segment I is a dextral strike-slip fault that trends N30°E at the southern end of the 1999 rupture. Dextral offset ranges from 1.5 to 2.5 m (Fig. 3j). Vertical slip ranges from 0.5 to 1.0 m. It shows very similar sense and spatially shares a line with the 1906 Meishan rupture. As Kao and Chen (2000) reported, there are two suggested structures identified by aftershock groups of Chi-Chi earthquake acted as the southern termination of the entire Chelungpu fault. In fact the western one coincides the segment I present in this article, and the other has not been confirmed based on current field investigation. On the other hand, segment IV is the most complex part of the fault rupture. It consists of an extraordinary zone of reverse faults, anticlines, and monoclines (CGS, 1999; Lee *et al.,* 2001) (Figs. 2a, and 3b, 4). The principal form of this zone of disruption is a 2-km-wide zone of anticlinal warping. Reverse faults and tight kink bands flank the anticlines. The flanking fault scarps and monoclinal scarps are commonly between 2 and 5 m in height (Fig. 3a). This zone of deformation incrementally added to the structural relief of a preexisting minor anticline (Chinese Petroleum Corporation [CPC], 1982). We might treat this segment as a developing tear fault, which will eventually cut through its original structural elements as its northern two ancient analogs, i.e., the old CLPF, CLPF(O), and the Holifault (HLF) in Figure 2. Although a right-lateral strike slip has been derived from the focal mechanism of aftershocks (Kao and Chen, 2000), the field investigations only recorded a minor strike-slip component (CGS, 1999; Lee *et al.,* 2001). This is probably caused by different structural behaviors involved in different scales.

Discussion

Seismogenic Domain of Central Taiwan

The 1999 Chelungpu rupture incrementally increases our understanding of the influence of fault geometry on seismic sources. This is a well-behaved event in that the rupture involved the entirely of a well-defined active thrust fault and

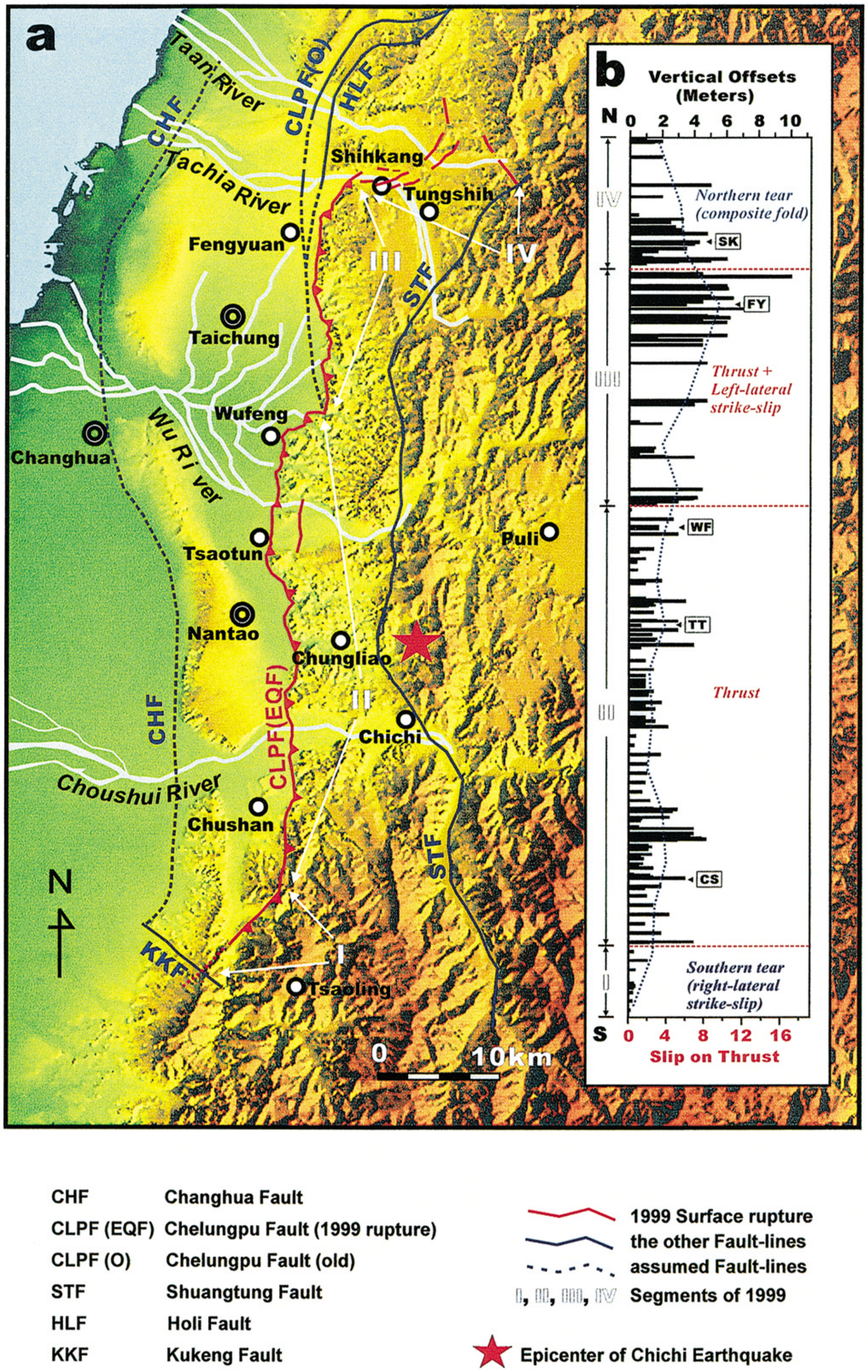

Figure 2. (a) Map showing the 1999 rupture (red lines) (CGS, 1999) with specified segments: I, II, III, IV (white) and the neighboring major faults (blue). (b) Field observations of the vertical offsets and derived horizontal shortening under the assumption of 30° for dipping angle of fault plane (note: only applicable for segment II and III, where low angle thrust fault was found). Blue line represents running average of 5 km. Red star locates the epicenter of 1999 Chi-Chi earthquake. The abbreviations of SK, FY, TT, and CS represent town names of Shihkang, Fengyuan, Tsaotun, and Chushan, respectively.

Figure 3. (a) This picture, viewing southward in the northern bank of Taan river, shows the segment IV. A fold scarp, across the picture from the bottom to top, formed during Chi-Chi earthquake and destroyed the buildings construsted on it. (b) The 1999 rupture offset the bedrock exposed on Tachia river valley to form a new waterfall and to tear down a bridge. Left-hand side is the hanging wall and the total vertical displacement is 7 to 8 m, the largest vertical offset recorded in Chi-Chi earthquake. (c) Picture showing the segment III of 1999 rupture runs along the mountain front, indicating the Chelungpu fault is recently active. (d) Segment II offset runway and playground of an elementary school. (e) Segment II disrupted a paddy field in front of a retaining wall, which was modified from a pre-existing scarp. (f) Segment II crossed over and damaged a modern bridge, which is supposed to survive in a strong earthquake. (*Continued on next page.*)

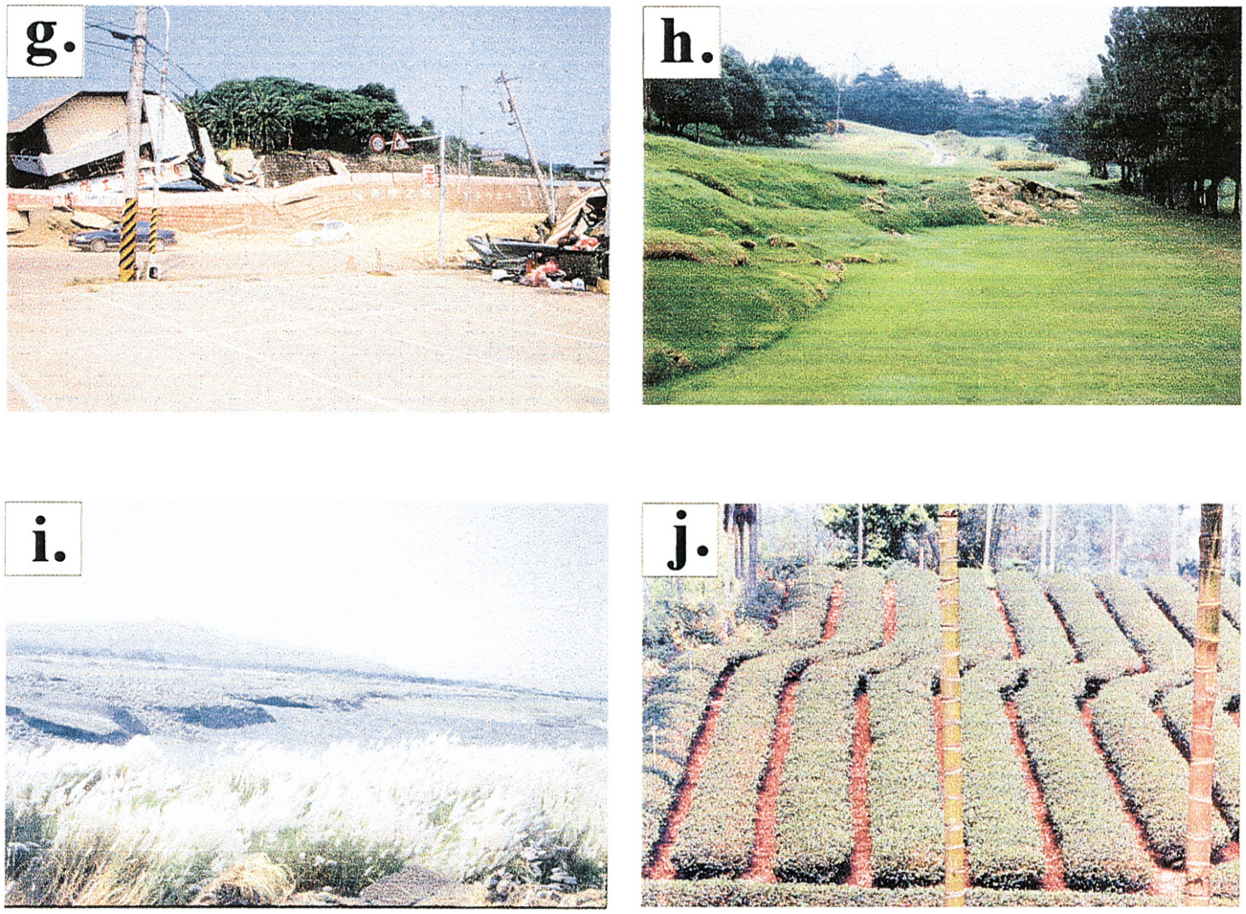

Figure 3. (*Continued*) (g) Segment II exactly runs along a pre-existing scarp front. (h) Segment II intercepted the fairway of a golf course, indicating that the course designer has modified the original mountain front. (i) Segment II crosses the Chouhsui river, the biggest river in Taiwan. (j) The tea plantation plays as a strain marker to show the right-lateral slip of segment I.

accommodation structures on both ends. Most well-documented thrust-fault ruptures involve multiple segments or partial rupture of solitary segments (Rubin, 1996). In this case, both the southern and northern ends of the rupture are within previously recognized transition zones that separate the Changhua/Chelungpu/Shuangtang system from neighboring systems to the north and south (Fig. 1b). The Changhua/Chelungpu/Shuangtang system roots into a decollement at a depth of only about 5 km, whereas the north- and south-adjacent thrust systems appear to dive several km deeper into the crust before they root into detachments (Chen, 1978; Chiu, 1971; Suppe, 1986; Namson, 1981, 1983, 1984). The system to the north has produced four major folds between the STF and the west coast but no thrust faults analogous to the CLPF and CHF (cross section AA′ in Fig. 1). The broad open fold near the coast is probably a fault-bend fold and the tight folds farther inland may be the ancient analogs. A large earthquake in 1935 involved about 3 m of reverse slip on a west-dipping fault and about 2 m of dextral slip on a northeast striking fault (Otuka, 1936) (Fig. 1b). The former is probably a back thrust on a large, deep, decollement. The dextral-slip rupture west of the northern end of the 1999 rupture truncates the CHF on the north and is most probably an accommodation structure that helps to separate the two structural domains. The dextral-slip rupture of 1906 and segment 1 of the 1999 rupture serve a similar purpose on the south (Fig. 1b, 3j). These two dextral-slip ruptures are co-parallel and may even be parts of the same accommodation structure. Rupture parameters in 1906 (Omori, 1907) were very similar to those of segment I in 1999. South of the 1906/segment I accommodation structure, the deformation front extends much farther west than it extends west of the CLPF (Fig. 1b). And there does not appear to be a thrust fault that intersects the surface. Instead, young folds belie the existence of active blind thrusts.

Thus, the 1999 rupture represents rupture of an entire geometrically defined thrust fault and adjacent accommodation structures. This certainly supports the belief that mappable discontinuities may strongly influence the source dimensions of large earthquakes. This recognition of the in-

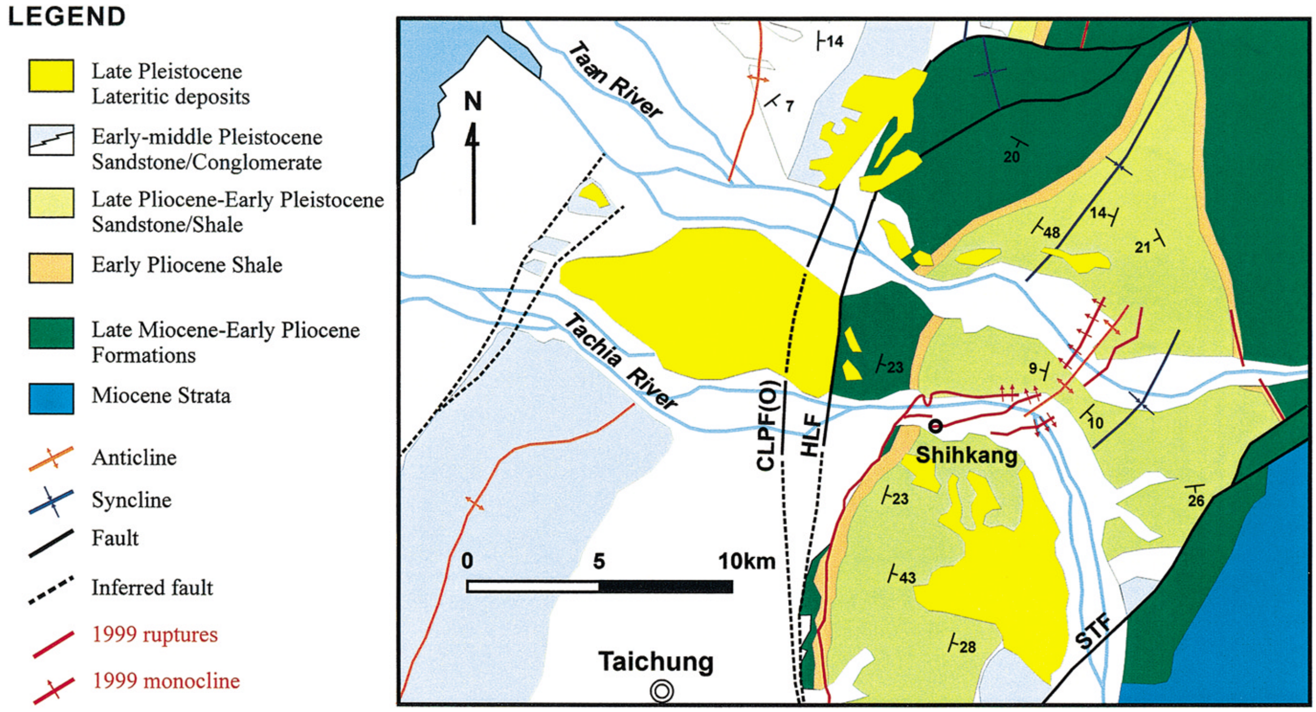

Figure 4. Geological map around northern ending of 1999 surface rupture. The major thrust runs northward along an early Pliocene shale and terminates around Shihkang, then connecting to a complicated deformation system that is mainly following a pre-existing anticline. Based on river terrace study, a mountainward migration of fault trace can be suggested as from CLPF(O) to HLF to 1999 rupture line.

fluence of fault geometry encourages thorough investigations of the geometries of neighboring faults. A more exact description of the geometries and kinematic behavior of these structures would be the best way to achieve more reliable and useful forecasts of future seismic sources.

Fault Trace Migration

1999 rupture also brought us a new lesson regarding to the fault-line migration. As defined on a geological map, the hanging wall and footwall of CLPF are composed of strata formed during the Pliocene and late Pleistocene, respectively. Besides, the trace of CLPF(O) has been confirmed by surface outcrops exposed on the Taichia and Taan river banks and the subsurface gravity analysis along the eastern flank of Taichung basin (Meng, 1963; Chang, 1971; CPC, 1982; Chang, 1994). The Holi fault (HLF) is another overthrust running on the hanging wall of CLPF and subparallel to it. Based on the fluvial deposits of river terrace covering on CLPF(O) but cut through by HLF, it can be concluded that the HLF was active when the activity of CLPF(O) had ceased (Chen *et al.,* 2000b). However, the activity of HLF has ceased due to the intact latest covering deposits. Looking at the Figures 1 and 3, the northern part of 1999 rupture follows neither the old scar of CLPF(O) nor of HLF, but unexpectedly further migrates east and southward onto the original hanging wall and connects to a pre-existing anticline on the ground surface. Except for the similar curve shape, the corresponding features and structures of 1999 ruptures was developed recently. Therefore, we conclude that the segment III and IV of 1999 rupture are the latest phase of fault-line evolution. This trace migration might represent a subsurface decollement evolution from deep level shale upward; however, more subsurface investigations are needed to reach this conclusion. In addition, the present fold system of the northern part will eventually become a tear thrust in the future as its ancient analogues, the CLPF(O) and HLF.

The Relationship between Ruptures of 1999 and 1906

The 1906 earthquake caused a surface rupture, named Meishan fault (MSF), which was recorded as an oblique-slip fault, composed of 2.4 m right slip and 1.2 m dip slip (Omori, 1907; Hsu and Chang, 1979). The faulting character is nearly equivalent to the southernmost tip of the 1999 rupture. As illustrated in the Figure 4, these two dischronous ruptures also spatially share the same curved line. However, another strike-slip fault, namely, the Kukeng Fault (KKF), was previously reported spatially crossing the extension of the 1999 rupture. So far no solid evidence has been worked out whether the KKF has been cut through or not. Nevertheless, the aerial photo and geomorphic feature studies both suggest that it is possibly the case. Before reaching a conclusion that the MSF is the southern extension of the CLPF, more investigation for the 1999 southernmost tip is needed.

Active Folds

Since the middle 1990s, active folds drew much attention of scientists working on neotectonics (Shaw and Suppe, 1994; Mueller and Talling, 1997; Suppe *et al.,* 1997; Oskin *et al.,* 2000). Only few of them have evidence to describe the coseismic movement (Mueller and Suppe, 1997). As described previously, the coseismic rupture—segment IV—is actually an anticlinal system, centered by a sigmoidal anticline axis trace that is flanked by minor kink folds and reverse faults (Fig. 4). The associated scarps, either of fault or of monocline, suddenly disrupted during the Chi-Chi earthquake and severely destructed the objectives sitting above (Fig. 3a). In addition, at Tsaotun another accessory surface deformation is found in the east of the major thrust line (Fig. 2), which is actually a broad surface warping caused by synclinal folding. Although no observable rupture was found, rapid surface deformation also caused a serious damage along the trace. What we lessoned from this is that the fault-related fold can move coseismically. Furthermore, they may play minor roles in context of regional geology; however, they are equally important when we attempt to assess the earthquake hazard.

Concluding Remarks

The over-90-km surface rupture that formed during 1999 Chi-Chi earthquake allows us to re-evaluate the seismogenic structures in Central Taiwan. An unusual fault trace migration is manifested in the north, indicating the fault plane of CLPF has undergone a mountainward process over the past 0.7 Ma. Considering structural discontinuities on both of southern and northern ends of 1999 ruptures, the area delineated can be treated as a seismogenic domain. The lack of historical large earthquakes in the west of the CLPF suggests that active faults beneath the folds of these regions should be considered prime candidates for future rupture. Coseismic movements of active folds were vividly observed and also destructive during the Chi-Chi earthquake. Prior knowledge of the surface deformations associated with these structures would allow better land-use practices. Prior knowledge of the kinematics of these structures would be a first step in creating useful estimates of future seismic shaking. Paleoseismic histories of these structures would enable better estimates of the likelihood that these dormant neighbors of the CLPF will disrupt within the next several decades.

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