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The Detection of Three Active Faults on the Taoyuan Terrace, Northwestern Taiwan by Shallow Reflection Seismics

Chien-Ying Wang[1,*], Jin-Dar Chiu[1], and Liang-An Lin[1]

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ABSTRACT

The Taoyuan terrace is located in northwestern Taiwan, and is bordered on the southeast by the fold-and-thrust belt of western Taiwan foothills and on the northwest by the Kuangying shelf. Owing to the blocking of the Kuangying shelf (a basement high), the northwestward tectonic movement has uplifted this area and induced three suspected faults (from north to south): the Shuanglienpo fault, the Yangmei fault, and the Hukou fault with increasing degrees of deformation. This paper reports on the use of the shallow seismic reflection method to examine details of the underground features of these faults and their relationship to the surrounding structures. The results show that the structural layers have been bent into curved shapes but not broken in all sections across the fault scarps. This fact strongly indicates that these faults belong to the category of 'fault-bend-folds'. A curved anticline due to a hidden 'blind thrust' in the fault-bend-fold system can adequately explain the observed structural variations. We believe that the Shuanglienpo fault and the Yangmei fault may not be active, because they are covered by a flat, undisturbed Pleistocene Teintzuhu formation and have low bending angles. However, the Hukou fault may still have the potential to be active as revealed by its steep structural angles and some shallow disturbed layers. Thus, we should not completely ignore the possibility that the hidden blind-thrust under the Hukou fault could still move and trigger big earthquakes.

(Key words: Active faults, Taoyuan terrace, Taiwan tectonics)

1. INTRODUCTION

The Taoyuan terrace in northwestern Taiwan consists of five dissected tablelands (Fig. 1) which were formed from flood-plains in five stages, resulting from the intermittent uplift and eastward shifts of the dendritic drainage of the ancient Shihmenhsi river in the late Pleistocene

[1]Institute of Geophysics, National Central University, Chung-Li, Taiwan, ROC

**Corresponding author address*: Prof. Chien-Ying Wang, Institute of Geophysics, National Central University, Chung-Li, Taiwan, ROC; E-mail: wangcy@cc.ncu.edu.tw

time. These five tablelands are shaped like a composed northeastward tilted terrace (Fig. 2) with the Hukou tableland as a rising core. The boundaries between different tablelands form slopes which are mostly oriented in the north-south direction (Figs. 1 and 2). Around the Taoyuan terrace, the fold-and-thrust belt of western Taiwan foothills is sited on the southeastern border and the Kuangying shelf (or Kuangying basement high) on the northwestern offshore. It is believed that tectonic forces from the southeast pushed this terrace causing it to warp as it climbed up the Kuangying basement high (Ku 1963; Meng 1965; Tang 1963a,b, 1964; Chiu 1970; Huang et al. 1992). Figure 3 describes this situation, emphasizing the fold-and-fault

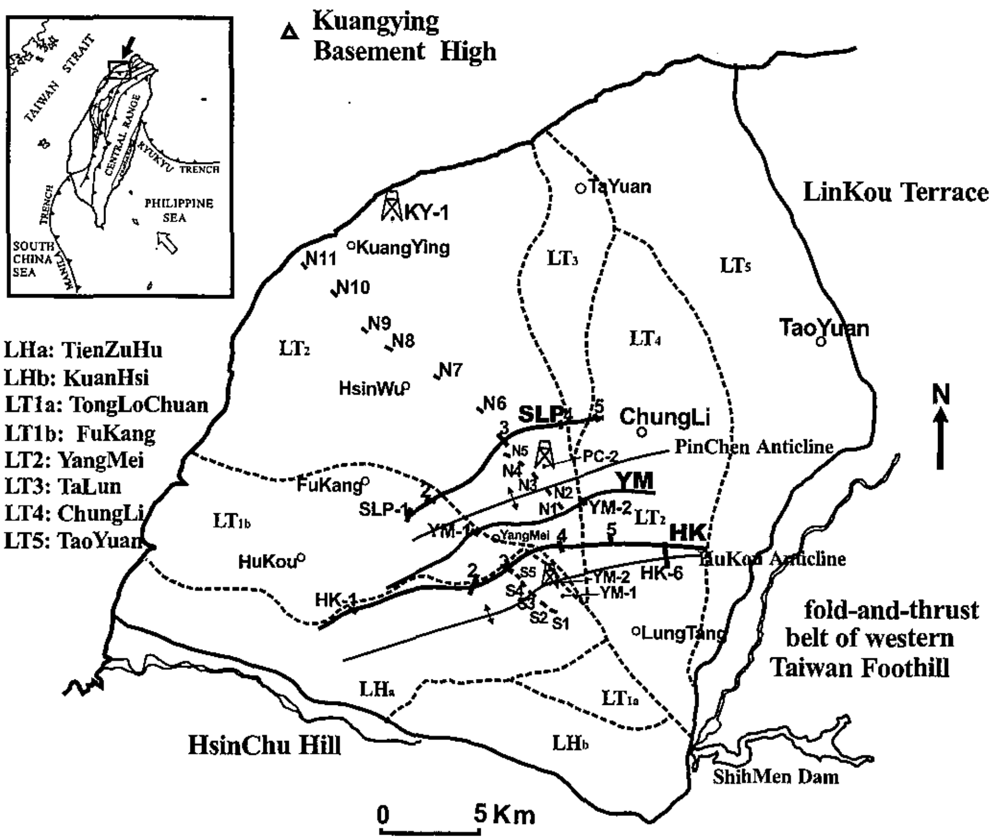


Fig. 1. A map of the Taoyuan terrace group (modified from Shih et al. 1986). Six terrace surfaces are identified: one LH (Lateritic Highland) and five LT (Lateritic Terrace) surfaces. All these terraces were delta fans, deposited during the Pleistocene time that tilted toward the northeast due to the tectonic pressure from the south or the southeast. Three active fault traces are identified (from north to south): Shuanglienpo (SLP), Yangmei (YM), and HuKou (HK). Several seismic lines and the four well locations (KY-1, PC-2, YM-2, and YM-1) referred in the text are also denoted.

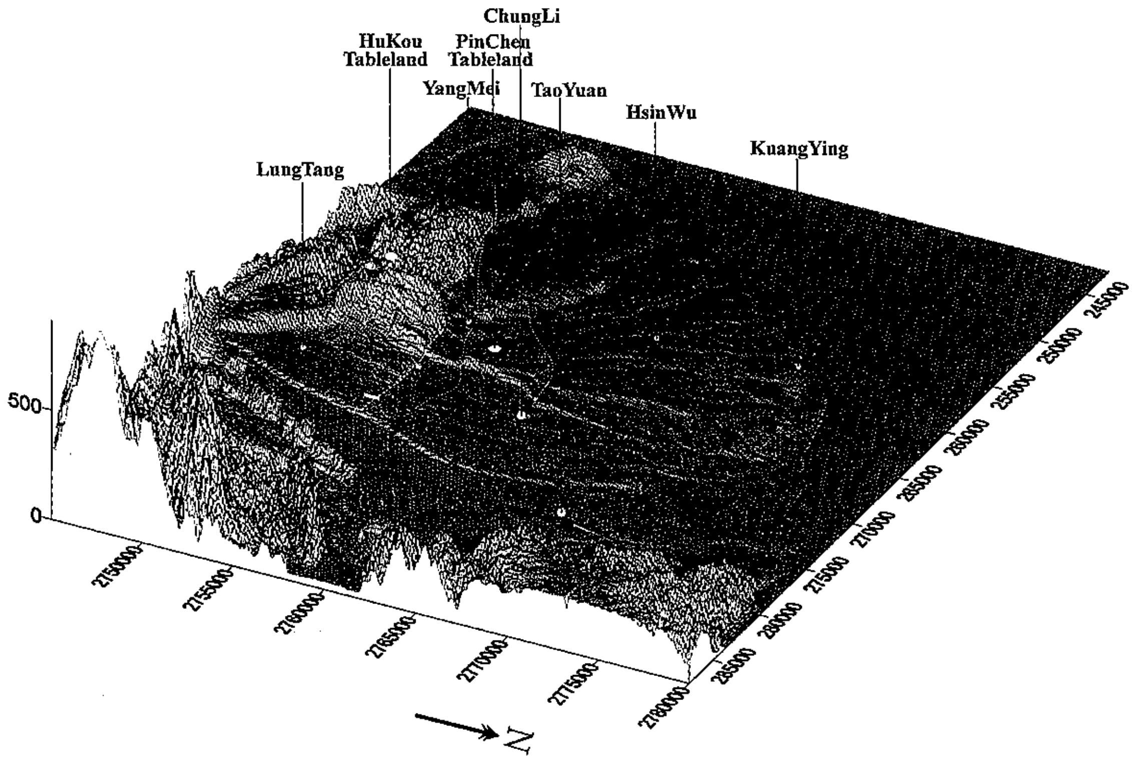


Fig. 2. A stereo topographic map showing the geomorphic variation of the Taoyuan terrace. The vertical scale of this DTM data were magnified 10 times. The viewing angle is from the northeast. Compare this figure with Fig. 1 for the site locations. Different terrace units and their topographic configurations are vividly described. The three fault traces, indicated by the dotted lines, apparently follow the tableland scarps which are perpendicular to the terrace boundaries. There seems to exist a graben between the Hukou fault and the Yangmei fault, and a tableland (Pinchen) between the Yangmei fault and the Shuamgliepo fault. This topographic shape faithfully reflects the effects of underground structural undulations.

forming mechanism, based on early petroleum exploration data (Hsiao 1967; Chang 1971; Chiu 1972). The tectonic movement may have deformed this land to form three faults (from north to south): the ShuangLienPo fault (SLP), the YangMei fault (YM) and the HuKou fault (HK) (Bollina 1977; Hsu and Chang 1979). Figures 1 and 2 apparently indicate that all three faults trend in an east-west direction and are perpendicular to the tableland boundaries. Since these faults traverse several tableland surfaces, they are considered quite young and have thus been ranked as active faults (CGS 2001).

During the 1960's, the Chinese Petroleum Corporation (CPC) explored the Taoyuan area looking for natural resources of oil or gas. Dense seismic lines and gravity mapping were

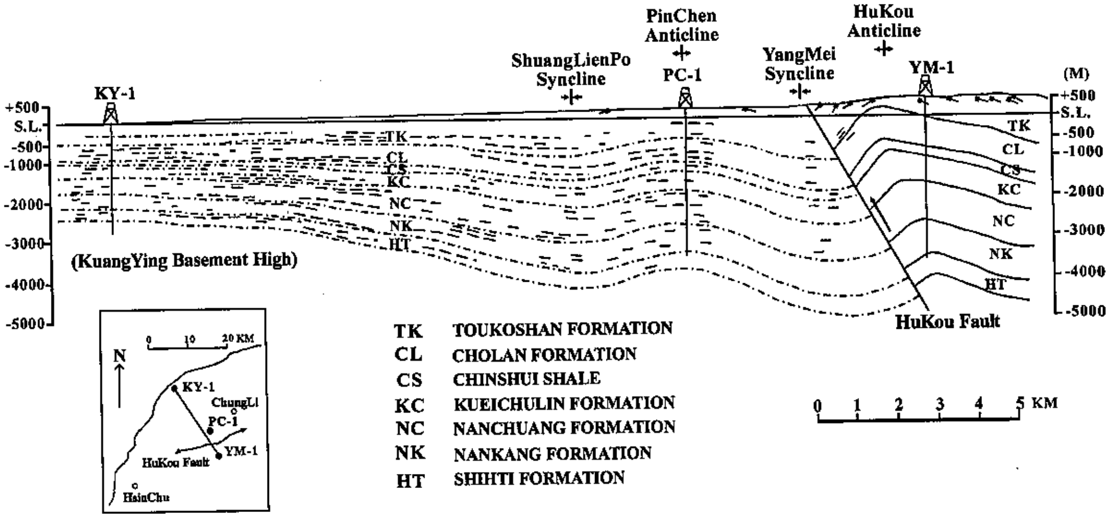


Fig. 3. An approximate underground structure distribution proposed by the CPC researchers (Hsiao 1967; Chang 1971; Chiu 1972) based on seismic and borehole data. To the northwestern offshore, there is a Kuangying basement high which represents a pre-Tertiary basement rise. Above it deposited the Miocene formations (HT, NK, NC, KC), the Pliocene formations (CS, CL), and the Pleistocene formation (TK). The tectonic pressures from the southeast have uplifted these layers and folded them into two anticlines and two synclines. The three active faults are located at the borders of these folds. Note that the Hukou fault is purposely emphasized.

conducted, and several wells with depths greater than 3 km were drilled (Wang 1964; Hsiao 1967; Chang 1971; Lim 1971; Chiu 1972). Figure 3 shows a representative cross section of the exploration results of this era. The figure illustrates that a layered structure was deposited with complete formations from the early Miocene to the Pleistocene without much difference from the standard western Taiwan deposition sequences. Lying on the gentle slope of the Kuangying shelf, all the layers are thicker toward the southeast. The following Pleistocene tectonic movement has modified this sloping structure into folds and thrusts. Two anticlines, the Hukou and the Pinchen anticlines, together with two synclines, the Shuanglienpo and the Yangmei synclines developed, with larger deformation at the southern side. There were several wells drilled near the climaxes of the anticlines, but without significant amount of gas being found. Besides the folds, the Hukou fault was also pointed out in Fig. 3. It passes through the northern flank of the Hukou anticline and dips to the south. The existence of a deep Hukou fault has been seriously discussed in several papers (Tang 1963; Elishewitz 1963).

The Taoyuan terrace, due to its neighboring to Taipei, the capital of Taiwan, is heavily populated and industrialized. The existence of active faults has become a public issue of great concern, especially after the 1999 Chi-Chi earthquake (M_L=7.3) which occurred in middle

Taiwan. The Chi-Chi earthquake triggered an active fault with extremely large surface ruptures and caused severe damage. The purpose of this paper is to explore the three faults on the Taoyuan terrace, and to find their relationship with the structures in the vicinity, using the shallow seismic reflection method. We measure the activity level of the fault by examining details of the structural features on the seismic sections. In addition, many short seismic lines, deployed over a long range, perpendicular to the fault were composed to describe a large profile, which helps us to understand the rule of a fault within the framework of background geological structures.

2. METHOD, FIELD WORK AND DATA PROCESSING

The method used in this study is the shallow seismic reflection method, which is a high-resolution seismic method designed to detect shallow structures (at most 1000 m deep), using small budgets and limited man power (Steeples and Miller 1990). This kind of system is quite suitable for a small organization such as an institute to study structures that are not too deep. The equipments for the work are; 1) source: EWG-III weight drop impact pulse generator, 2) receiver: OYO 40-Hz geophone, 3) recorder: DAS-1 48 channel seismograph. The parameters used for the survey are; 1) source interval: 6 m, 2) receiver interval: 3 m, 3) near-offset: 60 m, 4) fold: 12, 5) sampling rate: 0.25 msec, 6) low-cut filter: 40 Hz. Most of the field work was carried out at night time to avoid the traffic noise. The data processing follows the standard procedures for CDP data, except for emphasizing on some dip filters. The survey area is full of strong groundrolls. A combination of longer near-offsets and different kinds of filters is necessary. A dip filter, based on the Butterworth recursive filter (Hale and Claerbout 1983), has proven to be quite successful in suppressing the groundroll while producing limited side-effects.

Another important data processing procedure we need to worry about is static correction for the shallow seismic reflection data. Due to the relatively short period concerned, the problem of static shift is more profound than in oil exploration surveys, which is simply a matter of order. In this study, we line up the first arrivals according to the rule of 'surface consistency' in both the shot domain and the receiver domain. This is then followed by a Monte-Carlo type of residual static correction to further tune up the signals. A detailed description of such static correction procedures is given in Wang et al. (1994).

The positions of the seismic lines are shown on Fig. 1. There are two kinds of seismic lines: one to detect the fault (SLP-1 to SLP-5, YM-1 to YM-2, and HK-1 to HK6) and the other to map the structures surrounding the fault (N1 to N5, N6 to N11, and S1 to S5). The first kind deploys long seismic lines (about 500 m) at appropriate positions to inspect the fault. They usually have a higher fold and require careful treatment to ensure the results qualify for fault evaluation. The second kind of line, on the other hand, includes many short seismic lines (about 150 m long), each composed of at most 24 shots, and distributed sparsely about 1 or 2 km apart. This is a new idea in the shallow seismic surveying, called 'wide-spread' seismic lines, which attempts to map large scale structures by using a small-scale but cost effective way. Except for reasons of efficiency, the distribution of seismic lines in such a way is sometimes necessary, due to the space restrictions in densely inhabited streets. The sparsely distributed seismic lines help to reduce the environmental impact of unavoidable survey noises. The sections obtained from these wide-spread lines, though coarse, can be gathered to form a longer profile, which is valuable for interpreting the faulting structure around the studied fault. The data processing of the wide-spread lines requires some tricks. We need to keep the reflection events to be 'true amplitude' in order to exhibit the signal characteristics of some key beds that have strong reflections. By putting the sections in a row, we can trace the key beds and fix the structural relations along the profile. The technique of wide-spread lines is quite effective, easy to carry out and, most important, affordable.

3. RESULTS

3.1 Shuanglienpo Fault

Figure 4 shows the five seismic sections across the suspected traces of the Shuanglienpo fault along the northern scarp of the Pinchen tableland (check Figs. 1 and 2 for locations, or for more details see Chiu 1998). The quality of these sections is remarkably good; they have identifiable seismic reflection images even down to the depth of 600 m. In order to easily measure the dip angles, the horizontal and the vertical axes in Fig. 4 and all other similar figures in this paper have been kept in the same scale. In Fig. 4, sections SLP-1 and SLP-5 are located outside the range of the Pinchen anticline and their layers are flat, although a little slanted. Otherwise, the structures in the other three sections: SLP-2, -3, and -4 are apparently crooked in curved shapes. Two significant layer boundaries, A and B, are denoted on these sections. After comparing them with the well data (to be shown later in Fig. 5), we are able to set boundary B as the line separating the Chaomen member and the Chaochin member of the Yangmei formation. According to the local geology (Tu and Chen 1990), the Quaternary Yangmei formation represents deposition in a deltaic environment, which is equivalent to the Tokoushan formation in middle Taiwan. The Chaomen member is composed of interbeded conglomerates, sandstone and mudstone, with the conglomerate being dominant in the upper parts. Above the Yangmei formation deposits the Tientzuhu formation, which is made of thick unconsolidated gravel beds capped by a thin lateritic soil layer. The flat Tientzuhu formation overlies the dipping Yangmei formation, which forms an angular uncomformity along boundary A in Fig. 4. Hence, the curved structure of the Yangmei formation must have formed before the depositing of the Tientzuhu formation.

It is surprising to find that all the structural layers in Fig. 4 are smoothly and continuously curved, and not exist a single track of structural offset. The layers are bent upward, but not 'broken'. The upwinding angles are about 10-15 degrees. The absence of layer fractures in these seismic profiles strongly opposes the existence of a Shuanglienpo fault. It just looks like a structural bending to form a low angle fold, which was thus named the Shuanglienpo syncline by the CPC (e.g., Fig. 3).

To investigate the structure of the Pinchen anticline and its relationship with the Shuanglienpo fault, we further apply the 'wide-spread' line technique to acquire the necessary seismic data (N1 to N5), along a long profile across the anticline (depicted in Fig. 1). Figure 5 shows the results. Six seismic sections are compiled up side by side to form a profile. By

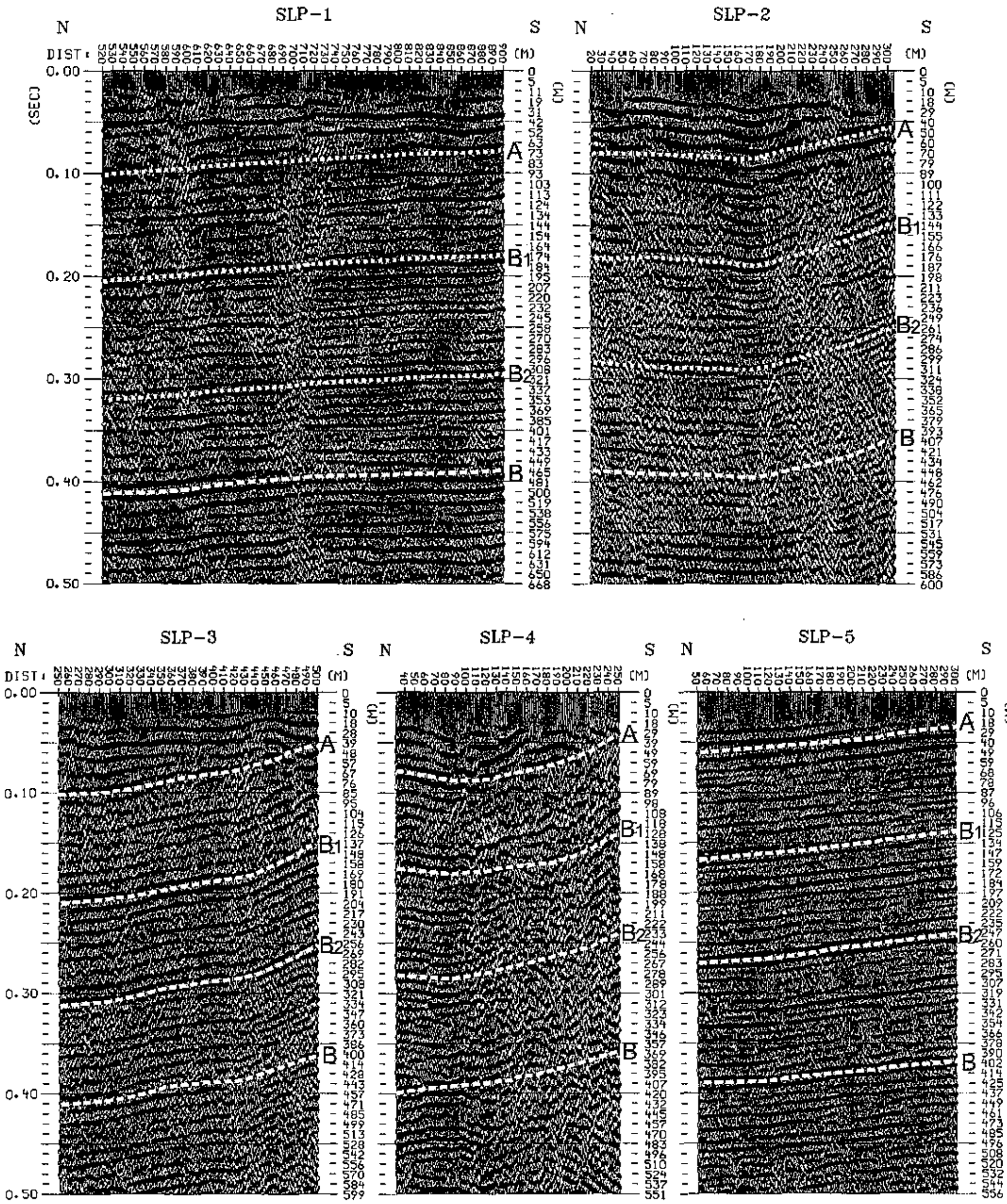


Fig. 4. Five seismic lines (SLP-1 to SLP-5) are used to detect the Shuanglienpo fault. These seismic sections are plotted using the same horizontal and vertical scales in order to measure the layers' dipping angles. It is quite obvious that the structural layers are bent but not broken. Seismic lines SLP-1 and SLP-5 are outside the Pinchen tableland area, and their layers are just gently declined. The dip angles on all these sections are as small as 10-15 degrees.

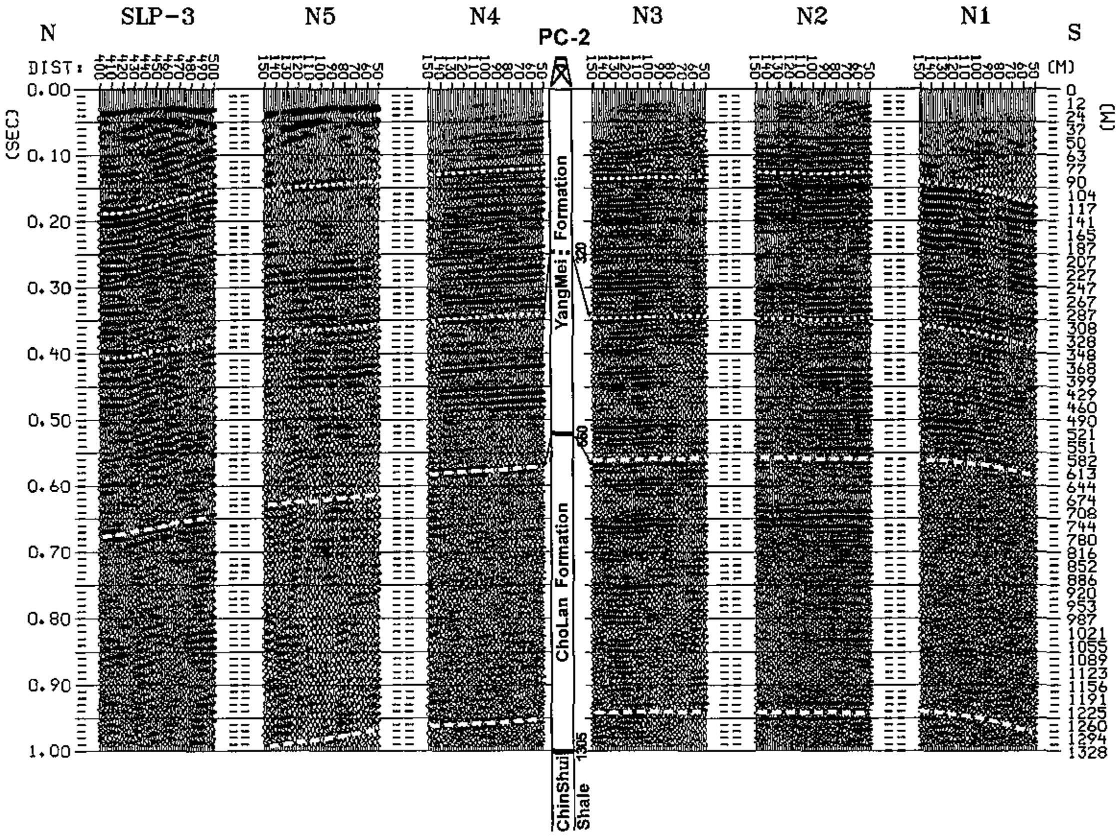


Fig. 5. A sequence of 'wide-spread' seismic lines showing the slightly folded structure of the Pinchen anticline. Check Fig.1 for the location of each line. The pattern of the deposition phase variations and the borehole data are well correlated, which helps to identify the formation boundaries. The shape of an anticline is obvious with the axis set between lines N2 and N3. Note that the structure is covered by a relatively flat layer on the top.

placing a well log column (PC-2) at the middle position, we can interpret the layered structure with its pertinent lithologic formations. The slightly folded structure of the Pinchen anticline can be easily seen in Fig. 5. More interestingly, the anticline's axis is shifted to the south, approximately near line N2, which makes line N1 have a higher dip angle than the others. This axis's deviation to the south has lessened the pressure along its northern wing where the Shuanlienpo fault is supposed to be sited. This observation further reduces the possibility that the Shuanglienpo 'fault' is really a fault. The low compression may have made the area a shallow depression or at most a small syncline. In addition, as seen in Fig. 5, there is a fairly flat layer deposited on the top (above 0.15 sec), which is the Tientzuhu formation mentioned in Fig. 4. This constraint further restricts the age of this anticline to the Pleistocene, i.e., at least over 100,000 years.

To the north of the Shuanglienpo fault, up to the coast, there is a broad flat plain on which six 'wide-spread' lines were deployed (N6 to N11 on Fig. 1). Figure 6 shows the sequence of seismic lines, to exhibit the inclination of the layers deposited on the sloping surface of the Kuangying basement high. Since the separation distances between lines is too wide (>2 km), their mutual correlations are too weak to be established. However, using the KY-1 well data as a control for the northwestern corner, we may still be able to roughly sketch a general dipping structure. The dip angles are very small, only 1 or 2 degrees, and look almost flat. This wide range of flat layers implies little tectonic movement in this region, thus no more folds or faults are being created.

3.2 Yangmei Fault

Between the Pinchen and the Hukou anticlines, lies the Yangmei syncline, shown on the

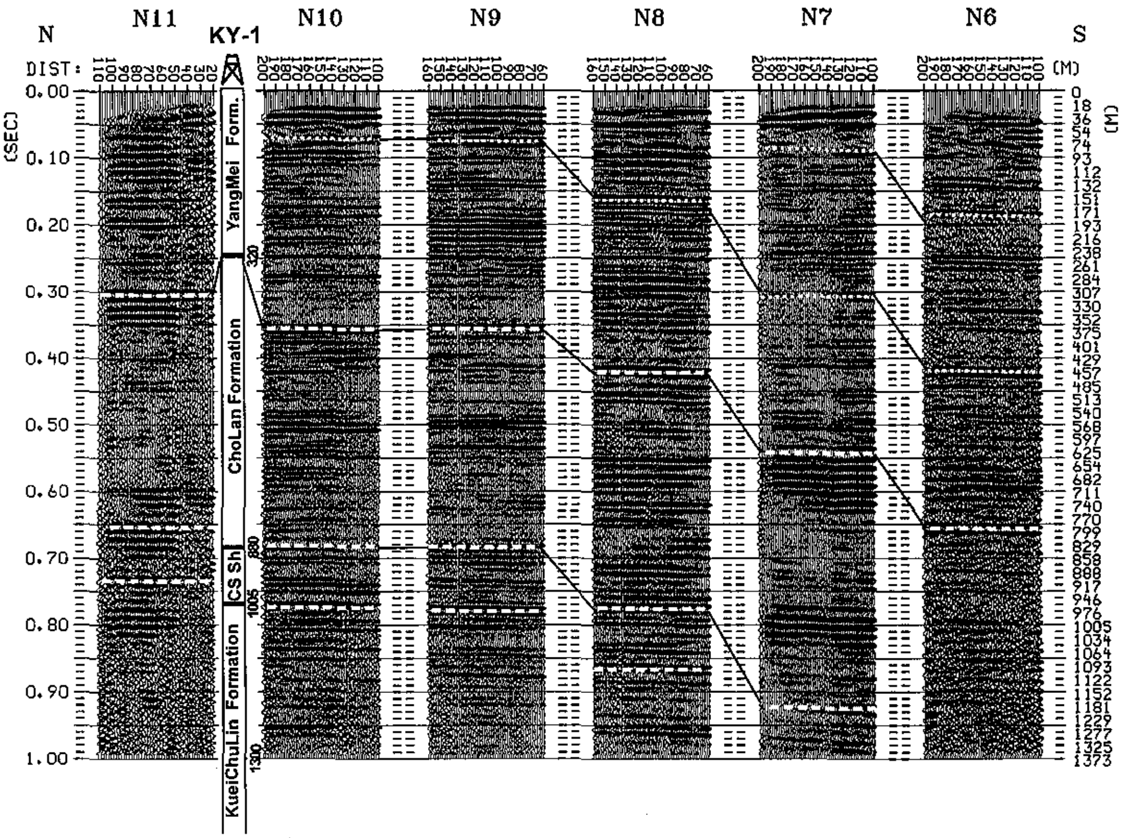


Fig. 6. A sequence of seismic lines that exhibits inclination of deposited layers on the slope of the Kuangying basement high. Since the separation between the lines is too wide (>2 km), their mutual correlation is too weak to define a clear structure variation. However, by using the KY-1 well to control the northwestern side, we may sketch a rough outline of this slightly dipping structure.

structural profile in Fig. 3. This Yangmei structure even looks like a graben bracketed by two tablelands that formed above the two anticlines (Fig. 2). Two active faults have assumed to exist on the northern and the southern boundaries of this depression, i.e., the Yangmei fault and the Hukou fault (Fig. 1). Figure 7 shows the two seismic sections across the Yangmei fault. The layers of the sections are slanted to the south in a continuous and smooth manner. The dip angles of the layers (15-20 degrees) are a little higher than those for the Shuanglienpo fault (10-15 degrees). This same dip angle can also be found on the N1 section in Fig. 5, which is located at the nearest north of the fault but on the Pinchen tableland (Fig. 1). Therefore the similar continuous layering can be extended over a wide range and a great depth. These facts, when putting together, point to the denial of existence of this Yangmei 'fault'. This suspected 'fault' may just be the northern sloping wing of the Yangmei syncline; no breakages or fractures of the layers are visible which would confirm a fault.

3.3 Hukou Fault

From the geomorphic considerations (Fig. 2), the Hukou tableland, or under it the Hukou anticline, represent the most elevated and involved part of the Taoyuan terrace group. Several

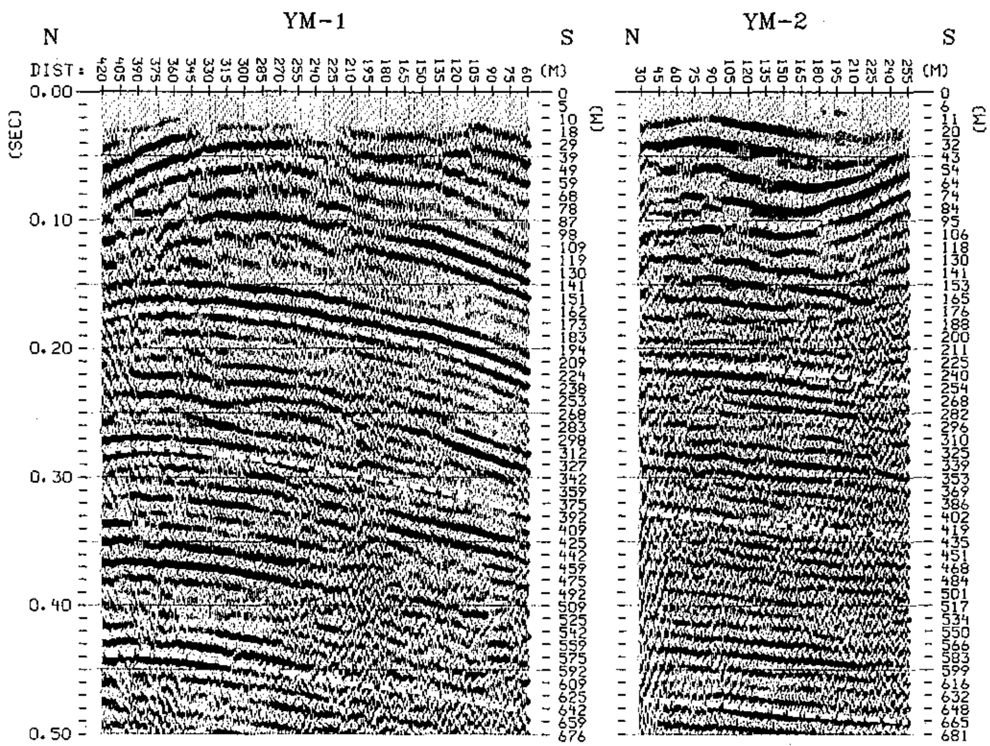


Fig. 7. Two seismic lines (YM-1 and YM-2) are used to detect the Yangmei fault. The structural layers are tilted, but smooth and continuous. Some irregularities that appear in the shallow part indicate lateritic deposits which were probably disturbed by some kinds of slumping.

fault scarps along this fault have been reported on the northern boundary of the Hukou tableland, with structural offsets of several to ten's of meters (Tang 1963; Shih et al. 1986). However, other researches have thought that some of these fractured fault scarps may only be local phenomena. A series of shallow seismic lines were deployed to detect the Hukou fault (Fig. 8, or for details see Lin 2000). Six of these seismic lines (HK-1 to HK-6) were chosen and are described here in Fig. 8. The locations of these seismic lines are given in Fig. 1. It is interesting to note, from sections HK-1 to HK-4, that the structural layers beneath the Hukou fault are strongly bent to form an elegant curvature that rises harmoniously to the south. The measured degree of bending is as high as 40° which is much larger than those of the Shuanglienpo fault (15°) or the Yangmei fault (20°). This large bending angle implies that the Hukou fault may have suffered greater compression and thus have a higher potential to fracture. However after more searching, we still cannot find a significant offset of the layers on many seismic lines distributed along the fault. The bending has made the Yangmei formation (between boundaries A and B in the sections shown in Fig. 8) rise and is exposed at the surface at the higher part of the Hukou tableland. The variation in the curved structures is continuous without significant sign of fracturing.

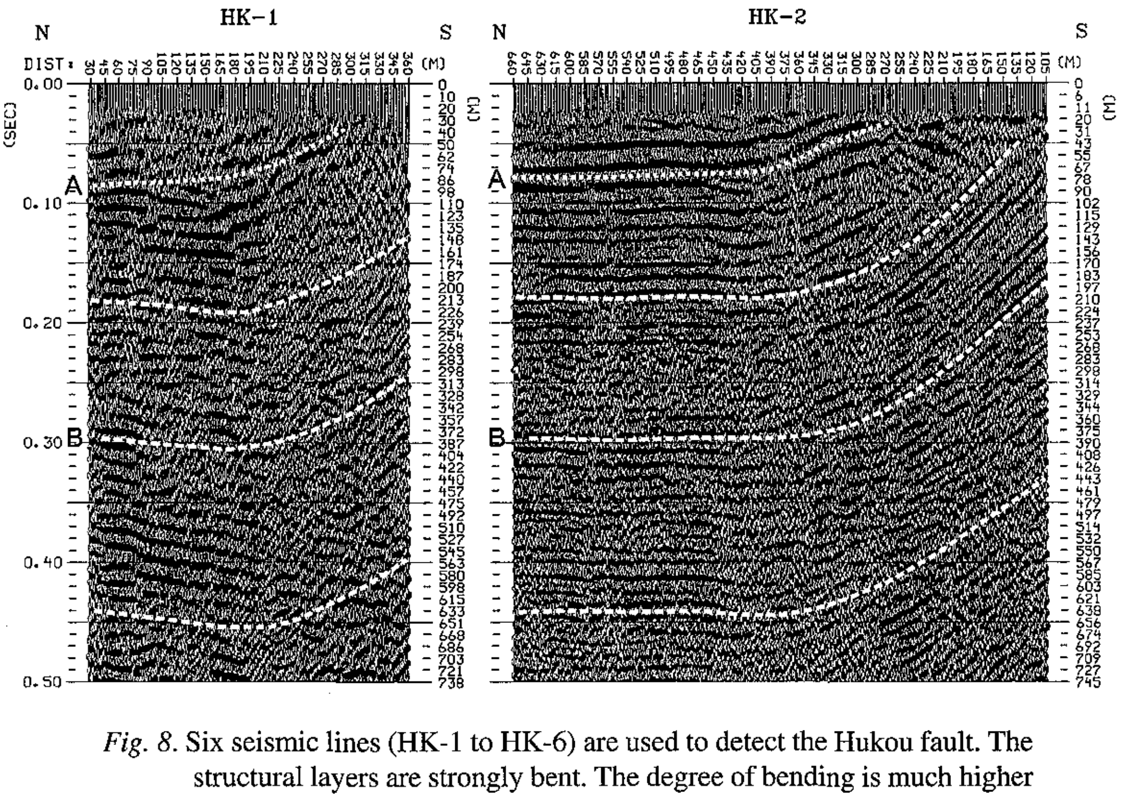
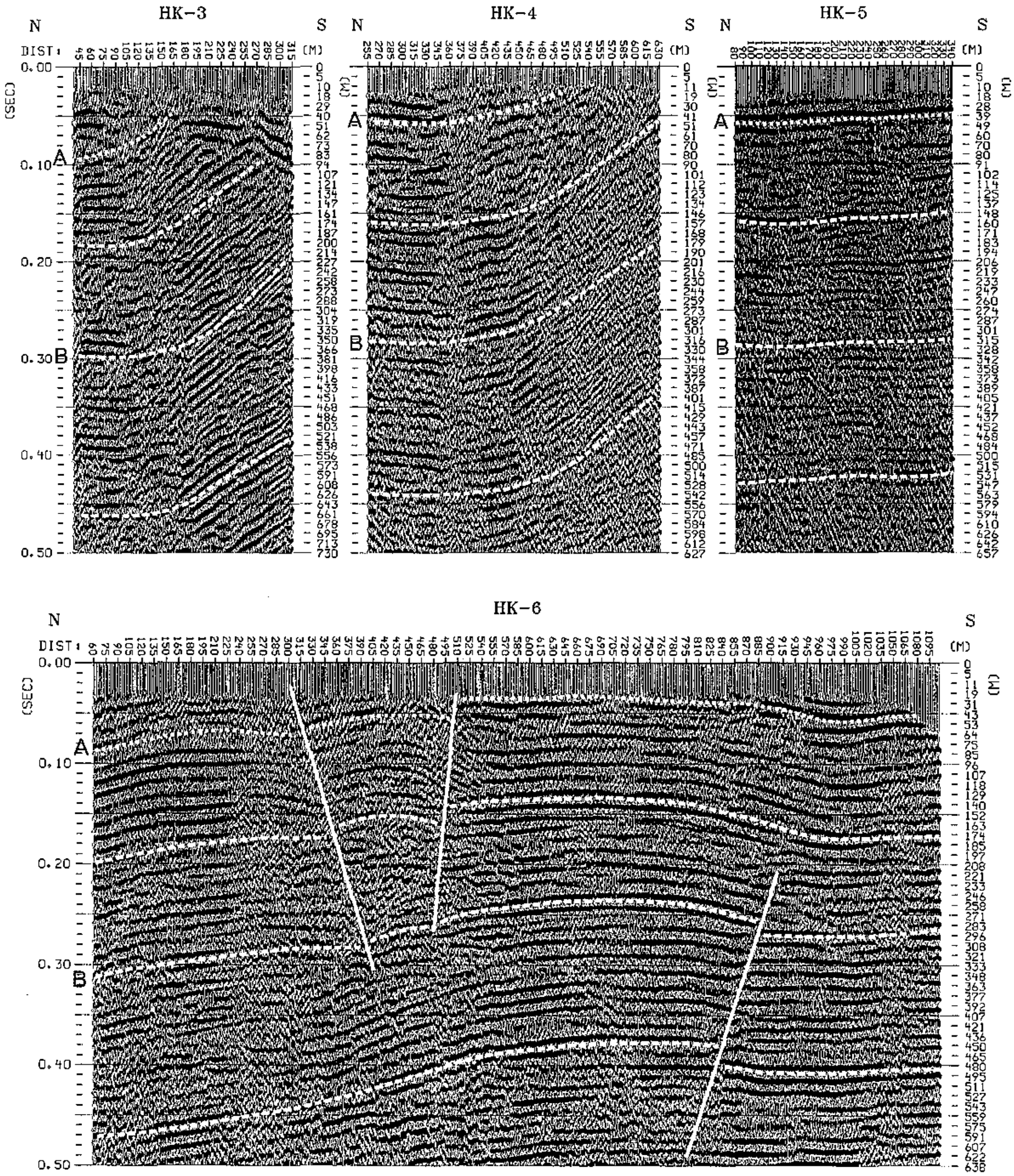


Fig. 8. Six seismic lines (HK-1 to HK-6) are used to detect the Hukou fault. The structural layers are strongly bent. The degree of bending is much higher than for other faults mentioned above. The dipping angle can be up to 50 degrees. Among them, HK-5 and HK-6 are located on the flat Chungli terrace surface, outside the area of the Hukou tableland. See the text for a detailed explanation of these two sections.



(*Fig. 8.* continued)

In Fig. 8, there is a flat HK-5 line, located at the foot of a local tableland (check Fig.1 and Fig. 2 for the location), which is used to constrain the extension of the fault to the east. An unusual HK-6 line, which is located on the flat Chungli terrace surface (Fig. 1 and Fig. 2), requires special attention. This HK-6 section shows some interesting alternatively curved structural variations and some exceptionally visible "fractures". The quality of this section is so good that it cannot be disregarded. This is quite unexpected. The structure starts to give clues of faults until coming to the far end of the Hukou fault. Nevertheless, we may attribute these fractures to be caused by the stopping interaction before the Hukou system meets the fold-and-thrust belt of western Taiwan foothills (Fig. 1). This would explain the fracture dipping to the north, instead of to the south, on the low-right part of the HK-6 section. However, the fracture pattern in HK-6 especially at the upper-left, definitely supports the possibility that the Hukou fault remains active. This section intends to indicate that the Hukou fault should be preserved as an active fault.

Besides fault detection, we also used five 'wide-spread' short seismic lines (S1 to S5) to explore the general structure of the Hukou anticline, as shown in Fig. 9. The layers are apparently slanted and they are good enough to define a tight folding at this sharp anticline. Two wells (YM-1 and YM-2) can be used to set up the formation's boundaries. Fine deposition sequences can be observed on this high-resolution seismic profile, especially those for the Yangmei and the Cholan formations. Figure 9 also shows that the Hukou anticline is asymmetric, with the northern flank being steeper than the southern flank. This is consistent with the fact that the deformation of the Hukou anticline is due to the force from the south. The high dip angles seen in S4 and S5 can be extended to HK-2 or HK-3, which are then joined to form an overall picture of structure variations along the northern boundary of the Hukou tableland. No structural discontinuity is uncovered in this profile, that is a fact similar to those we have found for other faults on the Taoyuan terrace.

4. DISCUSSIONS AND SUMMARIES

On all the seismic sections made across the possible fault scarps on the Taoyuan terrace, we found that the structural layers varied quite smoothly and continuously. The layers were bent upward, but not broken at the suspected fault locations. It seems that the scarps may actually represent boundaries of curved strata which are parts of anticlines or synclines, and are not likely due to the presence of faults. A good explanation of such structural bending can be adopted from the 'fault-bend-fold' theory of the thin-skinned thrust model, established by Suppe (1985) for western Taiwan. Figure 10 illustrates the fault-bend-fold model proposed by Suppe and Namson (1979), which quite appropriately explains the curved, bent layers developed along the HuKou fault. The model describes a 'blind thrust' hidden under the Hukou anticline, which slides along a basal shearing plane (or decollement) within some weak, incompetent substrata. This thrust system also has a 'ramp-flat' geometry. The hanging-wall block moves up and over the foot-wall block progressively as the faulting proceeds. When the faulted hanging-wall strata are transported to the top of the ramp, then to the position where the fault assumes a flat position, they are flexed into an anticline. This anticline structure

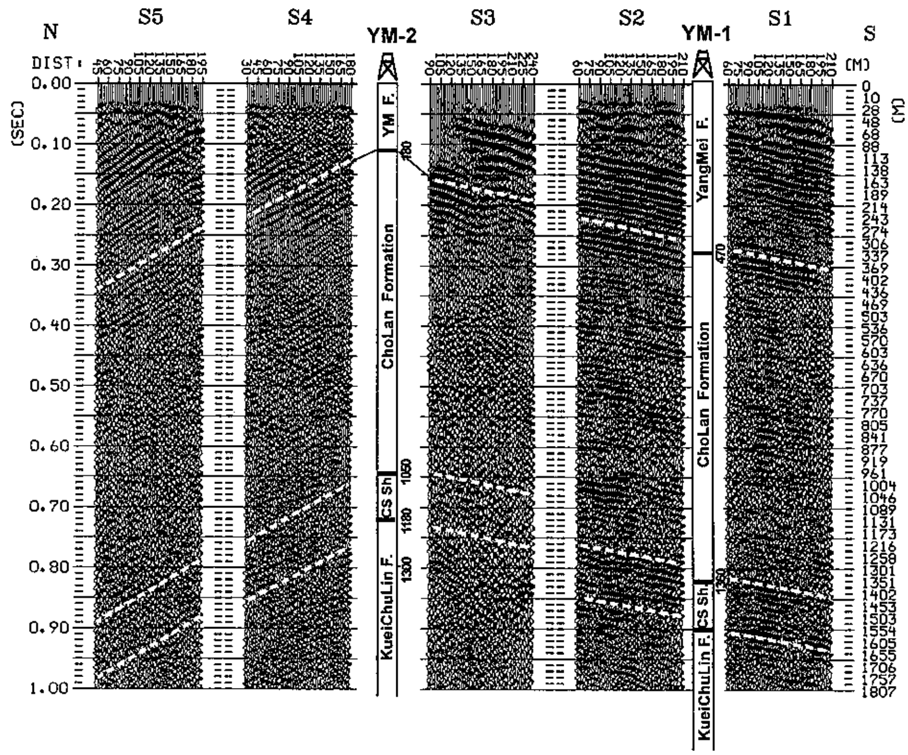


Fig. 9. Five 'wide spread' seismic lines are used to reveal structural variations in the Hukou anticline. The layers are apparently slanted which undeniably indicates a tight folding on this sharp anticline. Two wells properly control the formation boundaries. Fine deposition sequences are visible on this high-resolution seismic profile.

grows in amplitude as the faulting continues until reaching the summit of the ramp. The growing anticline bends the layers above or in front of it into a curved shape. As described in Fig. 10, the short length of the shallow seismic survey illustrates only a small portion of the faulting structure. Hence, in our seismic sections, we may just look at a small part of the fold developed by the 'blind thrust' under it.

In summary, the results of this study support the hypothesis that a 'blind thrust' is hidden under the Hukou anticline. If the definition of a fault needs fractural movements, the three suspected faults discussed in this paper are actually not faults. However, due to their good match with the present surface topography, it may not be appropriate to completely exclude their potential to be reactive in the form of 'blind thrusting', which may cause large earthquakes. Taking a closer look, the Shuanglienpo fault and the Yangmei fault could be of low activities, as can been seen because they are covered by a flat, undisturbed Pleistocene Teintzuhu formation and the layers have a low bending angle. However, the Hukou fault may be of high active potential, as revealed by the high dip angles and some fractures seen on the seismic sections. It is suggested that we should not completely ignore the possibility that the hidden blind-thrusts under the Hukou fault could still move, although the possibility could be low.

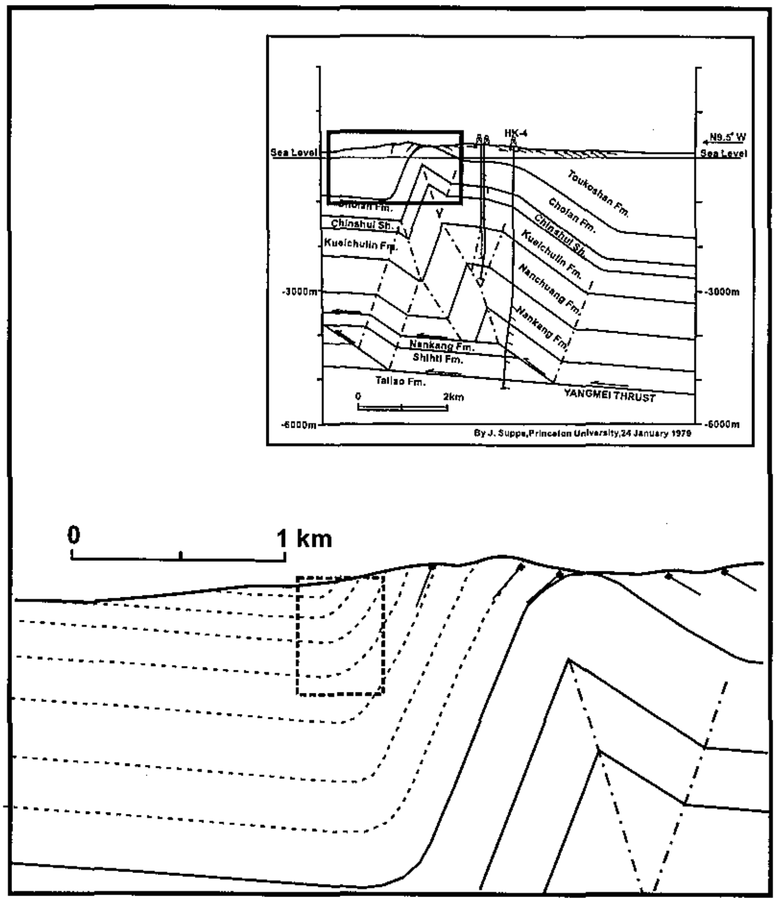


Fig. 10. The fault-bend-fold model of Dr. Suppe (Suppe and Namson 1979) explains the curved, bent layers in the HuKou fault quite well. The model predicts a 'blind thrust' hidden under the HuKou anticline. The movement of the blind thrust above a ramp created the anticline, which deforms the upper layers into curved shapes, as observed in the seismic sections. The area denoted by the dashed square is the part where the seismic sections lie.

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