Terr. Atmos. Ocean. Sci., Vol. 18, No. 1, 55-66, March 2007

Low-Angle Reverse Faulting During Two Earthquakes on the Northern Part of the Chelungpu Fault, Deduced From the Fengyuan Trench, Central Taiwan

Yoko Ota[1, *], Masanobu Shishikura [2], Kiyoshi Ichikawa [3], Mitsuhisa Watanabe [4], Makoto Yanagida [5], Takenobu Tanaka [5], Hiroshi Sawa [6], Masaru Yamaguchi [7], Yuan-Hsi Lee [8], Shih-Ting Lu [8], Tung-Sheng Shih [8], and Sakiko Amagasa [9]

(Manuscript received 23 August 2006, in final form 19 October 2006)

ABSTRACT

A trench and two boreholes located at the western margin of a young terrace, east of Fengyuan city, show the style and frequency of surface faulting on the northern part of the Chelungpu fault, central Taiwan. Both the 1999 earthquake fault and penultimate earthquake event are characterized by low-angle reverse faulting with overturning of younger strata. The penultimate event occurred between ca. 1400 yr BP (1340 - 1170 cal yr BP) and 2000 yr BP (2120 - 1800 cal yr BP). The age of the lower part of the terrace gravel is ca. 4000 yr BP; thus the two faulting events occurred during the past ca. 4000 years. The amount of horizontal shortening and vertical displacement since the penultimate event are significantly larger (3.7 - 3.9 m

[1] Yokohama National University, Yokohama, Japan
[2] Active Fault Research Center, Geological Survey of Japan, AIST, Tsukuba, Japan
[3] Komazawa University, Tokyo, Japan
[4] Toyo University, Tokyo, Japan
[5] Hanshin Consultants Co. Ltd, Tokyo, Japan
[6] Tsuruoka National College of Technology, Tsuruoka, Japan
[7] NHK, Japan Broadcasting Corporation, Tokyo, Japan
[8] Central Geological Survey, Taipei, Taiwan, ROC
[9] Itabashi Science Museum, Tokyo, Japan
* *Corresponding author address:* Prof. Yoko Ota, Yokohama National University, Yokohama, Japan; E-mail: ota@iceice.com

for horizontal and ca. 5 m for vertical) than those (2.7 m for horizontal and ca. 2 m for vertical) of the 1999 earthquake. The age of the penultimate earthquake at the Fengyuan site is the oldest earthquake recorded among the known penultimate penultimate events on the Chelungpu fault so far and suggests that this part of the Chelungpu fault may be a fault segment independent of the central and southern parts of the fault.

(Key words: Chelungpu fault, Fengyuan site, Trenching, Low-angle reverse fault, Shortening, Timing of penultimate faulting, Paleoseismology, Earthquake history)

1. INTRODUCTION

Since the destructive 1999 Chi-Chi earthquake, the pattern and displacement of surface ruptures along the Chelungpu fault (Fig. 1a) have been mapped in detail (e.g., Ota 1999; Central Geological Survey 2000; Kelson et al. 2001; Chen et al. 2001; Rubin et al. 2001). Our knowledge of the history of the Chulungpu fault and its progressive deformation in relation to the surface ruptures also has rapidly progressed (e.g., Chen et al. 2002; Ota et al. 2003, 2004). The segmentation of the Chelungpu fault has also been proposed based on the nature and amount of surface rupture (Chen et al. 2001; Rubin et al. 2001). Trenching is helping to expand the history along the fault (e.g., Lee et al. 2001; Chen et al. 2001a, b; Ota et al. 2001). Although 14 trenches have been excavated across the Chelungpu fault (Fig. 1b; Ota et al. 2005), most are concentrated along the central part of the fault. Because the 90-km long Chelungpu fault may be segmentated (Chen et al. 2001; Rubin et al. 2001), the timing and frequency of paleoearthquakes could differ from place to place. The focus of this study is thus to investigate paleoseismicity along the northern part of the fault, where trenches have not been excavated. We selected the western margin of the lowest terrace, east of Fengyuan city for trenching and boring (Fig. 1c) because this site records both the 1999 surface rupture and deformation during an earlier earthquake on the youngest terrace (Ota et al. 2004). Until our work, the northernmost trench site on the fault was Loc. 14 (Fig. 1b) studied by Yuan et al., on the north of Tachia river, which has not been published. Our study was also briefly summarized in a preliminary report (Shishikura et al. 2002).

2. METHOD

The trench site is located on the fault scarp east of Fengyuen (Figs. 1b, c) where two active faults have been identified (Ota et al. 2003, 2004). The western fault (Fault A) marks the western boundary of the lowest terrace, and records at least two surface faulting events; one is the 1999 rupture and the other is the faulting that dislocated the youngest terrace. The scarp found above the eastern fault (Fault B) is also distinct; however, because this fault did not rupture in 1999, we selected the western fault (Fault A) for trenching.

Because of restrictions on available land for trenching, we excavated the trench oblique to the fault trend (Figs. 2, 3). The trench was 22 m long and had a maximum depth of 4 m (Fig. 3). The north and south walls each consisted of two parts (upper and lower) separated by a wide step. We made two borings on the hanging wall and footwall (Fig. 2). After excavation, we cleaned the trench wall by hand, installed a 0.5 m grid for the vertical and 1m for horizontal, and prepared trench logs of the south and north walls (Figs. 4, 5, and 6). The trench log for the east wall is not included in this paper because no additional information was obtained from it. We dated 10 radiocarbon samples at The Geo-Science Laboratory (Table 1). In the text and figures, we report 14C ages in ^{14}C yrs BP; calibrated ages are listed in Table 1.

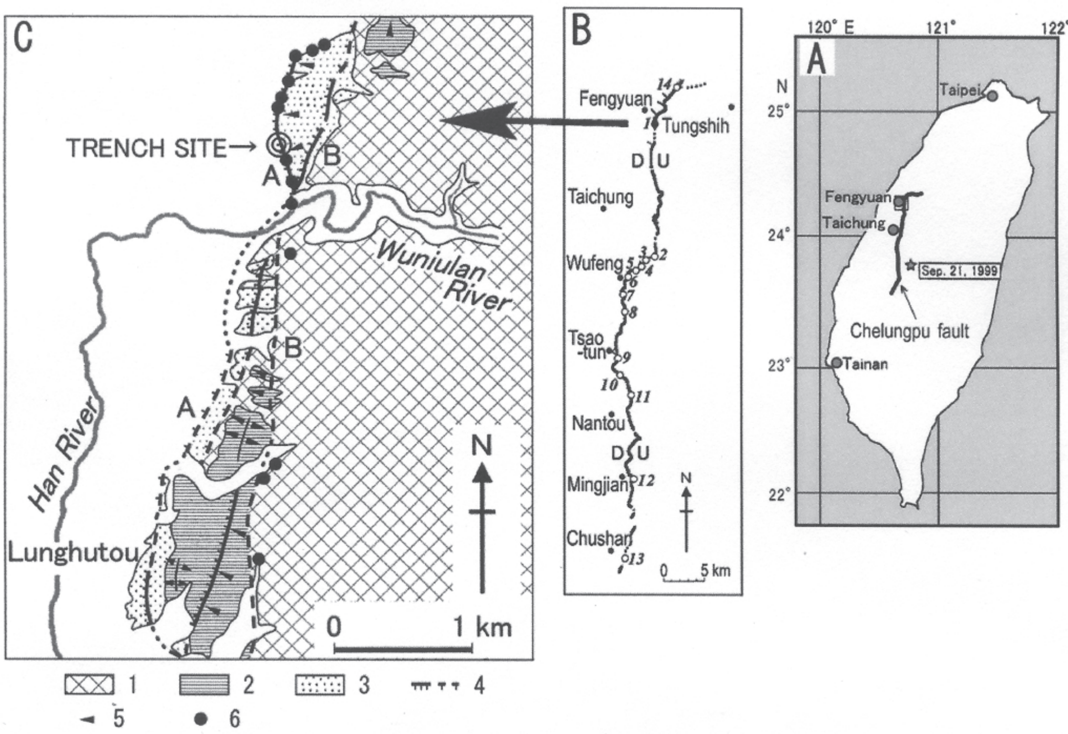


Fig. 1. Location of the trench site. (a) The location of the Chelungpu 1999 surface rupture in Taiwan; (b) Trench sites along the Chelungpu fault (Ota et al. 2005). Our trench site is located closely to the northernmost section of the Chelungpu fault; (c) The location of Fengyuan trench site in relation to terraces and faults (after Ota et al. 2004 for the mapping of terraces and active faults). 1) mountains and hills; 2) middle terrace; 3) lower terrace; 4) active fault; 5) tilt of terraces; and 6) locations where the rupture during the Chi-Chi earthquake was reported by Central Geological Survey, 2000.

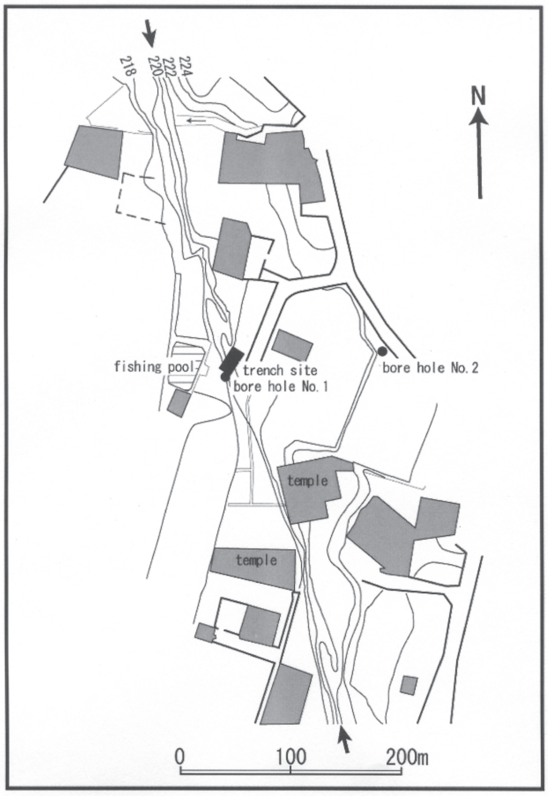


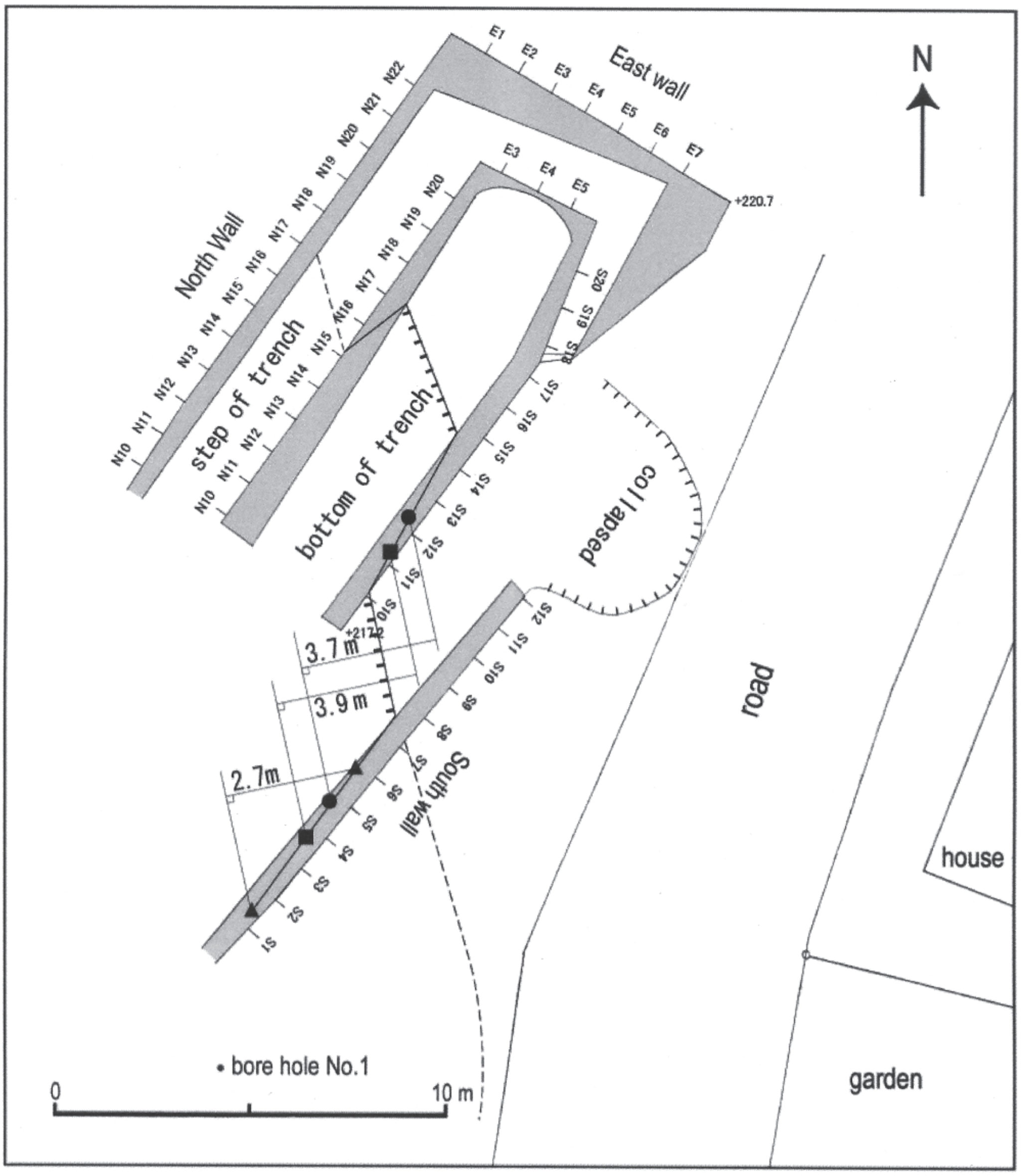
Fig. 2. Location map of the Fengyuan trench site and boring sites. Thick arrows indicate Fault A of Fig. 1c.

3. STRATIGRAPHY AND RADIOCARBON AGES OF TRENCH WALLS

3.1 Stratigraphy

We classified deposits exposed in the trench walls into nine units: five silt and gravel beds (Bed A, B, C, D, and E) and four humic soils (H1, H2, H3, and H4; Figs 5, 6). Here we describe the lithology, thickness, and radiocarbon ages of each bed from top to bottom and identify faults on the south wall (fs0, fs1,fs2a, and fs2b) and the north wall (fn0 - fn3).

Bed H1 is a black A horizon of the soil that developed beneath the land surface before the 1999 Chi-Chi earthquake. On the south wall, it is ca. 30 cm thick and includes some plant roots and charcoal. This bed is not seen on the north wall because it disappeared after the earthquake. Because of overturning by the fault, Bed H1 is nearly 70 cm thick at S3. Bed A is preserved in the upper part of the south wall and is a ca. 20 - 30 cm thick yellow brown sand that contains charcoal. On the north wall, most of Bed A was removed. Bed H2 is a dark brown buried A horizon ca. 20 cm thick, dated at 790 ± 60 yr BP., that is exposed just above the step on the lower part of the south wall. On the north wall this soil is only locally preserved at N15. Bed H3 is a light brown weakly humic A horizon, 20 - 25 cm thick, that grades into Bed H2. Bed H3 is exposed on the lower step of the footwall of fault fs2a in the south wall and in the upper



▲ 2.7m amount of horizontal shortening of Bed H1
■ 3.9m amount of horizontal shortening of Bed C
● 3.7m amount of horizontal shortening of Bed D

Fig. 3. Plan view of the trench. Shaded areas are the sketched trench walls. The actual amounts of horizontal shortening of Bed H1, Bed C and Bed D are obtained from measurement between the reference points for these beds, which are shown in Fig. 5. See text for detail.

Fig. 4. Eastern part of the south wall between S6 and S4. Arrows mark fault fs1. Horizontal marks, 1 m interval; vertical marks, 0.5 m interval.

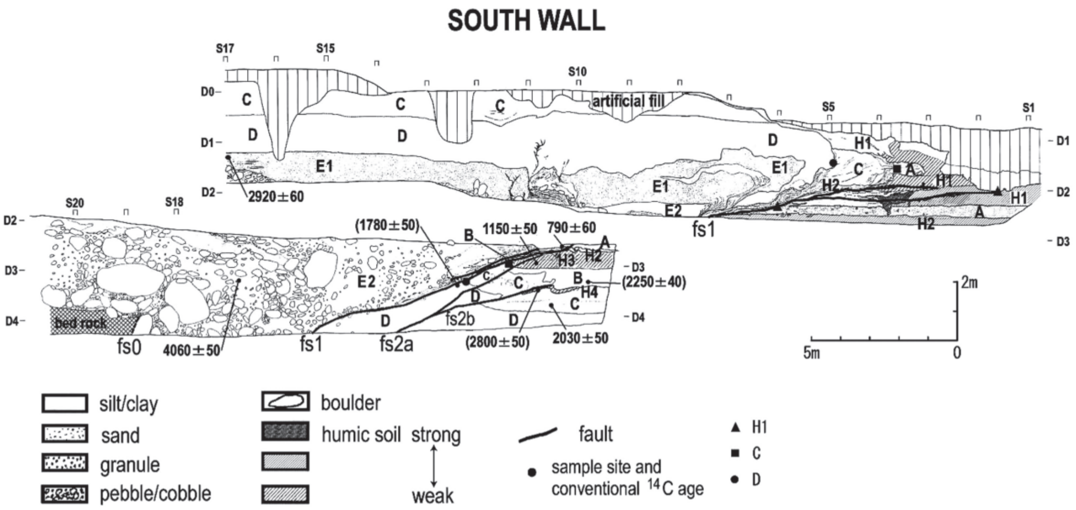


Fig. 5. Trench log of the south wall. Several sub-parallel reverse faults are shown. Reference points for obtaining the horizontal shortening are represented by solid triangles (Bed H1), squares (Bed C) and dots (Bed D).

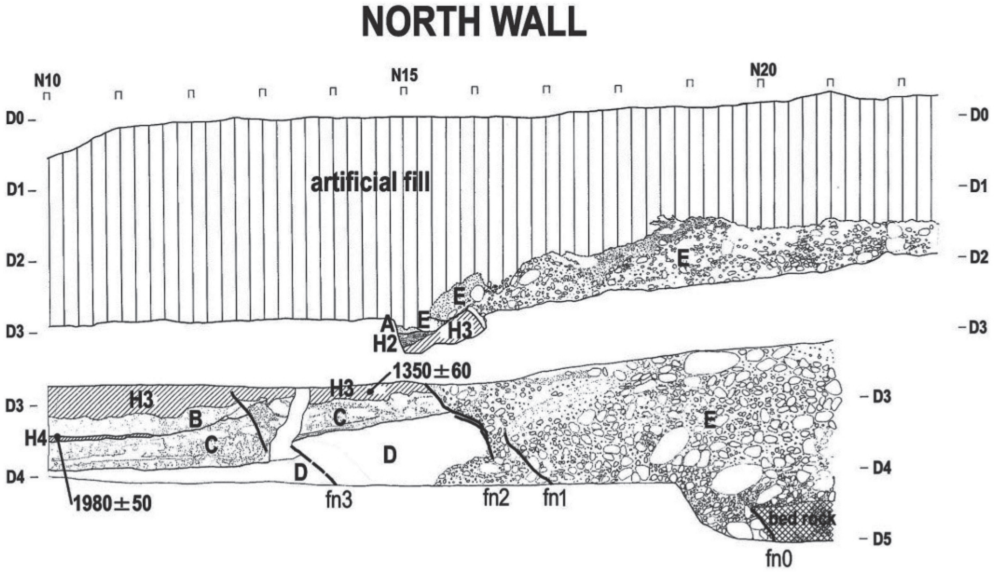


Fig. 6. Trench log of the north wall. The upper part is artificially removed.

Table 1. Radiocarbon ages of samples from the trench site. 1) ^{14}C ages are measured by AMS method; 2) These ages are not used for interpretation because of the abnormal ages compared to others.

horizon	sample name	Radiocarbon lab.no.	material	conventional ^{14}C yrs BP*	$\delta^{13}C$	calibrated age (2σ) cal yrs BP
H2	SL-12	Beta-163891	organic	790±60	-15.9	790-650
H3	SL-4	Beta-163892	organic	1150±50	-17.1	1180-950
H3	NL-7	Beta-163894	organic	1350±60	-17.0	1340-1170
B	SL-3	Beta-163884	organic	(2250±40)	-18.7	2340-2150
H4	SL-5	Beta-163895	organic	(2800±50)	-18.6	3000-2780
H4	NL-5	Beta-163896	organic	1980±50	-17.3	2030-1830
C	SL-8	Beta-163885	organic	2030±50	-20.1	2120-1800
D	SL-9	Beta-163888	organic	(1780±50)	-17.9	1830-1560
E	SU-5	Beta-163889	organic	2920±60	-19.6	3520-2880
E	SL-11	Beta-163890	organic	4060±50	-20.4	4810-4760 4700-4670 4650-4420

* By AMS, dates in parenthesis are ignored in the interpretation. See text in detail.

and lower parts of the north wall. We obtained two dates, 1350 ± 60, and 1150 ± 50 yr BP, from this bed. Bed B consists of massive light gray silt and fine sand, and blocky silt. This is only seen in the footwall of fault fs1 in the south wall and the footwall of fault fn3 in the north wall. This bed has an age of 2250 ± 40 yr BP. Bed H4 is found locally between Bed B and Bed C and is interpreted as a buried A horizon developed on Bed C. It is 10 cm thick and gives two ages, 2800 ± 50 and 1980 ± 50 yr BP, were obtained from Bed H4. Bed C consists of gray brown sand on the upper and lower part of the south wall and is 45 - 70 cm thick. Bed C is cut by faults fs1, fs2a, and fs2b on the south wall and by fn3 on on the north wall. The age from Bed C is 2030 ± 50 yr BP. Bed D is a thick (70 - 120 cm) dark brown to brown silty sand with some clay. It is mapped on the upper and lower south wall and the lower part of the north wall on both sides of faults fs2a and fs2b, and the footwall of fault fn2. It is also deformed by fault fn3. The radiocarbon age for this bed is 1780 ± 50 yr BP. Bed E includes sand and gravel that underlies the lowest terrace. The upper part (E1) is relatively well-sorted sand, and the lower Bed (E2) is a sandy gravel containing large cobbles, 20 - 30 cm in diameter; however, some are up to 150 cm in diameter. Bed E2 is unsorted and has no stratification. The ages from E1 is 2920 ± 60 yr BP and from Bed E2 is 4060 ± 50 yr BP. Shattered Miocene Chinsui shale is exposed on the eastern corner of the lower part of the north and south walls and is bounded by fault fn0 and Bed E on the north wall. We infer fault Fs0 between the bedrock and Bed E2 in the south wall.

.

3.2 Drilling Results

We drilled two boreholes, one on the footwall and the other on the hanging wall (Figs. 2, 7) and took continuous-core samples 10 m long. The upper part of both cores consists of fine-grained deposits, whereas the lower parts are coarse gravel. We correlate this gravel bed with Bed E (E2) in the trench walls. Comparison of the upper surface of Bed E suggests that the apparent amount of vertical offset since the formation of Bed E is about 5 m.

3.3 Radiometric Ages

Radiometric age determinations from the trench range from ca. 4000 to ca. 800 yr BP (Table 1). Because some ages are significantly older or younger than other ages from similar stratigraphic positions [2250 ± 50 yr BP (Bed B), 1780 ± 50 yr BP (Bed D) and 2800 ± 50 yr BP (H4)], we do not use them in our interpretation. Because datable material was not obtained from some units, the age of the penultimate faulting event is poorly defined.

4. INTERPRETATION OF FAULTING

4.1 Surface Faulting during the Chi-Chi Earthquake

On the south wall, subparallel faults, which splay into two strands, cut the Holocene deposits (Fig. 5). Fault fs1 is the youngest fault to ruptured the surface during the Chi-Chi earthquake, because it cuts the youngest Bed H1, as well as older beds. The faults on the south wall are very low-angle thrust faults with overturned beds on their hanging walls (Bed H1, A, and C). Near the surface the fault plane is nearly horizontal (Fig. 5). The angles of these faults are the lowest among all the faults in other trenches studied along the Chelungpu fault (e.g., Chen et al. 2001a, b). In our trench, the amount of lateral shortening of Bed H1 is as much as 2.7 m (Fig. 3; see 4.2 for interpretation), slightly larger than the vertical offset of ca. 2 m; accordingly slip along the fault is ca. 3 m.

On the north wall, four faults are identified in a zone about 8 m wide (Fig. 6). Fault fn0 displaces bedrock against Holocene strata, but does not continue upwards and is covered by the upper part of Bed E. Faults fn2 and fn3 cut the youngest Bed H3, thus they are interpreted as occurring during the Chi-Chi surface rupture, although the strata cut by fn2 and fn3 were removed by artificial modification in some places after the earthquake,

4.2 The Penultimate Faulting Event and Its Estimated Age

At the Fengyuan site, we infer an earlier faulting event based on the stratigraphic relation of beds with different ages: 1) On the south wall, Bed E is not observed on the footwall, implying that the vertical offset of Bed E is more than 3 m; 2) Bed B and younger beds are found only on the foot wall of fault fs2; 3) Fs2b cuts Bed H4 but does not cut Bed B and younger beds. Similarly, Bed B and younger beds are present only on the footwall of fault fn2 on the north wall. These relations suggest that the penultimate faulting event probably took place before the deposition of Bed B and after the deposition of Bed H4.

Two faulting events are confirmed through comparison of the amount of shortening due to faulting. The amount of shortening appearing on the trench wall does not represent the actual amount, due to the oblique direction of the trench to the fault strike. We, therefore, project the position of the eastern margin and western margin of Bed H1 along fault fs1 to the perpendicular plane relative to the measured fault strike. The same procedure was done for Bed C and D (Fig. 3). The along fault shortening of Bed H1, which is cut only by the 1999 earthquake, is 2.7 m. In contrast, the amount of horizontal shortening of Beds C and D, which were also faulted during the penultimate faulting event is nearly the same, 3.9 m for Bed C and 3.4 m for Bed D, significantly larger than the shortening for Bed H1. Vertical displacement of Bed H1 by the 1999 earthquake is ca. 2 m, whereas the vertical offset of Beds C and D is about 3.6 m. In addition, we measured a ca. 5-m offset of the surface of Bed E2, based on the drilling data (Fig. 7). This evidence shows two faulting events during ca. 4000 years at the Fengyuan site.

Unfortunately, it is not possible to precisely determine the age of the penultimate faulting event, because Bed B is undated. However, available ages imply that this event occurred between ca. 1400 yr BP (1340 - 1170 cal. yr BP) and 2000 yr BP (2030 - 1830 cal. yr BP); (see Table 1). And recurrence interval is longer than ca. 1400 years. The age of this penultimate event is much older than ages for the penultimate events from the central part of the Chelungpu fault (e.g., 430 - 150 yr BP; Chen et al. 2004), and our single recurrence interval is significantly longer than the several-hundred-year recurrence time estimated by Chen et al. (2004). Thus, the trench from the Fengyuan site has the oldest record for penultimate faulting and the longest recurrence interval along the Chelungpu fault so far.

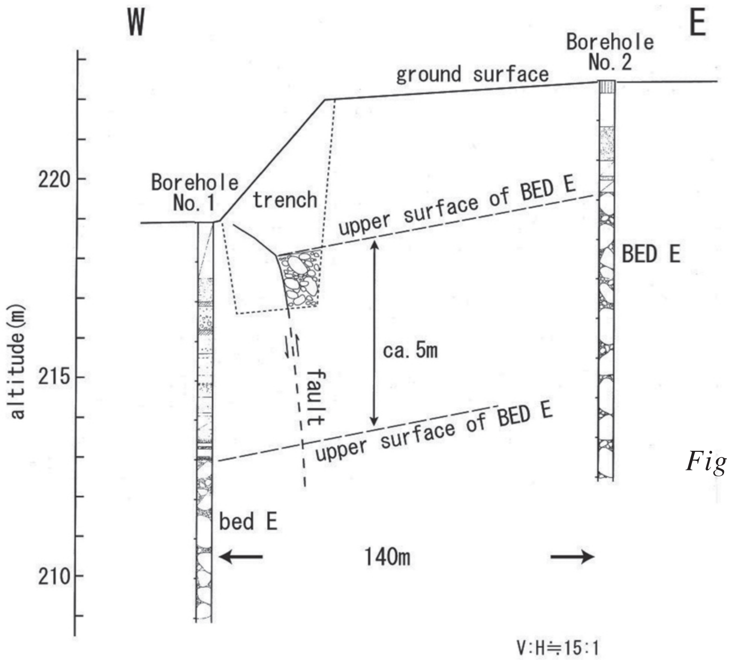


Fig. 7. Schematic diagram of faulting inferred from trenching and boring results.The vertical offset since the deposition of Bed E is ca. 5 m.

5. DISCUSSION

In order to better determine the earthquake history of the Chelungpu fault, more precise dating and additional trenches are needed along different faults segments, especially at the northern and southern segments. Specific problems that should be addressed include:

1) Changes in fault strike: Overlapping of strata due to horizontal shortening was observed at several sites on the Chelungpu fault (e.g., Ota et al. 2001). However, the amount of horizontal shortening, due to low-angle reverse faulting at the Fengyuan site may be partly due to the change in strike of the fault towards the northeast. This interpretation is only tentative and more trenches will be required to test this hypothesis.
2) The older age of penultimate faulting and the longer interval between faulting events: As mentioned, the estimated 1400 - 2000 yr BP age for the penultimate faulting event is the oldest recorded on the Chelungpu fault, implying a recurrence interval of greater than 1400 years. We infer that some earthquakes that occurred on fault B did not occur on fault A (Fig. 1c; Ota et al. 2003), after the formation of the lowest terrace. This conclusion is also tentative.
3) Results from each trench site should be examined if the nature and amount of faulting or timing of paleofaulting have any relationship to the four segments based on the 1999 surface rupture (Chen et al. 2001a; Rubin et al. 2001).

6. CONCLUSIONS

Two faulting rupture events are recorded at the Fengyuan trench site. The younger event is a low angle thrust faulting event that occurred during the 1999 Chi-Chi earthquake, and the older event is one which occurred between ca. 1400 yr BP and ca. 2000 yr BP. The occurrence of the older earthquake is supported by a comparison of horizontal shortening along the faults and the amount of vertical offset.

Acknowledgements This work was financially supported by Geological Survey of Japan. We thank the Central Geological Survey of Taiwan, ROC for logistical support during the trenching study. We also thank the landowner and people living near the trench site for their friendly interest in our work. We thank two reviewers, Dr. Alan Nelson and Dr. Takashi Azuma, for their constructive suggestions improving this paper.

REFERENCES

CGS (Central Geological Survey), 2000: Survey report of the 921 earthquake. Cent. Geol. Surv., MOEA, Taiwan, ROC, 314 pp. (in Chinese)

Chen, W. S., Y. G. Chen, and H. C. Chang, 2001a: Paleoseismic study of the Chelungpu fault in the Mingjian area. *West. Pac. Earth Sci.*, **1**, 351-358.

Chen, W. S., Y. G. Chen, H. C. Chang, Y. H. Lee, and J. C. Lee, 2001b: Paleoseismic study of the Chelungpu fault in the Wanfang area. *West. Pac. Earth Sci.*, **1**, 499-506.

Chen, Y. G., W. S. Chen, J. C. Lee, Y. H. Lee, C. T. Lee, H. C. Chang, and C. H. Lo, 2001: Surface rupture of 1999 earthquake yields insight on active tectonics of central Taiwan. *Bull. Seismol. Soc. Am.*, **91**, 977-985.

Chen, Y. G., W. S. Chen, G. Wang, P. W. Lo, T. K. Liu, and J. C. Lee, 2002: Geomorphic evidence for prior earthquake : lessons from the 1999 Chi-Chi earthquake, central Taiwan. *Geology*, **30**, 171-174.

Chen, W. S., K. J. Lee, L. S. Lee, D. J. Ponti, C. Prantice, Y. G. Chen, H. C. Chang, and Y. H. Lee, 2004: Paleoseismology of the Chelungpu fault during the past 1900 years. *Quat. Int.*, **115/116**, 167-177.

Kelson, K. H., K. H. Kang, W. D. Page, C. T. Lee, and L. S. Cluff, 2001: Representative style of deformation along the Chelungpu fault from the 1999 Chi-Chi (Taiwan) earthquake: geomorphic characteristics and response of man-made structures. *Bull. Seismol. Soc. Am.*, **91**, 930-951.

Lee, J. C., Y. G. Chen, K. Sieh, K. Mueller, W. S. Chen, H. T. Chu, Y. C. Chan, C. Rubin, and R. Yeats, 2001: A vertical exposure of the 1999 surface rupture of the Chelungpu fault at Wufeng, western Taiwan: structural and paleoseismic implications for the active thrust fault. *Bull. Seismol. Soc. Am.*, **91**, 914-927.

Ota, Y., 1999: Characteristics of earthquake fault associated with 921 earthquake, central Taiwan, especially on the relationship between earthquake fault and pre-existing Quaternary fault. *Proceedings, International Workshop on Chi-Chi Taiwan earthquake of September 21*, **4**, 1-4.

Ota, Y., C. Huang, P. B. Yuan, Y. Sugiyama, Y. Lee, M. Watanabe, M. Yanagida, T. Sasaki, H. S. Tang, U. T. Shu, D. Hirouchi, and K. Taniguchi, 2001: Trenching study at the Tsautun sites in the central part of the Chelungpu fault, Taiwan. *West. Pac. Earth Sci.*, **1**, 487-498.

Ota, Y., M. Watanabe, Y. Suzuki, and H. Sawa, 2003: Active faults along the Chelungpu fault, central Taiwan, especially its close coincidence in the location of 1999 Chi-Chi earthquake fault. *J. Geogr.*, **112**, 18-34. (in Japanese)

Ota, Y., M. Watanabe, Y. Suzuki, and H. Sawa, 2004: Geomorphological identification of pre-existing active Chelungpu fault in central Taiwan, especially its relation to the location of the surface rupture by the 1999 Chi-Chi earthquake. *Quat. Int.*, **115/116**, 155-166.

Ota, Y., Y. G. Chen, and W. S. Chen, 2005: Review of paleoseismological and active fault studies in Taiwan in the light of the Chi-Chi earthquake of September 21, 1999. *Tectonophysics*, **408**, 63-77.

Rubin, C. M., Y. G. Chen, J. C. Lee, H. T. Chu, R. Yeats, K. Mueller, and Y. C. Chan, 2001: Surface rupture and behavior of thrust faults proved in Taiwan. *EOS Trans. AGU*, **47**, 565-569.

Shishikura, M., Y. Ota, M. Watanabe, H. Sawa, M. Yamaguchi, M. Yanagida, T. Tanaka, K. Ichikawa, Y. S. Lee, C. T. Lu, and T. S. Shih, 2002: Paleoseismological study at Fengyuan site on the northern part of the Chelungpu fault, central Taiwan. *Annual Report on Active Fault and Paleoearthquake Researches*, **2**, 279-289. (in Japanese)

Ota, Y., M. Shishikura, K. Ichikawa, M. Watanabe, M. Yanagida, T. Tanaka, H. Sawa, M. Yamaguchi, Y. H. Lee, S. T. Lu, T. S. Shih, and S. Amagasa, 2007: Low-angle reverse faulting during two earthquakes on the northern part of the Chelungpu fault, deduced from the Fengyuan trench, central Taiwan. *Terr. Atmos. Ocean. Sci.*, **18**, 55-66.