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# Shallow Reflection Seismics Aiding Geological Drilling into the Chelungpu Fault After the 1999 Chi-Chi Earthquake, Taiwan

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## ABSTRACT

**Two shallow holes (~300m) were drilled to uncover cores to study the properties of the Chelungpu fault, which was activated during the 1999 Chi-Chi earthquake (Mw=7.6), Taiwan. Before drilling, we collected seismic reflection data near the wells to aid the drilling processes. The depths predicted by the seismic reflection sections proved to be very close to the drilling results. These seismic sections also provided details of underground 2D structures, which are of help in clarifying the relationship of the well with the neighboring geology. Besides this, we also present several seismic sections describing the undisturbed structures on the Chelungpu fault's footwall side opposite the violated hanging-wall side. A detachment type of movement is suggested to explain this extraordinary phenomenon. Finally, a combination of seismic and electric methods was implemented to explore the near-surface structure of the Sanyi fault, which is believed to be the counterpart of the Chelungpu fault but at a deeper location. The results show that the Sanyi fault is old and has ceased its movement, perhaps not having been involved in the Chi-Chi earthquake's action.**

**(Key words: Geological drilling, Shallow reflection seismics, Fault detection)**

## 1. INTRODUCTION

The Chelungpu fault is a reverse fault dipping shallowly to the east, which was activated during the 1999 Chi-Chi earthquake (Shin and Teng 2001), with extraordinarily large surface ruptures (as large as 5.6m vertically and 9.8m horizontally). This earthquake had several particular characteristics: (1) The largest displacement was observed in the northern portion of the fault near the town of Fengyuan, 50 km north of the epicenter, in contrast to less surface displacement in the southern portion (to be precise, south of Wufeng) (Chen et al. 2001; Yu

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et al. 2001). (2) The area of heaviest damage was limited within several tens of meters from the surface rupture (Kelson et al. 2001; Lee et al. 2002). (3) Seismic records along the fault indicate that high frequency seismic waves were generated in the southern portion, while the northern portion was dominated by the lower frequency wave components (Ma et al. 2001). (4) The strong motion records show that it was a low PGA (peak ground acceleration) and high PGV (peak ground velocity) type of shake, as compared to world earthquakes of similar sizes (Tsai and Huang 2000; Wang et al. 2000). (5) Seismic wave radiation analysis (Huang et al. 2000) indicates that the northern portion of the fault was triggered about 10 seconds after the initiation in the southern part, suggesting that the northern fault surface was triggered by the movement of the fault surface in the southern part.

In general, the seismic characteristics in the southern portion of the Chelungpu fault were similar to those of inland earthquake faults. On the other hand, those in the northern portion were somewhat similar to those of a 'Tsunami' earthquake, which is generally generated at a subduction trench (Seno 2000; Tanaka et al. 2002). This is suggested by the afore-mentioned fact that the motion of the fault surface is rapid but very smooth in the north in contrast to the south. From these observations, the Chi-Chi earthquake can be characterized as a mixture of inland and subduction zone 'Tsunami' earthquakes, with the latter being triggered by the former. If this is the case, the northern and southern fault zones could have contrasting mechanical, chemical, and physical characteristics. Thus, we decided to drill two wells (~300m), one in the north near Fengyuan (the Fengyuan well) and the other in the south near Nantou (the Nantou well) (Fig. 1a).

Before drilling, shallow seismic reflection surveys were conducted near the well sites to collect basic underground structural information. In this paper, besides describing the preliminary drilling results, we also pay attention to the seismic sections which were used to aid the drilling. Much effort was taken to explain the surface rupture patterns in terms of structural variations revealed in the shallow seismic sections. It is important to learn about faulting processes, not only in the surface geology, but also in the underground structural distribution.

Besides studying the Chelungpu fault, a combination of seismic and electric methods were implemented to explore the near surface structure of the Sanyi fault. This fault is believed to be a counterpart of the Chelungpu fault, but at a deeper location (Hung and Wiltschko 1993; Chen et al. 2000). The geophysical sections do help in the interpretation of a shallow well (70 m), drilled into the Sanyi fault, if properly arranged to complement one another.

## 2. GEOLOGIC SETTING OF THE CHELUNGPU FAULT

The geology near the Chelungpu fault (Fig. 1) is relatively simple (Chang 1971; CPC 1982). The structural layers involved are (from top to bottom): the Toukoshan Formation (gravels; Pleistocene), the Cholan Formation (sandstone and shale; Pleistocene and late Pliocene), the Chinshui Shale (shale; late Pliocene), the Kueichulin Formation (sandstone and shale; early Pliocene and late Miocene) and Miocene deposits, composed primarily of sandstone and shale, the top layers being part of the Kueichulin Formation and then the Hsinchuang Formation. The thrusting of the Chelungpu fault has caused the Chinshui and Cholan Formations to move upward and become exposed on the eastern hanging-wall side, forming the hill

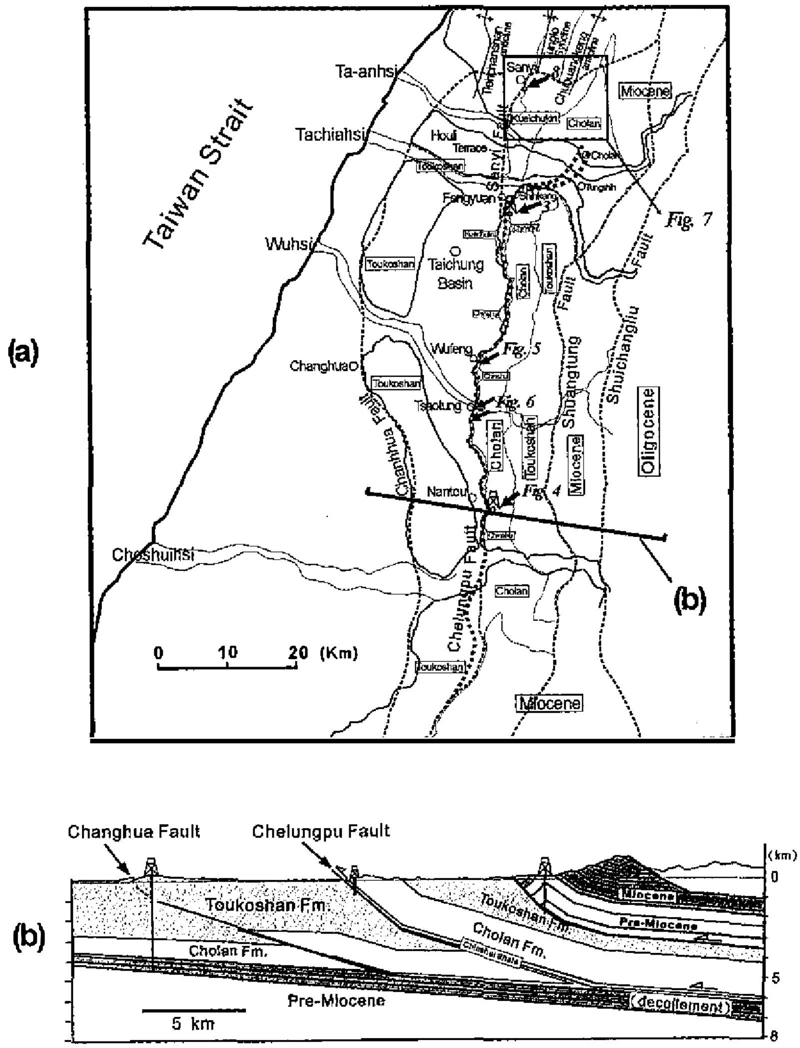


*Fig. 1.* (a) A simplified geological map of the area surrounding the Chelungpu fault and (b) a thin-skinned thrust model proposed by Suppe et al. (2000). Four sequential faults (from west to east) separate the structures of the Pleistocene (Toukoshan Formation), the Piocene (Cholan, Chinshui, and Kueichulin Formations), the Miocene, and the Oligocence. It is noticed that the Changhua fault (the most western one) bends to the east at its northern end, north of the Ta-anhsi river. The Chelungpu fault follows the boundary between the foothills on the east and the Taichung basin on the west. The Sanyi fault extends from the Chelungpu fault, near Fengyuan, and then goes straight north, but also bends to the east near Sanyi. The arrows point out the numbered places to be discussed in the next figures.

(Fig. 1b). This thrust fault is estimated to have been shortened by a total of 13 km over the last two million years (Angelier et al. 2000). The western footwall side is covered by a 3km-thick late Quaternary gravel deposit (including the Toukoshan Formation) which formed the Taichung basin of relatively flat structural layers. We have found these gravel layers to be very flat even just below the fault, as can be seen in the later seismic sections. Figure 1b gives a gross outline of the underground structure of the area, formed by compiling the CPC's (Chinese Petroleum Corporation) seismic reflection data and the thin-skinned thrust model proposed by Suppe (1985). It is obvious that the Chinshui Shale is the key bed controlling the thrusting mechanism. This layer has a thickness of about 300 m, composed mainly of shales, and is probably over-pore pressured (Suppe and Wittke 1977). The Chelungpu fault slides along this bed as a 'bedding-slip fault', which forms the flat-and-ramp boundary of the thin skinned model (Wang et al. 2000; Chen et al. 2000). The smoothly curved shape of the Chinshui Shale is apparently a result of thrust faulting.

## 3. TWO SHALLOW WELLS DRILLED INTO THE CHELUNGPU FAULT ZONE

Drilling into the fault zone with continuous coring is essential to understanding the faulting mechanism. Four issues are considered (Tanaka et al. 2002): (1) the fault zone's structure and its rock distribution, (2) an estimation of the velocity and the acceleration of the fault rupture at the time of the earthquake, (3) the strain localization situation, which generally induces high velocity motion and heat by mechanical wearing along the fault surface, and (4) the fluid path and permeability distributions in the fault zone. The fourth issue is especially important in the case of the Chi-Chi earthquake, as the slip-weakening friction law may be the dominant factor controlling the stress drop and the slip distribution. This kind of all core drilling provides us with a good opportunity to observe and analyze a complete succession of fresh fault zone rocks just after a big earthquake. This may improve our understanding of the fault zone structure and the dynamic processes of the seismic cycle.

The Chelungpu fault drilling was a joint Japan-Taiwan project, lead by Dr. M. Ando (Ando et al. 2001). Two drilling sites were selected, one located at Fengyuan City (northern site) and another at Nantou City (southern site). At the northern site, drilling was performed at an inclined angle of 50 degrees to the west. Figure 2 shows the borehole log columns. We have successfully penetrated possible earthquake fault ruptures at depths of 224m and 326m (drilling depths). The shallower fault zone (224m deep) was composed of relatively narrow (3m maximum), high-water content (>45 vol.%), soft fault breccia originated from the Chinshui/Kueichulin sedimentary rocks. The hole was extremely unstable around this depth. The deeper fault zone was composed of more consolidated, thicker (>10m) fault breccia with a very thin (2 cm) slip plane. By combining the observations and the seismic reflection data (to be discussed below), we consider the most probable earthquake rupture to be at the 224m fault zone, although there are some objections against this viewpoint.

At the southern site, drilling was performed vertically, and the fault surface was successfully penetrated at 175m deep (Fig. 2). The fault zone was composed of relatively consolidated, thick (>50m), foliated fault breccia centralized by 3 m thick black intra-fault materials. As a result of preliminary microscopic observations, this material was found to be composed of

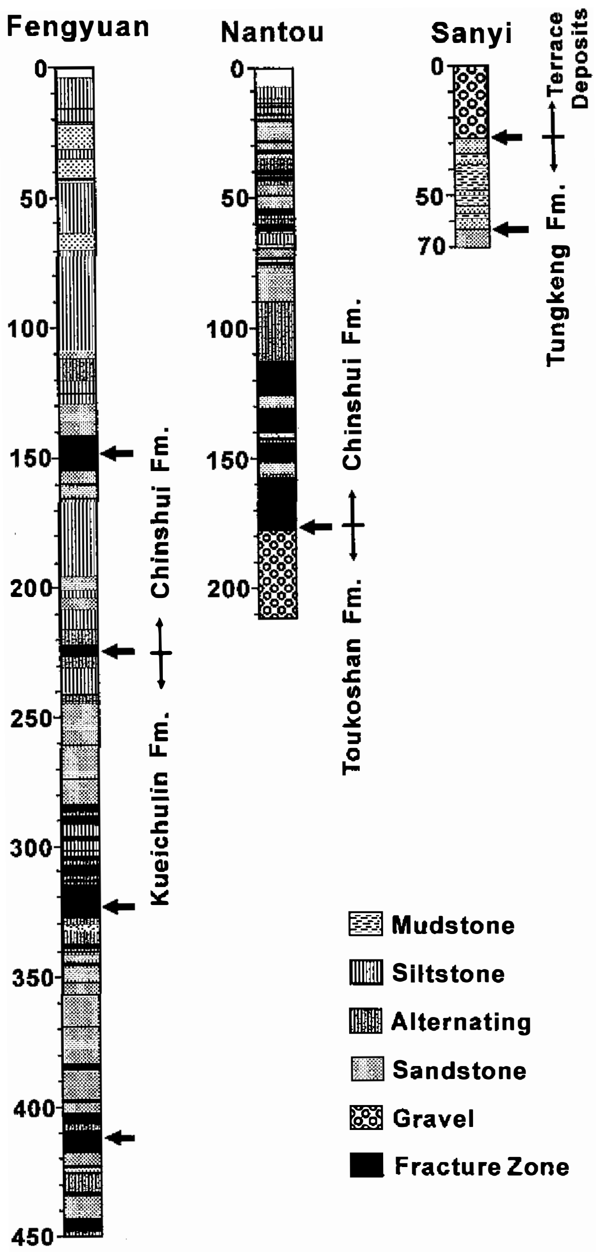


*Fig. 2.* The log columns from the three wells at Fengyuan, Nantou, and Sanyi. The Fengyuan well (450m) crossed four complicated fracture zones. The Nantou well (210m) is relatively simple, possessing a thick fracture zone of about 60m and beneath this the younger late Quaternary gravel deposits. The Sanyi well (70m) is a shallow borehole drilled into the Sanyi fault. The top layer of the Sanyi well is formed of a lateritic terrace deposit, full of loess and unconsolidated gravels.

ultrafine crushed minerals with a cryptcrystalline matrix. Thus, this material can be referred to as "ultracataclasite". The appearance of such a material indicates that high temperatures have been involved in the faulting processes. The fault surface acts as a boundary between the Chinshui Shale on the hanging-wall and the late Quaternary gravel deposits on the footwall. The rupture trace beneath the surface coincides well with the seismic reflection data, indicating that the 1999 earthquake rupture did occur at the 175m fault zone.

## 4. SEISMIC SECTIONS ACROSS THE CHELUNGPU FAULT

The shallow seismic reflection method was used to map the structure near the well. This method was modified from the oil-exploration type of reflection seismics, applied to the shallow depths (about 1km) of engineering interest (Steeples and Miller 1991; Pullan and Hunter 1991). The method just needs a small team, a small budget, and limited equipment, but can map shallow structures in sufficient detail. In this paper, the ability of the shallow seismic reflection method to map a structure tightly constrained by the borehole data is tested. This could be a significant measurement of the quality of the method.

The equipment and the parameters used for the survey are listed in Table 1, and the resulting seismic sections to detect the Chelungpu fault are shown in Figs. 3 to 6. Most of the sections are only several hundred meters long, and thus represent only the small, near-surface, close-to-the-fault portion of the larger structure described in Fig. 1b. In these sections (Figs. 3 to 6), the vertical depth axis and the horizontal distance axis have been arranged to be approximately the same scale, in order to present a more realistic picture of the underground structure. The depth axis was roughly estimated by converting the time scale using the velocities obtained in the CDP data processing. An error of about 10% should be allowed for the calculated depth.

Figure 3 shows a shallow reflection seismic section made adjacent to the Fengyuan well at the northern portion of the Chelungpu fault (check Fig. 1a for the location). The surface rupture induced by the earthquake occurred at the 480m position, as shown in the accompanying map of Fig. 3. It is interesting to see that the deformed structural layers uniformly dip to the

Table 1. Field survey equipment and parameters.

| Items | Equipment | Items | Parameters |
|---|---|---|---|
| Source | EWG-III impact pulse generator | Receiver interval | 2m |
| | | Source interval | 6m |
| Receiver | OYO 40Hz geophone | Near-offset | 100m |
| Seismograph | DAS-1 96 channel | Fold | 16 |
| | | Sampling rate | 0.25ms |
| | | Low cut filter | 40Hz |

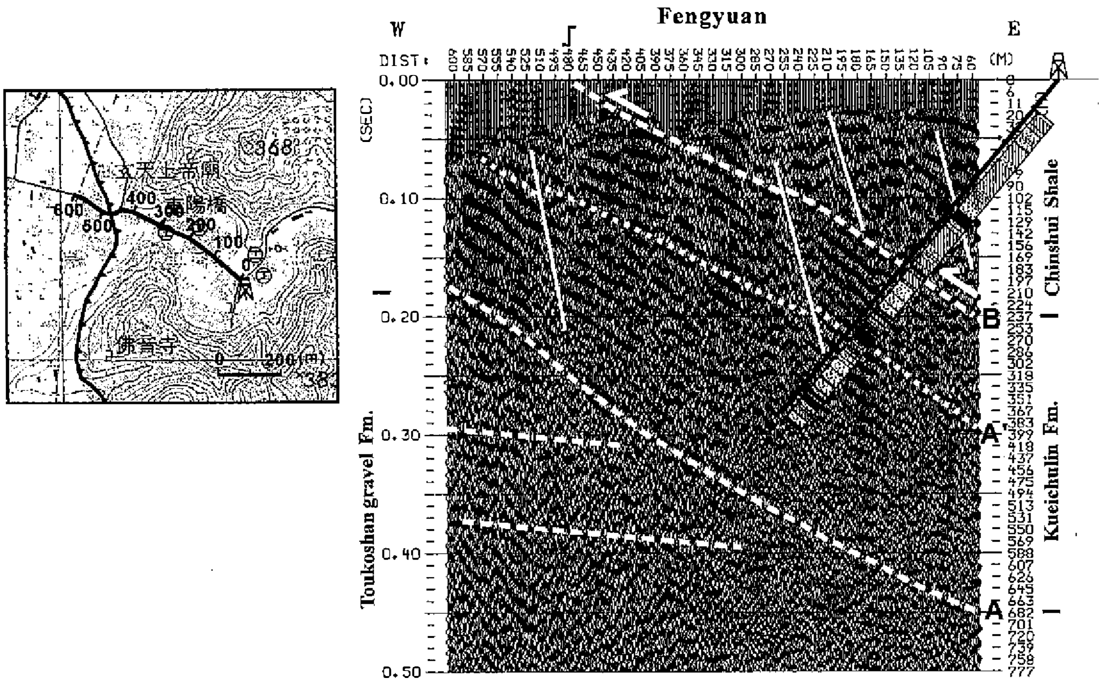


*Fig. 3.* A shallow reflection seismic section taken adjacent to the Fengyuan well at the northern portion of the Chelungpu fault. Most of the layers dip to the east, except the bottom one, which is flat. The surface rupturing caused by the earthquake is located at the 480 m position (shown by a step symbol). Symbol A represents the boundary between the Kueichulin Formation (inclined) and the late Quaternary gravel deposits (flat). Symbol B is located between the Kueichulin Formation and the Chinshui Shale (disturbed), which is supposed to be the fault surface of the earthquake. It is obvious that the B boundary can be connected to the place of surface rupture. There is a strong reflection boundary A' inside the Kueichulin Formation, which can also be tied to a fracture zone observed in the well. Fractures are indicated with slanted line segments, which are believed to have been caused by the faulting as it thrust upward along the layer boundary, causing fracturing at a 45° angle to the layer.

east at an angle of about 30 degrees. The letter symbol A denotes the boundary between the slanted Kueichulin Formation and the younger and flatter late Quaternary gravel deposits. Symbol B falls between the Kueichulin Formation and the Chinshui Shale (Hung et al. 2001). There is a strong reflection boundary A', which could be a lithographic boundary within the Kueichulin Formation. It is obvious that the Kueichulin Formation is composed mainly of uniformly dipping layers, while part of the layers in the Chinshui Shale have been twisted into bulging shapes. Some fractures, which are indicated by slanted line segments, have possibly been caused by the faulting, when the Chinshui Shale moved upward along the layer boundary (i.e., the bedding-slip fault). This upthrusting produced fractures at an acute angle (about 45° ) to the layers (Wang 2002). The Chinshui Shale has more fractures, since it is on the deformed hanging-wall side and is closer to the surface with less confining pressure. The Fengyuan well, which is inclined at 50°, meets boundary B at a depth of about 220 m and boundary A' at 330 m. Apparent fault breccia or gouges have been found concentrated at these depths, as described in Fig. 2. It is obvious that boundary B, which can be connected to the area of surface rupture, was the one that was moved during the earthquake. However, we may not exclude that boundary A' was also activated, since some fresh fault breccia were also found along this boundary in the well.

Two pieces of evidence, provided by Hung et al. (2001), indicate that boundary B (225m) may be the separation point between the Chinshui and Kueichulin Formations. One point is the fossil richness, which is apparently much higher above 225m than below this depth. Another is the lithologic variation shown by a gradual increase of sand content and interbedded sandstone and shale above 225m, while the sandstone becomes dominant below 225m. There is no exemption that the surface fractures found along the Chelungpu fault south of Fengyuan and north of the Choshuihsi river, are all within the Chinshui Shale. Hence, the B boundary (i. e., the bottom of the Chinshui Shale) should be the major fault, and the A' boundary could be a minor one, if it was also moved during the earthquake. Figure 3 also indicates that the well would pass through the Kueichulin Formation to meet the late Quaternary gravel deposits at a depth of about 650m. Drilling to this depth could not be undertaken by the project, so the well stopped at 450m.

Similar to the northern Fengyuan well, we also shot a shallow reflection seismic section adjacent to the Nantou well, at the southern portion of the Chelungpu fault. Figure 4 shows the result. Boundary B in this section is the boundary between the Chinshui Shale and the late Quaternary gravel deposits. The structures on two sides of this boundary are totally different, the lower one being almost flat and the upper one very distorted. Boundary C in the upper portion may separate the Chinshui Shale and the Cholan Formation. The Chelungpu fault slid along boundary B and became exposed at the surface near the 1000m position, which is right at the new Highway 2. The well was drilled through the Chinshui Shale, which was full of fault debris, such as gouges or breccia, especially between depths of 112m and 175m. 175m is the depth at which boundary B was hit by the well. The layers in the Chinshui Shale, as well as in the Cholan Formation, are obviously disturbed and distorted. In contrast, the layers in the late Quaternary gravel deposits are surprisingly flat, especially those just under boundary B. This observation can be explained by a weak and lubricated surface, just like that of boundary B, where the hanging-wall block became detached from the footwall block and moved separately.

The flat layering and undisturbed structure of the late Quaternary gravel deposits in the footwall is relatively strange, considering that the earthquake rupturing was so gigantic. More data on the footwall close to the fault trace, are given in Figs. 5 and 6 (for details, see Chen 2002). The seismic sections in Fig. 5 were collected during night time, in the streets of Wufeng City, right after the earthquake. The atmosphere was one of great sorrow, as the survey crew passed through this heavily damaged city. Fortunately, the data quality was quite good. Some

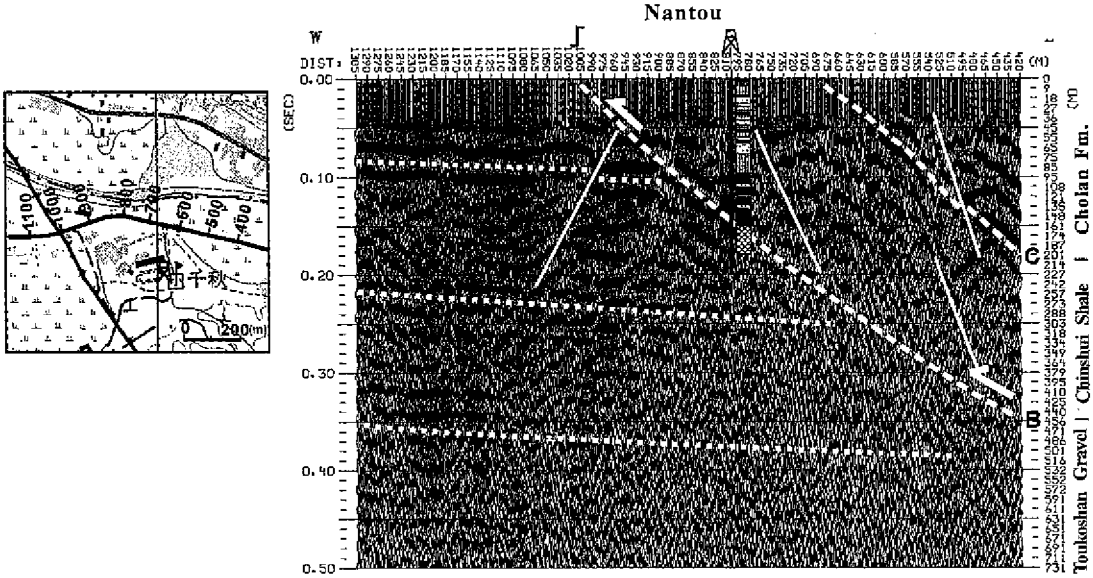


*Fig. 4.* A shallow reflection seismic section taken adjacent to the Nantou well in the southern portion of the Chelungpu fault. Symbol B indicates the boundary between the Chinshui Shale and the late Quaternary gravel deposits. C is the boundary between the Chinshui Shale and the Cholan Formation. The Chelungpu fault slid along boundary B and became exposed at the surface near the 1000m position. The well drilled through the Chinshui Shale was full of fault breccia. The depth of 175m is related to boundary B and beneath it comes the younger late Quaternary gravel deposits, which are surprisingly flat. In contrast, the layers within the upper Chinshui or Cholan Formations are greatly deformed and bent.

liquefaction has occurred in this town, due to the high water level in the upper alluvial deposits which contained a lot of coarse grains, as can be seen from low-frequency signals in the top layer of Fig. 5. The flatter layers below 0.1 seconds, however, belong to late Quaternary gravel deposits, which were apparently unaffected by the earthquake. In the Wufeng2 section, a little bending of the layers can be seen, which reflects the greater intrusion of the late Quaternary gravel deposits to the east, and more pressure from the hanging-wall side. A thrust fault shows up at the upper-right corner of this section. Although the contact is so direct, the faulting has not affected the late Quaternary gravel deposits on the footwall. This fault trace arrives at the surface at the 220m position, but where no surface rupturing occurred (Fig. 5 inlet map). The local topography may have altered the stress distribution at very shallow depths and changed the fault distribution at the surface (Kelson et al. 2001).

Figure 6 is another section that shows the interaction of the flat layers with the dipping layers. The sections are from the town of Tsaotung, where the Wuhsi river, the biggest river in the Taichung basin, flows through. The first section in Fig. 6 is located inside the town, where

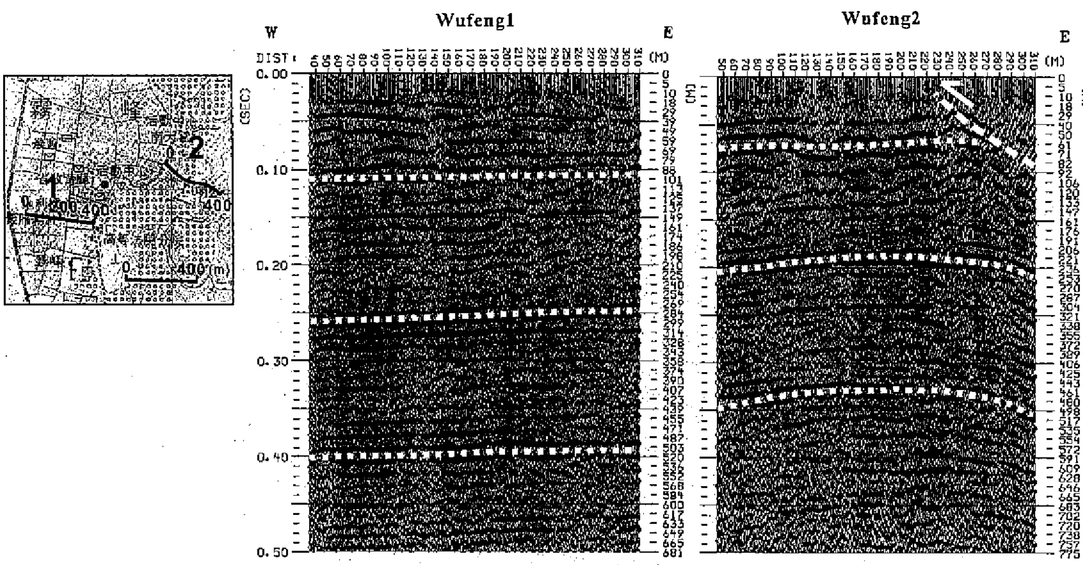


*Fig. 5.* Flat structures under the town of Wufeng. All layers belonging to the late Quaternary gravel deposits are dominated by gravels, with some interbedded shale and sandstone layers, that give strong reflections. A dipping signal in the upper-right corner of the Wufeng2 section indicates the fault, or equivalently, the Chinshui Shale. The place where it reaches the surface is the real boundary of the fault, as can be checked by the accompanying map.

the fault traces spray out in an 'En echelon' type. The seismic section (Tsaotung1) shows that the fault dip angle is quite high, about 45°. We have found that there are always higher dip angles along a river, since the surface of the fault plane becomes steeper there (Wang 2002). The layers in the footwall also have slight dipping angles. These two factors of layer dipping variation may be combined to produce multiple fault branches on the surface. This 'En echelon' phenomenon was not uncommon during the Chi-Chi earthquake, e.g., also occuring at the Choshuihsi river (Minjan), the Tsaohuhsi river (Chutzukeng), the Toubanhsi river (I-Jian-Chiao), etc.. If the faulting happened away from the river, it was shallower and simpler, as can be seen in the second section of Fig. 6. This section is located south of Tsaotung, in fact, at Chung-Hsing-Hsin-Chun (the site of the provincial government of Taiwan). The fault seems to follow a small dip angle (25°) to thrust upward. The motion was simple, creating a simple contact with the ground surface. Most of the slipping surfaces of the Chelungpu fault happened at the low boundary of the Chinshui Shale. One interesting hypothesis has been proposed for this: continuous thrusting along the Chinshui Shale has made this layer grow and thicken. The thickness of Chinshui Shale in the Chelungpu fault area is about 300-350m (Chang 1971), which is thicker than other places on the island, e.g., 250-300m in the Miaoli area (Tang 1967), and 150-200m in the Hsinchu and Taoyuan area (Hsiao 1967). Faulting might have occurred repeatedly over a long period, making the Chinshui Shale thicker.

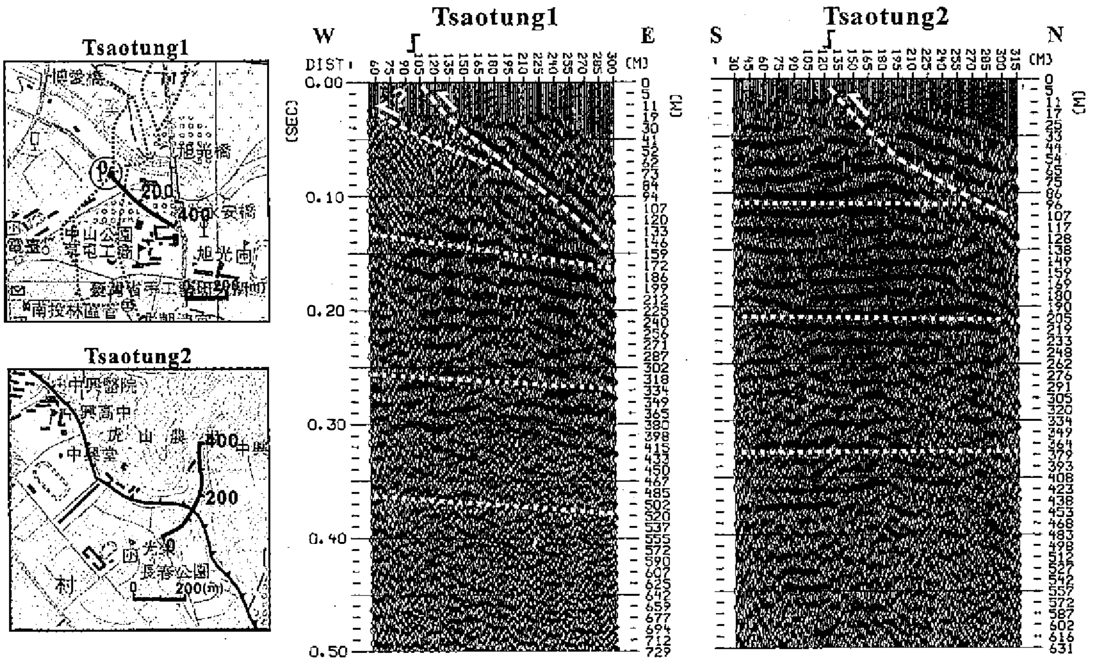


*Fig. 6.* Two seismic sections crossing the Chelungpu fault in Tsaotung. The first section (Tsaotung1) is from inside the town of Tsaotung and the second (Tsaotung2) is to the south, actually in Chung-Hsing-Hsin-Chun (the site of the provincial government). The accompanying maps show their locations. The fault traces are denoted by dashed or toothed lines. It is noted that the first map has the En echelon type of fault distribution, but the second map is a simpler one. The late Quaternary gravel deposits occupy the lower portion (below 0.1 sec) of both sections, where the layers are flat, or a little tilted without much disturbance. In contrast, the Chinshui Shale, in the upper-right corner, has been thrust up at a high inclination angle until it breaks the surface. The first section even has a branch extending further to the west, which could be an extrusion of the fault breakage passing through the near-surface part of footwall layers.

## 5. SEISMIC SECTIONS ACROSS THE SANYI FAULT

The Sanyi fault is closely related to the Chelungpu fault. In the geological map (CPC 1982), it was named the Sanyi-Chelungpu fault, which represented a long south-north boundary (ref. Fig. 1a) that developed along the deformation front of the western Taiwan foothills (Meng 1963). During the Chi-Chi earthquake, the trace of the Chelungpu fault suddenly turned northeast at Fengyuan, thus separating from the Sanyi fault (Fig. 1a). From a CPC seismic reflection section taken along the Ta-anhsi river (Hung and Wiltschko 1993; Lee et al. 2002), we found that the Chelungpu fault moves along the shallow Pliocene Chinshui Shale (about 1km deep), while the Sanyi fault runs along the deeper Miocene Tungkeng Formation (the lower part of the Hsinchuang Formation, about 3 km deep). The Sanyi fault also turns to the east at Sanyi (Fig. 7), then goes eastward and cuts through the southern part of the Chuhuangkeng anticline (Fig. 1a). There is plenty of evidence showing that the Sanyi fault is a low angle (10-

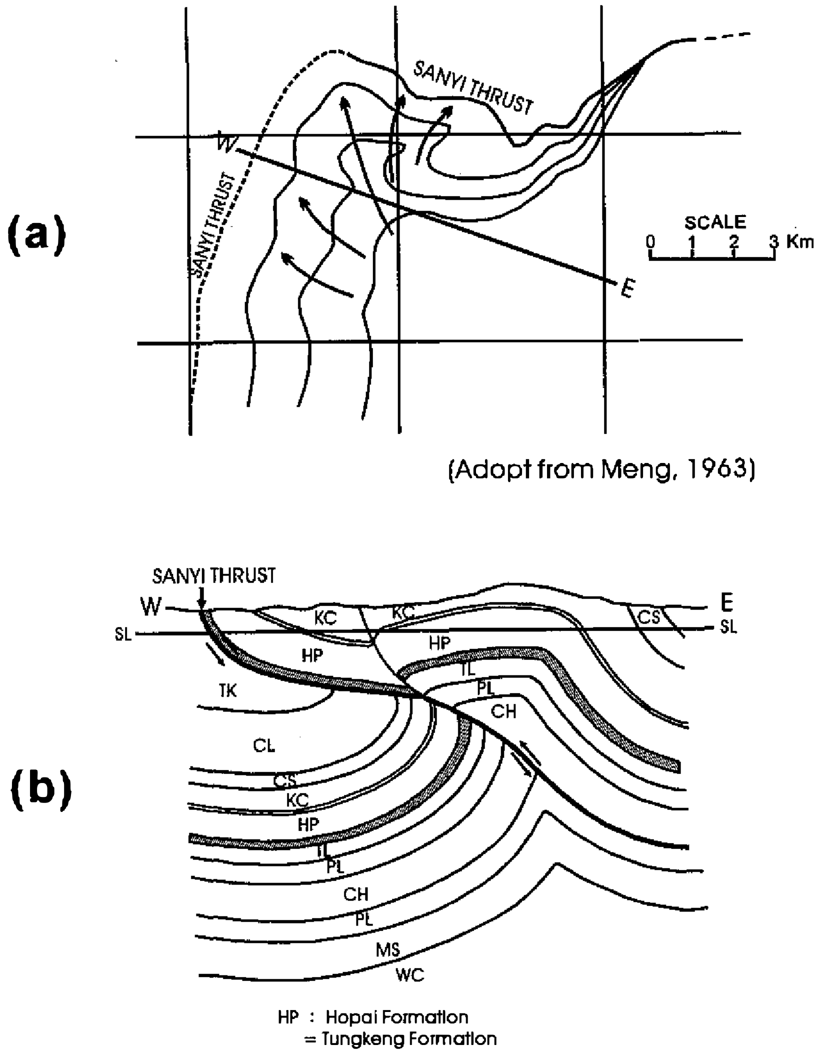


*Fig. 7.* The over-thrusting model adopted from Meng (1963). (a) is the map as indicated in Fig. 1 and (b) is a cross-section showing the over-thrusting of the Sanyi fault. It is noticed that the overthrust intrusion is in a 'tongue' shape. A similar structural pattern of this area can be found in Hung and Wiltschko (1993), though that is a well-designed balanced cross-section complied from many seismic reflection data and well logs.

20 degrees) overthrust fault (Meng 1963; Hung and Wiltschko 1993). Figure 7 shows such a structure. It has caused the lower Pliocene Kueichulin Formation and the upper Miocene Hsinchuang Formation to thrust by a distance of 7 km, until it rolls over and covers the Tunglo syncline (Figs. 1a and 7). This syncline is composed of young Toukoshan Formation near the surface. Some researches (Hu 1970; Hung and Wiltschko 1993; Lee 1994; Chen et al. 2000) have pointed out that, since the Sanyi fault is buried under terrace deposits at the Houli terrace (Fig. 1a), it can be ranked as an old fault and may have not moved for a long while.

The Sanyi fault turns to the east near Sanyi, which makes the overthrust part intrude like a 'tongue' (Fig. 7). This observation may also apply to the Chelungpu fault, as it turns to the northeast along the Tachiahsi and Ta-anhsi rivers. The movement may form some kind of intrusion along certain shallow boundaries in this 'two-river' area. Recently, some data from CPC (Dr. Fu-Ching Su, personal comm.) also indicate that the other fault, the Changhua fault (the most western fault in Fig. 1) may also turn to the east, north of the Ta-anhsi river, as indicated in Fig. 1a. This change of fault direction in this two-river area is not unique. The rise of structures in the northern region, i.e., the Miaoli highland, may have formed an obstacle that stopped further development of the fault systems that were initiated at the south. When approaching a syncline to the north, it will penetrate farther, such as at the 'Tunglo syncline vs. Sanyi fault' (Fig. 1a); otherwise, if it meets an anticline, it will terminate earlier, such as at the 'Chuhuangkeng anticline vs. Chelungpu fault'. This presents a new model for explaining the termination of the fault systems in the Taichung area at their northern edges.

To evaluate the activity level of the Sanyi fault, we acquired over 15 seismic reflection sections across the fault (for details, see Hong 2001). In this paper, we discuss one section taken near the town of Sanyi (actually beside the Chiaochen Elementary School) (Fig. 8). Along this same line, we also conducted a resistivity imaging profiling (RIP) survey (Fig. 9). The RIP is an electric pole-pole method using multiple channel receivers (electric potential poles) and multiple sources (electric current poles) to build up a multiple electric field coverage and to invert the underground resistivity distribution. The results of the RIP are always well correlated with the near-surface structure, which is especially useful for incorporation with the seismic method.

As suggested by the geophysical survey results, a shallow well was drilled at the 610m position of the seismic line (Fig. 8 inlet map). The core column of this well is depicted in Fig. 2. The top 28m has coarse mixed terrace deposits, the middle 28-63m shows weathered mudstone-and-sandstone, and below 63m, fresh, hard sandstone starts to appear, which is no doubt a part of the Tungkeng Formation. Due to budget limitations, this well terminated at 70m; however, we estimate that at 120m, it would penetrate the sandstone layer and enter the buried late Quaternary gravel deposits.

The seismic section in Fig. 8 shows that the Tungkeng Formation is thrust over the young, late Quaternary gravel deposits. This Tungkeng Formation is a part of the Hsinchuang Formation mentioned before, which occupies the upper-right portion of the section and has layers of interbedded sandstone-and-shale dipping to the east at an angle of 40 degrees. Some fractures cut through the dipping layers at a 45° angle to the layer. These fractures were induced by thrusting along the dipping Tungkeng Formation. The lower-left portion of the section in Fig. 8 belongs to the late Quaternary gravel deposits, which have flat layers inserted underneath the

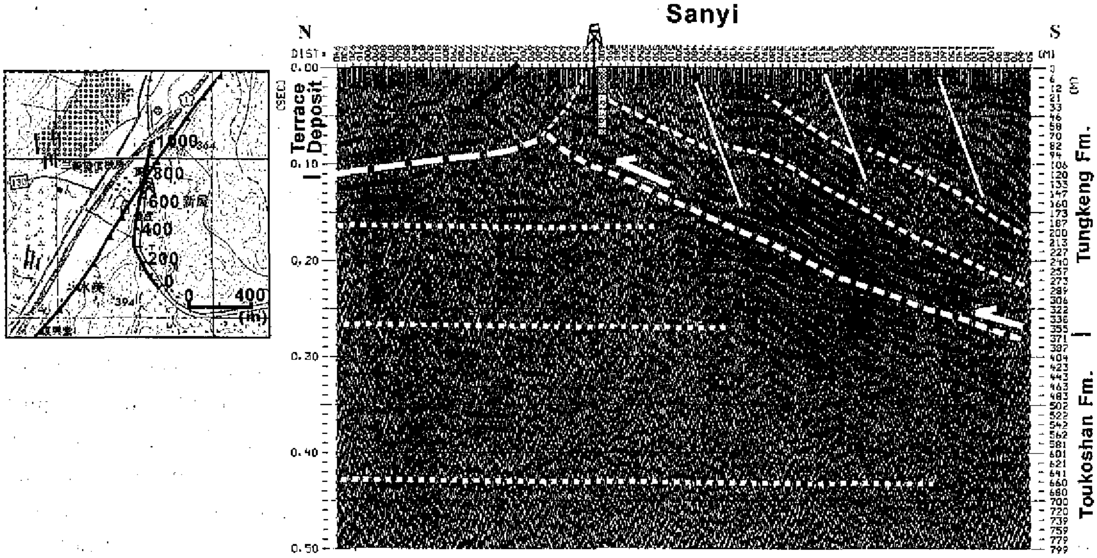


*Fig. 8.* A seismic reflection section crossing the Sanyi fault. The survey site was at the south of the town of Sanyi (Fig. 1a). The Sanyi fault slides along the Tungkeng Formation which contains layers that dip to the southeast. The flat layers of the late Quaternary gravel deposits are visible on the lower-left part of the section. The upper-left corner (arrowed) has an odd westward dipping layer which can be explained as a terrace deposit. An 'eroded-toe' model is proposed to interpret this unusual structure.

Sanyi fault. Some of the late Quaternary gravel deposits adjacent to the fault may have been distorted to some extent. Nevertheless, the most interesting part of this section is in the upper-left corner where a northwestward dipping layer is found (the slanted arrow in Fig. 8). The thrust 'toe' of the Sanyi fault may have been removed by erosion, then replaced by lateritic terrace material, which is thicker toward the northwest where a deltaic fan has been deposited in the fault's footland (see Fig. 9b for more detailed explanation). Due to this replacement of the fault's front toe by alluvial deposits, we may safely say that the Sanyi fault is dead, probably having ceased its movement a long time ago.

The results of the RIP method also support this 'toe erosion' model, shown in Fig. 9. It is quite interesting to find a very clear separation of low and high resistivity regions at the expected fault position. The high resistivity corresponds to the terrace deposits and the low resistivity to the Tungkeng Formation, with its shale content. An interaction occurs between 600-660m range, at the eroded 'toe' as indicated in the interpretation sketch of Fig. 9b. This Sanyi well must be drilled in the right position, where the fault front was removed and replaced by some newer deltaic fan deposits. Figure 9 clearly demonstrates that without the combination of the seismic and electric sections, it would be difficult, or even impossible, to explain the well log. This case elegantly proves the usefulness of combining multiple approaches to explore underground structures in greater detail.

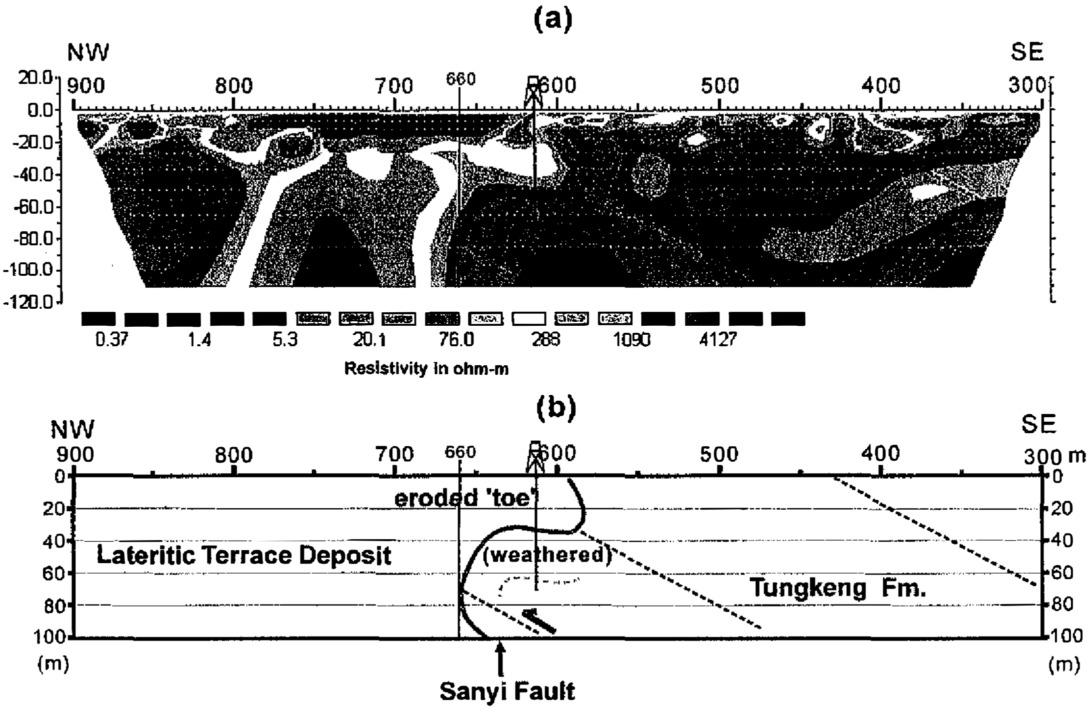


*Fig. 9.* The resistivity section resulting from the resistivity imaging profiling (RIP) method: (a) is the final resistivity section and (b) is its interpretation. The horizontal distance axis is similar to that in Fig. 8. An eroded area exists at the front toe of the Sanyi fault (the 600m-660m range). The well was purposely drilled into this particular region. The red dashed lines indicate the possible layering in the Tungkeng Formation, which is identifiable in the seismic section of Fig. 8.

## 6. DISCUSSION AND CONCLUSIONS

Compared with the oil-exploration type of reflection survey, shallow reflection seismics is economical and convenient. With proper operation, this method should be readily coordinated with the drilling to produce more information about the underground geology.

The two wells and their accompanying seismic sections at the Chelungpu fault have been used to create reliable pictures that illustrate the geological circumstances of the fault. The ambiguity as to which boundary was activated during the earthquake, like that at the Fengyuan well, is nicely solved by using information other than the borehole data. The northern Fengyuan well has a complicated rupture structure. Several fracture zones are found in the well and the seismic section, which are related to the Chi-Chi earthquake's movement with the result of multiple breakage patterns. The southern Nantou well, on the contrary, is relatively simple. The 40$^{\circ}$ dipping Pliocene layers on the hanging-wall side have thrust over the flat Quaternary layers. The separation by the fault is clear and easily seen in the well, as well as the escorted seismic section.

The case at the Sanyi fault is even more significant. Both the seismic and electric methods are used to aid the well drilling. Although the well is shallow (70m), the obtained geophysical sections do help us to interpret the drilling result. An eroded 'toe' on the fault's front part is found, which implies the long existence of the Sanyi fault, which may have ceased its activities and suffered great erosion.

This paper gives good examples which address the importance of seismic data incorporating with the drilling. The seismic section may point out key positions or interesting parts, and the drilling will excavate them for further examination. The cooperation is mutually beneficial. In Taiwan, it is always difficult to collect enough geological information just by shallow wells (<100m) drilled during the site investigation. The importance of using geophysical methods to acquire more information, to supplement the interpretation of shallow wells, is worth emphasizing. The cases described in this paper show some samples which may be used as typical references.

The shallow seismic method even aids in deep hole drilling (2 or 3 km) if the reflection signal can reach that depth. This will largely depend on the survey crew's skill and the equipment available. Over 120 channels and explosive sources are more properly considered, for instance. We are now preparing the data for the possible future deep hole drilling at the Chelungpu fault. This will be another challenge for the method.

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