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Geological Evidence of Paleo-seismic Events Occurred along the Chelungpu Fault Zone, Taiwan

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ABSTRACT

Field and excavation investigations show that at least two paleo-(historic) seismic events occurred along the northeastern segment of the Chelungpu fault during the period between 1800 AD and 500 AD before the 1999 Chi-Chi earthquake. The principal indicators of paleo-seismic faulting events are: (i) termination of secondary faults, (ii) deformation of deposits related to faulting, and (iii) liquefaction of deposits. The observational results show that the offset produced by an individual faulting event is ~ 1 m. It is inferred that the probable magnitude of these two paleo-earthquakes is 7.0-7.5.

(Key words: Chi-Chi earthquake, Paleo-earthquake, Excavation investigation, Chelungpu fault)

1. INTRODUCTION

On 21 September 1999, an earthquake (called Chi-Chi earthquake, Ms 7.6) shook Nantou country, central Taiwan (23.85°N, 120.81°E), killing approximately 2300 people and causing widespread damage. A nearly 100-km-long surface rupture zone associated with this earthquake occurred mostly along the pre-existing Chelungpu fault in the central western Taiwan (e.g. Central Geological Survey of Taiwan, 1999; Lin et al. 2001a,b,c; Ouchi et al. 2001). The co-seismic rupture zone was dominated by thrust faulting with a left-lateral component and extended over four segments arranged broadly in a right-stepping en echelon pattern (Lin et al. 2001a). After the shock, some studies have been carried out for understanding the relationships between the co-seismic ruptures and pre-existing fault, and between paleo- and historic-seismic events and faulting history on the Chelunpu fault (e.g. Lee et al. 2000, 2001; Lin et al. 2000, 2001a-c; Chen et al. 2001a,b; Ota et al. 2001). These studies provide the preliminary

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geological and seismological background for further studying the mechanism of the earthquake activity.

Historical records contain numerous accounts of earthquakes that caused extensive damage, thousands of deaths, and serious economic hardship throughout the world. There are numerous historic earthquakes occurred during the past 400 years in Taiwan (Hsu 1980). Historical documents report that an earthquake occurred in Nantou Country, the same region as the epicentral area of the Chi-Chi earthquake, and caused the rise of four small hills in the Sun-Moon Lake in Chin Dynasty (1827 AD) (Hsu 1983). There is, however, no detail historic record on the damage, location of epicenter and surface ruptures about this historic earthquake. Furthermore, there were two more instrumentally recorded earthquakes (M=7.1) that occurred in south and north of the Chelungpu fault, in 1906 and 1935 respectively, claimed more than 4500 lives and collapsed near 25000 houses (Hsu 1980; Cheng and Yeh 1999).

In this study, we strive to determine when large historic (or paleo-) seismic events had occurred along the Chelungpu fault, thereby derive an understanding of the frequencies and irregularities of their occurrences by field surveys and excavation investigations on two artificially excavated exposures along the Chelungpu surface rupture zone of the 1999 Chi-Chi earthquake. This knowledge of the long-term behavior of the Chelungpu fault provides important information for seismic hazard evaluation and the paleo- (historic-) events.

2. TECTONIC AND GEOLOGICAL SETTINGS

The study area is located in the west-central Taiwan (Fig. 1), where the Philippine Sea plate collides the Eurasian plate from the east (e.g. Suppe 1984; Teng 1990; Hu et al. 1997). The collision zone abuts upon the south-vergent Ryukyu subduction zone, where the Philippine Sea plate subducts beneath the Eurasian plate, and the west vergent Manila subduction zone, where the Philippine Sea plate overrides the crust of the South China (Ho 1986; Tsai 1986; Angelier 1986; Hu et al. 1997; Fig. 1).

In this district, there are four major active faults, Tamoupu-Shuangtung, Chelungpu, and Changhua faults from east to west, trending nearly north-south with moderate dips towards the east, and the Tuntzechiao fault trending northeast-southwest (Fig. 1). The former three faults are inferred as Category II active faults and the later is a Category I active fault along which the surface ruptures occurred during the 1935 Hsinchu-Taichung earthquake (M7.1) (Chang 1971; Bonilia 1977; Hsu and Chang 1979; Chang et al. 1998). The Chelungpu fault is one of the major faults in the west-central Taiwan, which is a geological and topographical boundary between the Neogene sediments and Quaternary deposits and also between the mountains and basins. The Changhua fault is also a geological and topographical boundary between the Pleistocene sediments and the Holocene deposits, and between the Western Coastal Plain and the Western Foothill. All these faults thrust over the Quaternary sediments or younger alluvial deposits (Bonilla 1977; Hsu and Chang 1979; Central Geological Survey of Taiwan, 1985). The basement consists mainly of the Miocene-Pleistocene shale, sandstone and mudstone, which are folded and deformed.

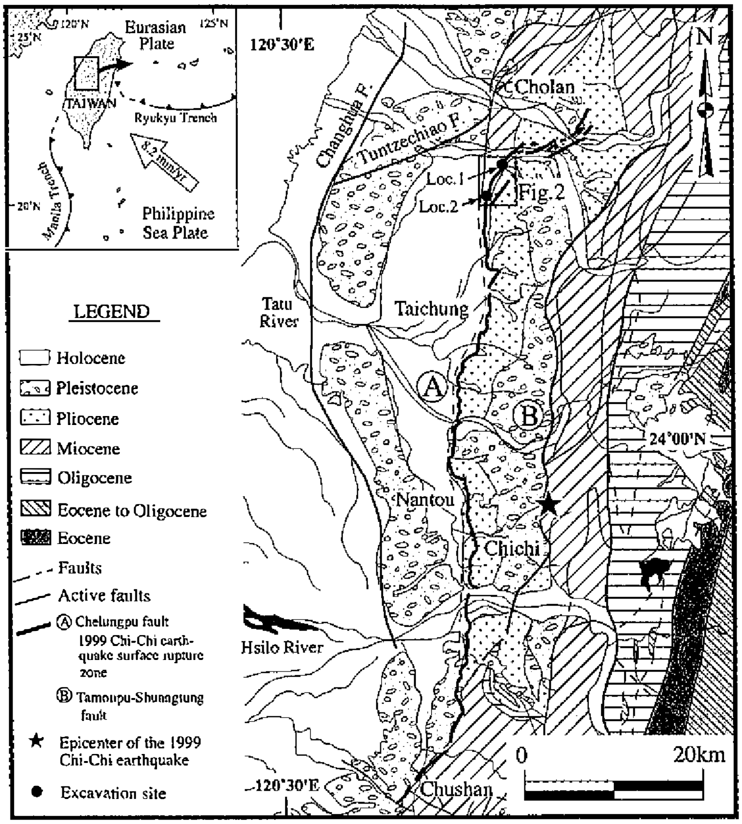

Fig. 1. Map shows the tectonic setting and geological outline of the study area (after Central Geological Survey of Taiwan, 1985, 1999; Hu et al. 1997, Lin et al. 2001a,b). Locs.1 and 2 show the locations of exposures A and B, respectively.

3. EXCAVATION SITES IN THE 1999 CHELUNGPU SURFACE RUPTURE ZONE

A nearly 100-km surface rupture zone associated with the Chi-Chi earthquake occurred in the west-central Taiwan extend from Cholan town of Miaoli country in the north to Chushan town of Nantou country in the south (Fig. 1). The surface ruptures are distributed in a narrow zone of several to several tens of meters, but generally are concentrated to a strip of 5-10 m wide along the pre-existing Chelungpu fault (Lin et al. 2001a,b; Ouchi et al. 2001). The Chelungpu surface rupture zone is composed of many distinct shear faults, surface flexure-folding structures and extensional cracks. Topographically, the Chelungpu surface rupture zone occurred almost along the boundary between the mountain ranges and basins. The co-seismic flexure-folding structures commonly occurred near the surface rupture zone from a few to hundreds of meters in width, which have an orientation in fold axes parallel or oblique to the surface rupture zone (Lin et al. 2001a). These flexure-folding structures were frequently found in the alluvial fans and terraces where the thick (generally > several meters in thickness) alluvial deposits overlay the bedrocks.

Two artificially excavated outcrops, Locs. 1 and 2 (Fig. 1), were carried out on the co-seismic fault-folding structures in the northeastern segment of the Chelungpu surface rupture zone. In these two outcrops, the surface rupture zone occurred almost along the boundary between the hill and basin, where the terrace surfaces formed by the Tachia River were deformed and displaced by the co-seismic faulting (Fig. 2).

At Loc. 1, the sewer (concrete pipe) was broken and offset by the co-seismic fault-folding, where the paddy fields were also flexure-folded (Fig. 3) and the east side of the surface rupture zone was uplifted ~7 m (Fig. 2). The co-seismic displacements measured at several locations in the northeast side 20-200 m to Loc.1 are 3-11 m horizontally and 4-7 m vertically (Lin et al. 2001a). For restoring the lifeline infrastructures, the damaged sewer was dug out at Loc. 1 so that an artificially exposed pit was formed. In order to observe the co-seismic flexure-folding and faulting structures, an excavation was made on this pit and a bend section (exposure A) was exposed (Figs. 3-6).

At Loc. 2, a road was offset approximately 4 m vertically by the co-seismic faulting (Fig. 2). For repairing the road, an exposure (exposure B) across the fault scarp was dug out in this site, which was smoothed and cleaned up for observing the co-seismic faulting and flexure-folding structures (Fig. 7). The details of these two exposure walls are sketched in Figs. 5 and 8, and described in the following paragraphs.

3.1 Exposure A

The deposits exposed in this exposure consist mainly of unconsolidated alluvial deposit and topsoil of paddy field (Figs. 4 and 5), which can be divided into six stratigraphic units (Units-1~6) as follows.

Unit-1 is composed of the topsoil of paddy field, showing gray, brownish gray to dark gray in color, which capped all the top of exposure wall. Unit-2 consists mainly of sandy clay, varying in color from gray on the top and light gray to yellowish gray from top downward the base. The gently folded beddings can be clearly identified. Unit-3 is composed of sand and pebble, showing light gray to brown gray in color. The pebbles are a few to a few tens of cm in diameter, but generally 5-15 cm. Unit-4 consists of clayey fine-grained sand, showing gray to yellowish gray in color. The Unit-4 is only observed in both ends of the exposure wall, and is fault-bounded with Units-2, 3 and 5. Radiocarbon dates of the charred wood fragments, formed in the top of Unit-4 in the left side of exposure wall, yielded a radiocarbon age of 450$\pm$40 y.B.P. (^{14}C ages were calibrated in this study, P.= Present means 1950 AD, Table 1). There is a 10-20 cm thin dark humus layer at the base of the unit in the right side of the exposure wall, yielded a radiocarbon age of 770$\pm$60 y.B.P. These dates indicate that Unit-4 was formed between 450 and 770 y.B.P. Unit-5 is composed of sand and pebble, in light gray to brown-gray in color, which is similar to that of Unit-3. The pebbles are a few cm to 1 m in diameter, generally 10-30 cm, which are larger than that of Unit-3. Unit-6 is also composed of sand and pebble with sedimentary characteristics similar to that of Unit-5 in yellowish gray in

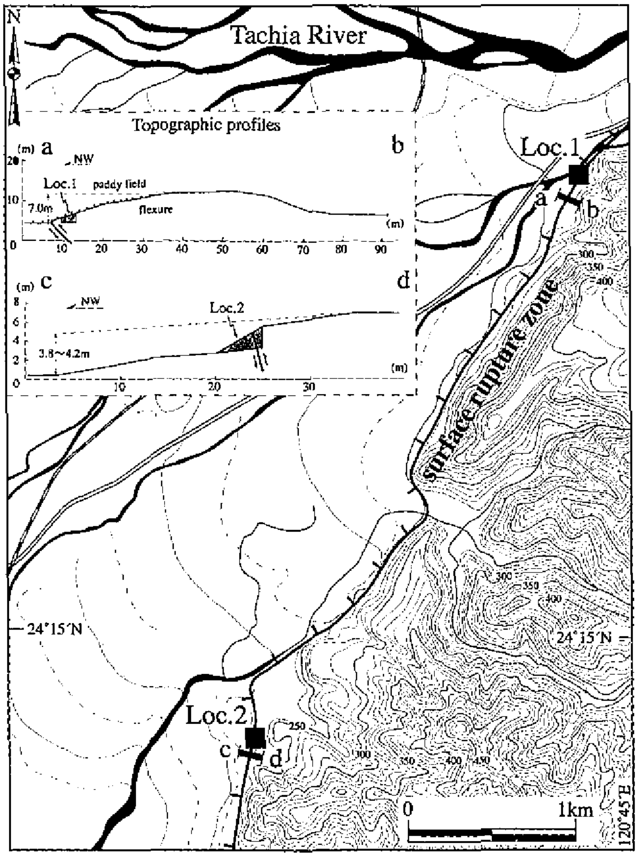

Fig. 2. Topographic map showing the locations (Locs. 1 and 2) of the exposures (A and B) and the distribution of the surface rupture zone in the study area around Locs. 1 and 2. Note that the rupture zone occurred mostly along the boundary between the hill and basin where the terraces formed by the Tachia River and its branches. a-b and c-d sections show the co-seismic fault scarp and flexure occurred at Locs. 1 and 2, respectively. The topographical map of 1/25,000 published by the Combined Service Forces, Republic of China in 1970 was used.

color.

All the stratigraphical units in this exposure wall were deformed by faulting and folding (Figs. 3-5). Unit-1 was flexure-folded into wavy form by the co-seismic flexure-folding during the Chi-Chi earthquake but not obviously displaced. There are a lot of extensional cracks developed in upper two units, where the topsoil of the paddy field and sandy clay layers were disturbed and folded (Figs. 4 and 5). All the stratigraphic units, except Unit-1, were displaced by F1, F2 and F3 faults. On the basis of the direction of bend section (Fig. 5) and the attitudes of F1 and F2 faults (Fig. 5a), we infer that F1 and F2 faults are a continuous fault striking

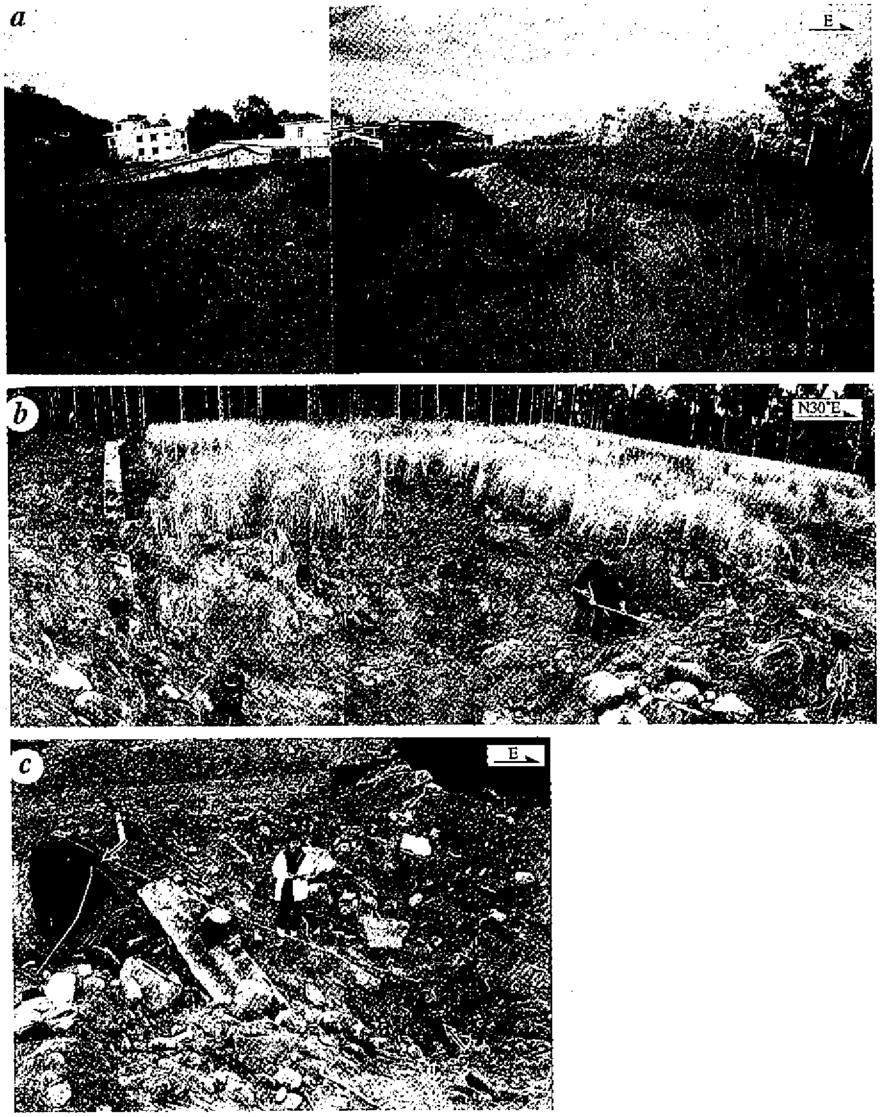

Fig. 3. Photographs showing the exposure A at Loc.1. a: The paddy fields were flexure-folded during the Chi-Chi earthquake. b: Over-all view of the exposure A. The exposure was excavated on the flexure-folded paddy field after the earthquake. c: Close-up view of the lower left side of (b) where the concrete pipe was broken and offset by the co-seismic fault-folding. Left side (southwest side) was uplift approximately 3 m, where a pit was dug out for restoring after the earthquake. Allows show the broken and offset concrete pipe.

Fig. 4. Exposed wall of exposure A at Loc. 1. The grid lines interval 1 m. See Fig. 5 for details.

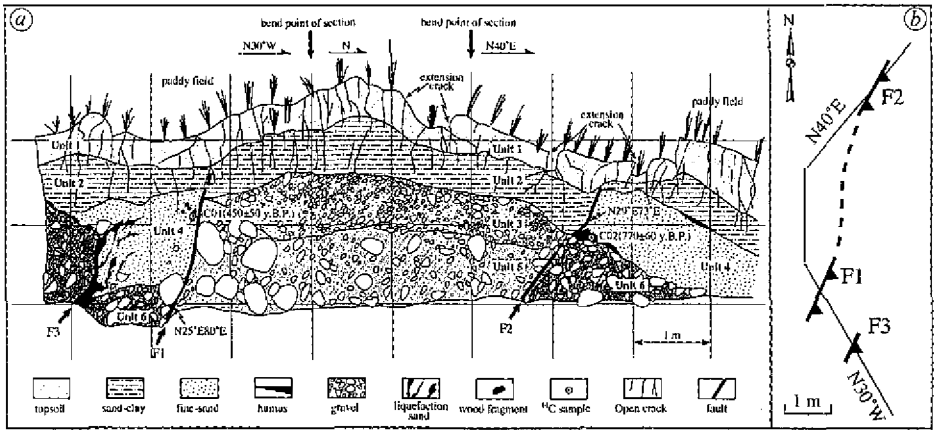

Fig. 5. Sketch (a) of the exposure A shown in Fig. 4 and plane view of the section (b). F1-F3: faults. Note that all the strata were disturbed and displaced by F1-F3 faults except Unit-1. The topsoil of paddy field (Unit-1) was deformed by the co-seismic flexure-folding during the Chi-Chi earthquake. Note that the bedding structures of Unit-4 in the left side were disturbed by liquefaction. F1 and F2 faults are considered as a continuous fault and F3 fault is a branch fault of F1-F2 fault as shown in (b).

N25°-30°E and dipping SE with a steep angle and F3 fault is a branch fault of F1-F2 faults2 (Fig. 5b). Some pebbles were dragged by faulting and parallel to the fault planes of the faults. Units-3 and 5 are situated in the center of the exposure wall and are fault-bounded on Units-4 and 6 in both ends of the exposure wall. In the southern side of the wall, the beddings of sandy layers of Unit-4 were disturbed as the flow structures, probably caused by liquefaction (Figs. 5 and 6). Gray colored clayey silt materials and small pebbles were mixed with the yellowish sand in this unit. The Units-4 and 6 thrust over Units-2, 3 and 5 along F1-F2 fault. The offset of Units-4 and 6 along F1-F2 faults in the exposure wall is estimated to be ~ 2 m (Fig. 5)

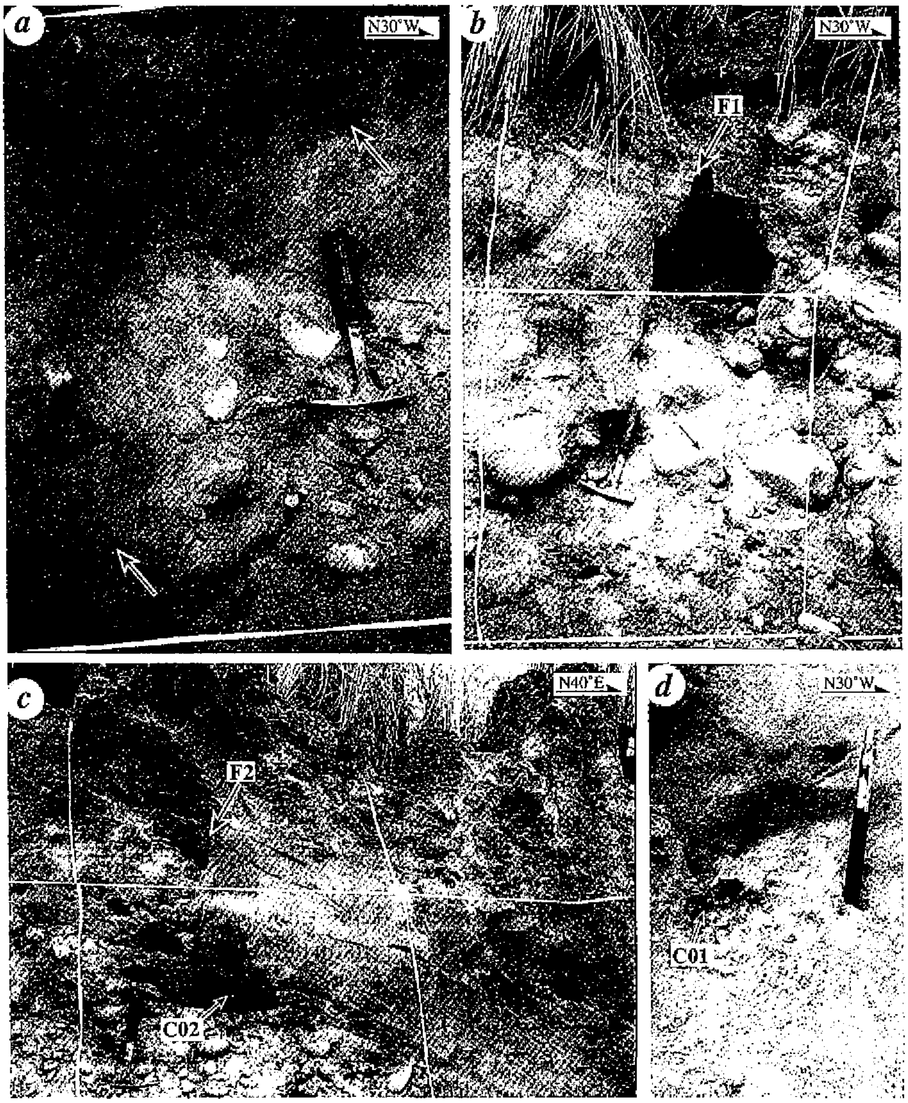

Fig. 6. Close-up views of the exposure A. a: Liquefaction (indicated by arrows) occurred in Unit-4. b and c: Fault contact between fine-grained sand layer (Unit-4) and sand-pebble layers (Units-2, 3 and 5). F1 and F2 indicate F1 and F2 faults shown in Fig. 5. d: Charred wood fragments included in Unit-4 which yielded a radiocarbon age of 450 ± 40 y.B.P.

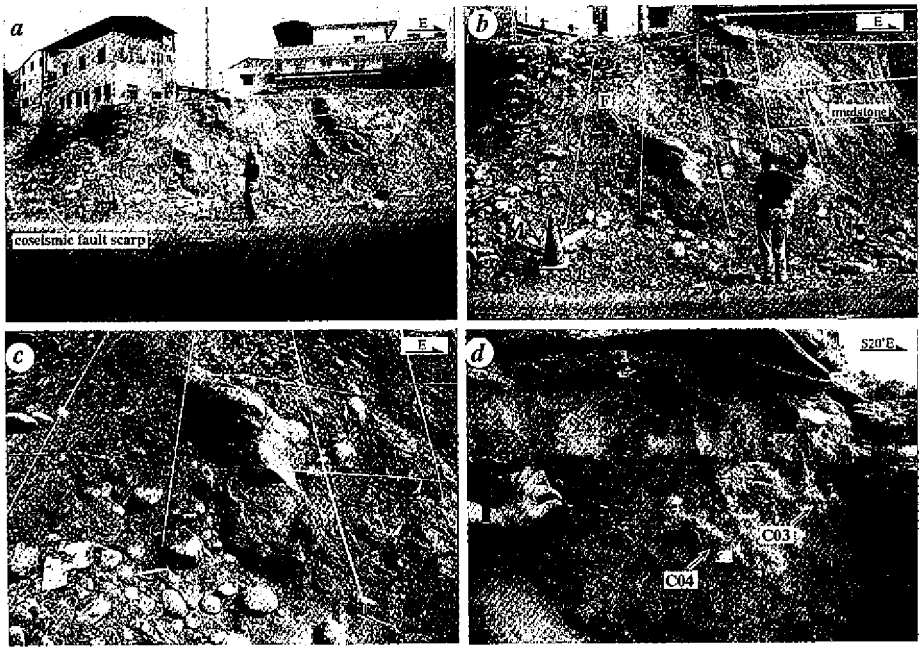

Fig. 7. Photographs showing the exposure B at Loc. 2. a: All view of the outcrop. Arrow indicates the debris on the co-seismic fault scarp. b: All view of the exposure B. Arrow indicates the pre-existing fault plane (F). c: Close-up view of (b). d: Top deposits containing some charred wood fragments in the exposure B yielded radiocarbon ages between 70 ± 40 y.B.P. and 210 ± 40 y.B.P.

although Units-4 and 6 were not exposed in the footwall of Fl-F2 faults. The offset of ~ 1 m in Unit-2 is observed along F2 fault (right side of Fig. 5a). The offset of Unit-2 along Fl and F3 faults is unclear because the deposits were disturbed by liquefaction.

3.2 Exposure B

The strata exposed in Exposure B consist of unconsolidated alluvial deposits and Pliocene-Pleistocene mudstone (Fig. 7). The alluvial deposits are composed of sands and pebbles, showing gray, brownish gray and yellowish gray in color. At the top of the exposure wall, there is a humus layer showing gray to brown gray in color, including some artificially produced glass pieces and charred wood fragments which yielded radiocarbon ages of 70±40 y. B.P. and 210±40 y.B.P. (Fig. 8). This shows that the surface covered the alluvial deposits is a recent flood plain bench formed 70±40 y.B.P.

The alluvial deposits were displaced by F fault and the co-seismic surface ruptures. The pebbles were disturbed and reoriented parallel to the fault plane along F fault (Figs. 7 and 8). The terrace surface was displaced approximately 4 m in vertical by the co-seismic faulting at

Table 1. ^{14}C measured and calibrated ages.

Sample-Code*	^{14}C measured age (y.B.P)	$\delta^{13}C$ (permil)	^{14}C calibrated age (y.B.P)**
Beta-137428 (C01)	430±40	-23.7	450±40
Beta-137429 (C02)	650±60	-17.5	770±60
Beta-137431 (C03)	230±40	-26.7	210±40
Beta-137432 (C04)	70±40	-25.0	70±40

Sample-Code*: ^{14}C ages were measured and calibrated by Beta Analytic Inc. in USA.

(y.B.P)**: This means before 1950 AD.

this location (Fig. 2). The alluvial deposits were filled in a 2-m-wide extensional crack in the center of Exposure wall where the sedimentary structures such as imbrication structure of pebbles were disturbed (Fig. 8). The topmost covering alluvial deposits, however, is not displaced by F fault as shown in the topographical profile across the fault zone (Fig. 2). These facts indicate that the terrace surface at this location was only displaced due to the co-seismic faulting of the Chi-Chi earthquake.

4. DISCUSSION AND CONCLUSIONS

4.1 Paleo-events

Geologic and geomorphologic evidence shows that the late Quaternary deposits and terrace surfaces have been deformed and displaced by the Chelungpu fault (Bonilla 1977). The Chelungpu surface rupture zone associated with the 1999 Chi-Chi earthquake nearly occurred along the pre-existing late Quaternary fault scarp of the Chelungpu fault (Lin et al. 2000, 2001a,b). This indicates that the 1999 surface rupture zone was duplicated along the pre-existing Chelungpu fault. Two historic disastrous earthquakes mentioned earlier generated significant surface ruptures in the western coast of Taiwan. The 1935 Hsinchu-Taichung earthquake (M7.1), occurred near the northern end of the Chelungpu fault, was associated with a 53-km-long surface rupture zone mainly along the Tuntzechiao and Shitsushan faults, which is located on the northern-northwestern side of the Chelungpu fault (Otuka 1936; Yeats et al. 1997). The 1906 Chiayi earthquake (M=7.1) occurred near the southern end of the Chelungpu fault, and was related to a 13-km-long surface rupture zone mainly aligning with the pre-existing Meishan fault (Omori 1907; Hsu and Chang 1979; Yeats et al. 1997). In Chin

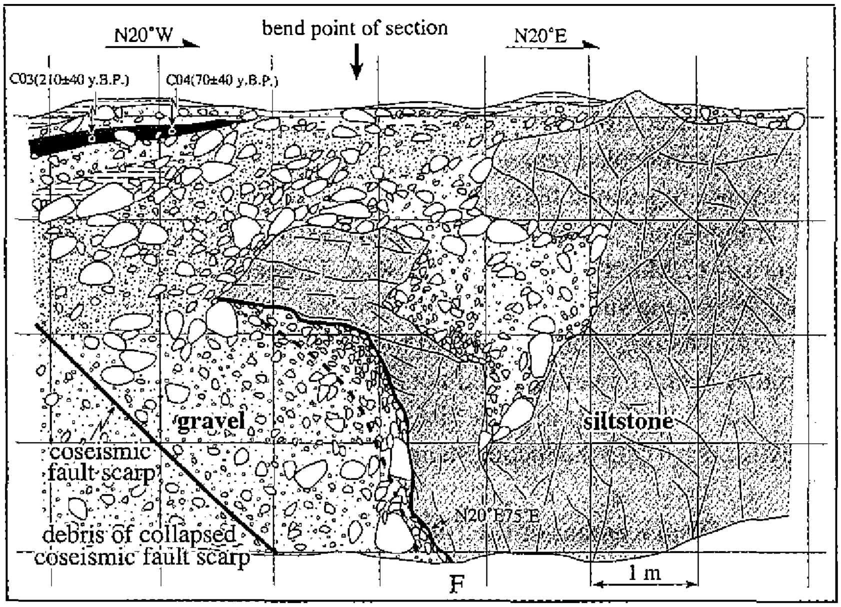

Fig. 8. Sketch of the exposure B shown in Fig. 7b. Note that the co-seismic displacement ruptured the alluvial deposits and formed a fault scarp. Charred wood fragments included in the top deposits on the terrace yielded radiocarbon ages of 70 ± 40 y.B.P. and 210 ± 40 y.B.P. Note that the top deposit is not disturbed and displaced by the pleaoseismic faulting before the earthquake in this location. F: Pre-existing fault.

Dynasty (1616~1911 AD), the historic records report that there are two M=6.5 (17 March 1811 and 4 March 1845) and one M=7.0 (3 December 1848) earthquakes occurred in Nantou Country and its vicinity (Hsu 1980; Cheng and Yeh 1999) which are close to the epicentral area of the Chi-Chi earthquake. Furthermore, it is also reported that there is an earthquake occurred in Nantou Country and caused the rise of four small hills in the Sun-Moon Lake in Chin Dynasty (1827 AD) (Hsu 1983). This earthquake, however, is not documented in the earthquake catalogs of Taiwan in 1604~1988 AD (Cheng and Yeh 1999) or in 1644-1979 AD (Hsu 1980). It is, therefore, unknown whether or not these earthquakes were generated by slip on the Chelungpu fault, because there is no detail historic record on the damage, location of epicenter and surface ruptures about these historic earthquakes.

Our excavation investigations described above show that 1) the alluvial deposits of 450±40~770±60 y.B.P. were deformed and offset by F1~F3 faults and that of 70±40 y.B.P. were not deformed, 2) the offset of Units-4 and 6 along F1-F2 fault is estimated to be ~ 2 m and that of Unit-2 is about 1 m, and the liquefaction occurred in Unit-4. On the basis of these results, we infer that there is at least two seismic faulting events with surface rupturing occurred along the Chelungpu fault during the period between 1500 and 1880 AD. The penultimate paleo-event related to the liquefaction of Unit-4 occurred in the period from 450±40 y.B.P. (1500±50 AD) and to the formation of Unit-2. The last paleo-event occurred in the period after the formation of Unit 2 to 70±40 y.B.P. (1880±40 AD). The penultimate paleo-event is consistent with that inferred from the trenching survey at Tsautun sites on the Chelungpu fault which revealed that an probable event occurred before 300-500 y.B.P. (Ota et al. 2001). Considering the recurrence of seismic faulting and historical records, we infer that the last paleo-event occurred during recent 200 years which is probably related to one of the events occurred in 19-20th centuries (17 March 1911, 4 March 1845, 3 December 1848, and 1827 AD). The trenching survey at Wufeng site showed that there is one paleo-seismic event occurred along the Chelungpu fault which is probably related to the 1845 AD earthquake (Lee et al. 2000). The 19-20th century event, however, could not be recognized by trenching survey (Ota et al. 2001) at Wufeng site which is just near the site of Lee et al. (2000). It is, therefore, necessary to do more study for clarifying the inconsistency among these studies and historic records.

4.2 Magnitude and Displacement of the Inferred Paleo-seismic Events

Historic documents show that the magnitude of 8 historic earthquakes (1906-1999) including the 1999 Chi-Chi earthquake with surface ruptures having obvious displacement in Taiwan is ≥6.7 (Yeats et al. 1997; Lin et al. 2001a). The displacements generated along reverse fault or strike-slip fault with large vertical displacement component by one historic seismic faulting event of magnitude ≥7.0~7.3 in Taiwan are 1-2.4 m horizontally and 1-2 m vertically (Omori 1907; Otuka 1936; Bonilia 1977; Hsu and Chang 1979; Yeats et al. 1997). The displacements of the surface ruptures measured along the Tuntzechiao fault (Fig. 1) in the northwest of the Chelungpu fault accompanying the 1935 Hsinchu-Taichung earthquake (M7. 1) and the 1906 Meishan earthquake (M7.1) are 1.5-2.0 m horizontally and 1.0-2.0 m vertically (Otuka 1936). On the other hand, the offset of Uints-4 and 6 along F1-F2 fault in Exposure A (Fig. 5) is estimated to be at least 2 m and that of Unit-2 is about 1 m as described above. This indicates that offsets were accumulated on the Units-4 and 6 and that the offset produced by an individual faulting event is ~ 1 m. The paddy fields were folded and offset ~7 m vertically and 4-7-m high fault scarp formed during the Chi-Chi earthquake as shown in Fig. 2. There is, however, no obvious topographical evidence and historic record showing the surface fault scarp generated by the co-seismic faulting of history (paleo-) earthquake. We explain, therefore, that the vertical offsets produced by these two paleo-events were small and the related fault scarps were eroded in the flood plain bench. F1~F3 faults observed in Exposure A are probably main or branch surface faults of the two paleo-seismic events, along which surface offsets were produced. Therefore, we believe that the main offsets accompanying these two paleo-seismic faulting events are no larger than that produced by the co-seismic faulting during the Chi-Chi earthquake so that it is difficult to recognize it in field. It is thus inferred that the magnitude of this historic earthquake is not larger than that of the Chi-Chi earthquake (Ms7.6). Based on the documentation above, we conclude that ≥2 m offset of Units-4 and 6 was probably generated by two paleo-seismic events with estimated magnitude of 7.0-7.5 occurred along the Chelungpu fault during the period between 1880 and 1500 AD.

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