臺灣石油地質　第二十八號
第 15-46 頁，23 圖，1 表，民國 82 年 12 月

PETROLEUM GEOLOGY OF TAIWAN NO.28
P.15-46, 23 FIGS. 1 TAB., DEC., 1993

Inversion Tectonics and Evolution of the Northern Taihsi Basin, Taiwan

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ABSTRACT

The Northern Taihsi Basin is the deepest part of the entire Taihsi Basin and equivalent to the position of the Northern Taiwan Foreland Basin of late Cenozoic. Also retarded by the Kuanyin Uplift, the Northern Taihsi Basin has suffered from structural inversion due to the fact that it was in the path and stood against the collision of Eurasian and Philippine Sea Plates during the Penglai Orogeny.

The tectonic trend of the Northern Taihsi Basin is N79° E (almost E-W) and quite different from the NE-SW trend of those basins in offshore Taiwan such as the Tungyintao Basin, the Nanjihtao Basin, the Pengchiahsu Basins, and the Taiwan Basin. What kind of tectonic mechanism governs the Northern Taihsi Basin is still a puzzle, but is considered to be probably related to the variant extensional regime with different rifting direction. Due to lack of directly strong evidence, this paper will not focus on this viewpoint. A series of typical horst-graben structures have been found and they indicate that the basin has already been subjected to extension in the synrift stage during Eocene to Oligocene, the tectonic evolution and mechanism will be the main interest of this study.

From Eocene to middle Miocene, the basin still remained in rifting regime, whilst since the late Miocene the regional stress had undergone a basic change owing to stress release on the Taiwan Foreland by the Penglai Orogeny.

From late Miocene, the N79° E pre-existing horst-graben within the Northern Taihsi Basin commenced to be governed by tectonic inversion including strike-slip motion and later bulk contraction of inverted grabens. The commonly found and typical characteristics of inverted structure are that minor and remarkable reverse faults, or minor positive flower structures occur in postrift sequence (the middle and late Miocene), whilst at the depth of synrift sequence the net extension or apparent normal fault still remained and still maintained a normal fault geometry but was in fact thrust faulting in process. Generally speaking, most of the inverted features were developed along graben edge located between major boundary fault and antithetic or synthetic fault. The structural elements with low fault angle and high intersect angle between stress direction and fault strike would be highly inverted rather than those of high fault angle and low intersect angle.

By comparison of each graben, it is certain to find that the extent of inversion decreases not only from the Kuanyin Uplift toward offshore of the Tachia City, but also from Taiwan Island toward the Nanjihtao Ridge. The east part of the Hsinchu Graben was strongly inverted and its graben space was narrowed or eliminated locally. The Paishatun Graben was moderately inverted while the Wulipai Graben and residual grabens near the east side of the Nanjihtao Ridge were just mildly or partially inverted.

The formation of the Northern Taihsi Basin commenced with extension in early Eocene or much earlier than Eocene, highly developed in Eocene, and generally ended in Oligocene. Through small scale rejuvenation in early and middle Miocene, extremely variable compressional or transpressional regimes have superimposed since the stage of the Penglai Orogeny and result in the tectonic inversion of the Northern Taihsi Basin.

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INTRODUCTION

The study area is located on the offshore Hsinchu-Miaoli area (Fig. 1) and is equivalent to the nearby area of the Northern Taiwan Foreland Basin. In the onland of Taiwan Island, strike-slip motion has been mentioned by many authors such as Chiu (1971), Huang (1986), Meng (1962 and 1965). It is an important and interesting study on how do these strike-slip faults extend to the offshore area? How do the Kuanyin Uplift and the Penghu Uplift play an important role during the Penglai Orogeny? In our attempt to answer these questions, the present study starts from the Northern Taihsi Basin. This is also because of the fact that the seismic data from offshore is always better than the onland ones on account of lack of regolith effect and noise from the topography effect.

In this study, we found that the strike-slip motion and tectonic inversion have superimposed in the Northern Taihsi Basin. The tectonic framework of this study will provide a new and appliable concept on the future exploration for the Chinese Petroleum Corporation. This study is just the first step in the conceptual development concerning inverted basin in the Offshore Hsinchu-Miaoli area, an advanced study will follow.

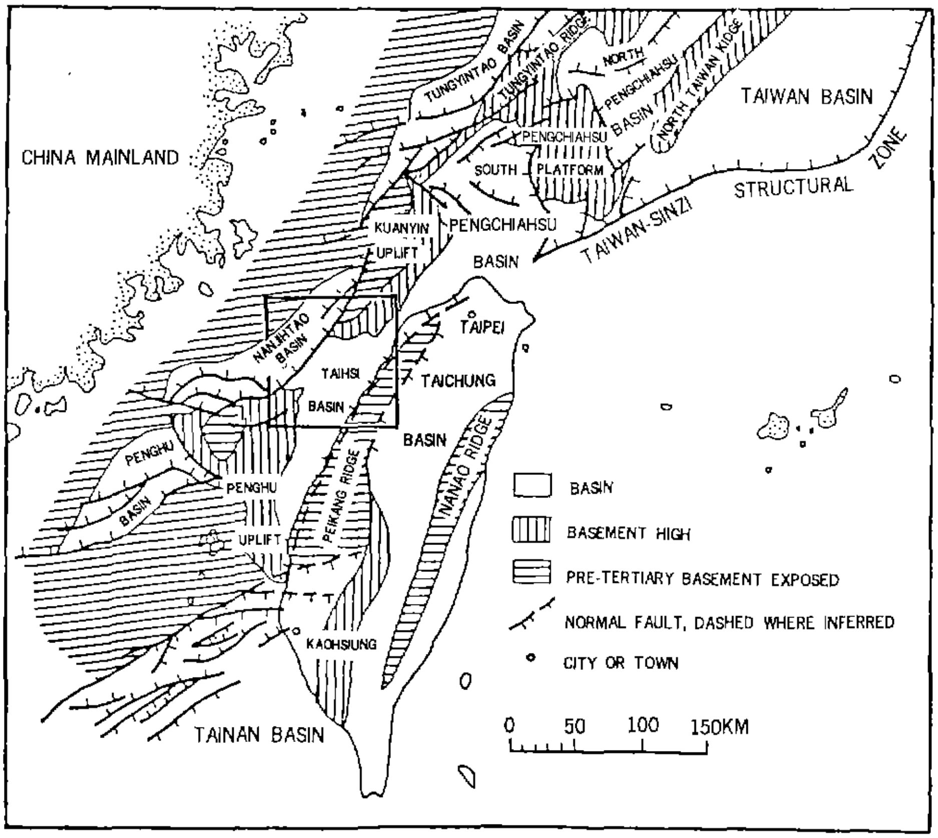


Figure 1. Studied area within the rectangular region and nearby related geological framework. The geological framework map is derived from Sun (1982).

From the guidence of the staff of Offshore and Overseas Petroleum Exploration Division (OOPED) and Suppe(1984), it is found that many old normal faults are reactivated by later compressional deformation near the offshore of the Hsinchu City. This paper will extend the above mentioned concept and combine with the tectonics of similar inverted basin such as the one developing in the foreland deep between the Alpine Mountain and the Southern North Sea Basin.

Many famous geological inversion models (Letouzey, 1990; McClay, 1989; Cooper *et al.,* 1989) are applied to the extensional-compressional basin in order to reveal the true structural evidence. In order to present a detailed interpretation, it becomes necessary to temporarily give names to the major faults and grabens (Fig. 2). The results on the Northern Taihsi Basin are very important and meaningful for hydrocarbon exploration because the new tectonic model of inverted basin could be applied to other similar foreland area of Taiwan.

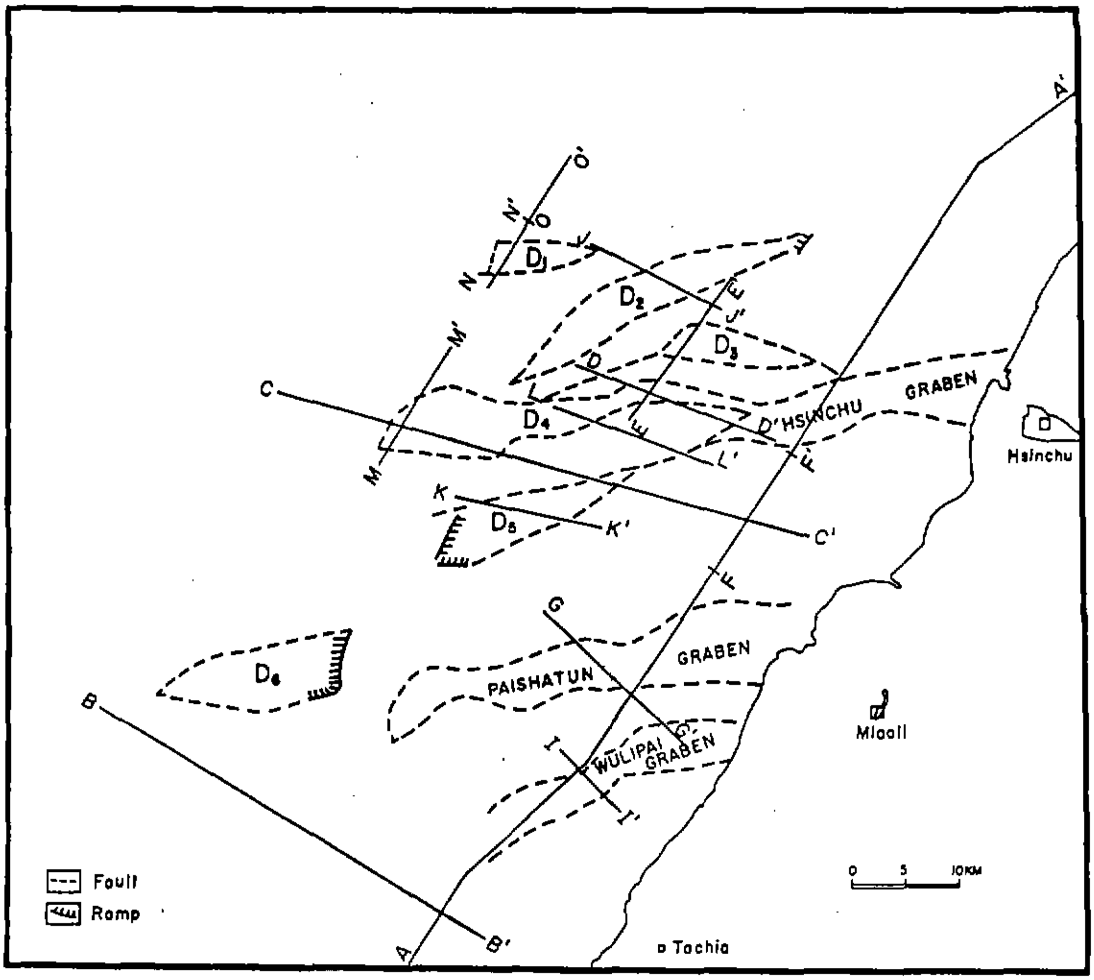


Figure 2. Showing lines and major grabens within study area used to express basinal or tectonic features. (The D1 ~ D6 Grabens are also termed as small grabens.)

REGIONAL GEOLOGY

The Northern Taihsi Basin is located on the offshore of Miaoli-Hsinchu and bounded by: the Kuanyin Uplift in northern side, extending part of the Penghu Uplift in the south, and the Nanjihtao Ridge in the western side. The eastern boundary is modified by the thrust sheet from the Central Mountain Range and is difficult to determine.

A series of typical horst-graben structures have been found and they indicate that the Northern Taihsi Basin has already been subjected to extension in the synrift stage during Eocene to Oligocene. By the end of deposition of Eocene and Oligocene, the rift stopped and was replaced by the continuous, broad regional subsidence, and contemporaneous deposition of the eastward thickening Neogene sequence in terms of Tertiary sea level change. During the stage of early-middle Miocene, only weak rejuvenation was the major tectonic event. From the early stage of the Penglai Orogeny, Taiwan Island have been subjected to imbricate thrusting, especially in the Central Mountain Range area. Geographically, the Penglai Orogeny seems to shift or retreat eastward. The San-Yi fault is considered to be the most superfical and the westernmost low angle major thrust fault (Hung, 1992). Beneath the San-Yi fault, or the subthrust of the San-Yi fault, fault settings were still characterized by normal fault system, therefore the inversion tectonic would have taken place. But due to the bad resolution of seismic data, the reactivated events are not so easily found onland.

The NE-SW showing line A-A' expresses the geological morphology of the whole Northern Taihsi Basin, the Kuanyin Uplift, the extending part of the Penghu Uplift and their overlying sequences (Fig. 3). The deepest part seems to be near the southern side of the Northern Taihsi Basin. The total thickness of sediments in the basin center is over 7.4 km. The other E-W seismic profile C-C' (Fig. 4) shows the Tertiary and Quaternary sequences seemingly thickening from the Nanjihtao Ridge eastward to Taiwan Island. High angle reverse faults and antiforms occur. It could be found that line A-A' expresses much more obvious morphology of the Northern Taihsi Basin rather than that of line C-C'.

In this paper, we divide all the sequences into two depositional systems:

- the synrift sequence including the Oligocene, the Eocene, and the underlying unknown Paleocene;
- the postrift sequence including the middle and lower Miocene.

According to the isopach map shown in Figure 5a, there were two large depocenters in the Oligocene. The smaller one was located on the offshore of the Hsinchu City. The larger other was located on the offshore of the Tachia City and could possibly indicate the major rifting depocenter of the Northern Taihsi Basin. In the lower and middle Miocene sequence, there was a large scale depocenter just located above the Paishatun Graben (Fig. 5b). The axes of depocenters of the lower-middle Miocene are coincident with the tectonic trend of the Northern Taihsi Basin.

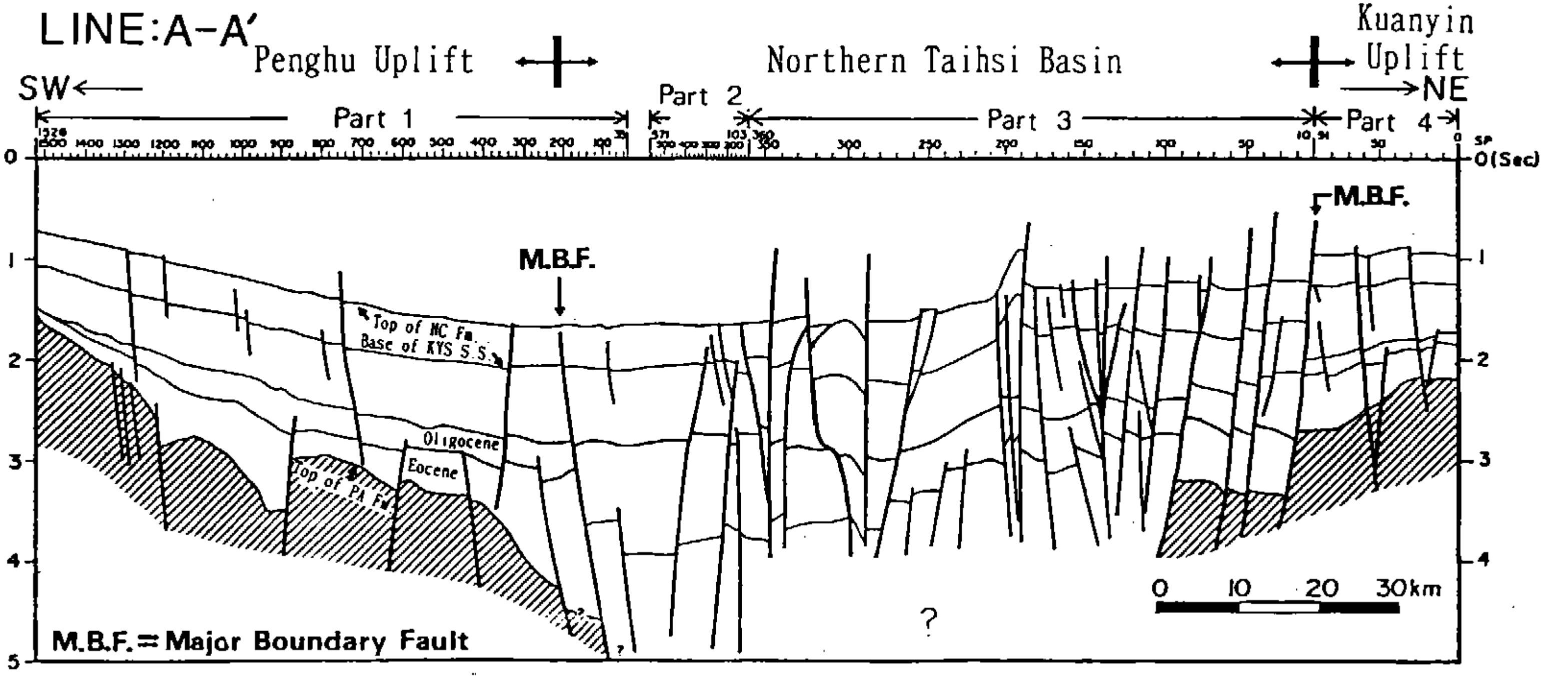


Figure 3. NE-SW sketched line exhibiting the morphology of the Northern Taihsi Basin, the Kuanyin Uplift, and the Penghu Uplift.

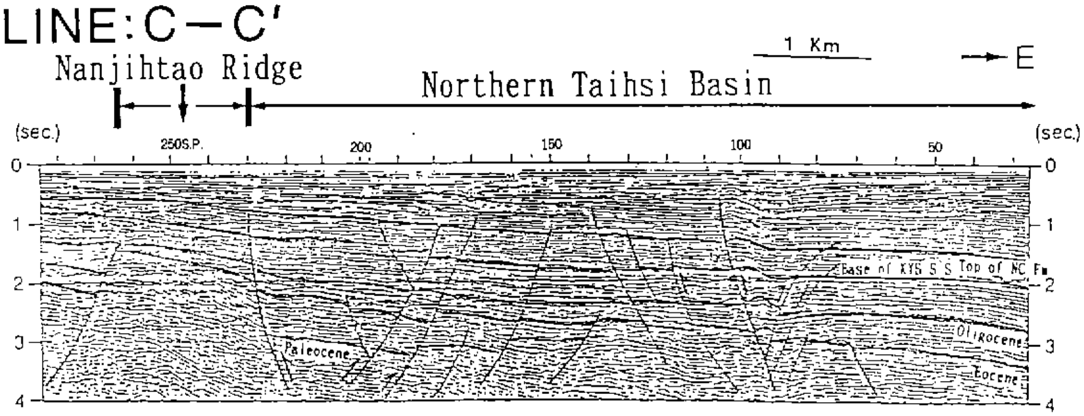


Figure 4. E-W seismic profile C-C' also showing the morphology, sequence, and fault pattern of the Northern Taihsi Basin and the Nanjihtao Ridge.

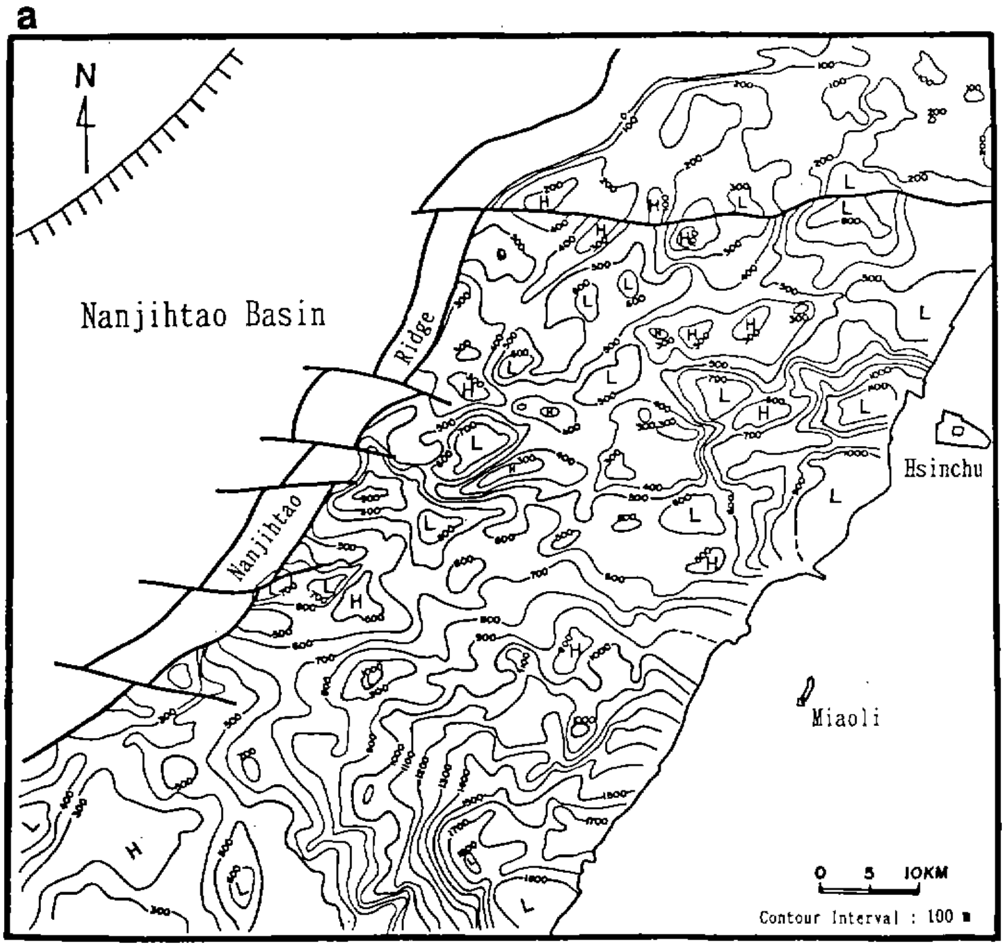


Figure 5. (a) The isopach map of the Oligocene. The larger depocenter is located near the offshore of the Tachia City. (b) The isopach map of the lower-middle Miocene. The axis of the largest depocenter located on the Paishatun Graben (near the offshore of the Miaoli City) expresses the almost E-W trend.

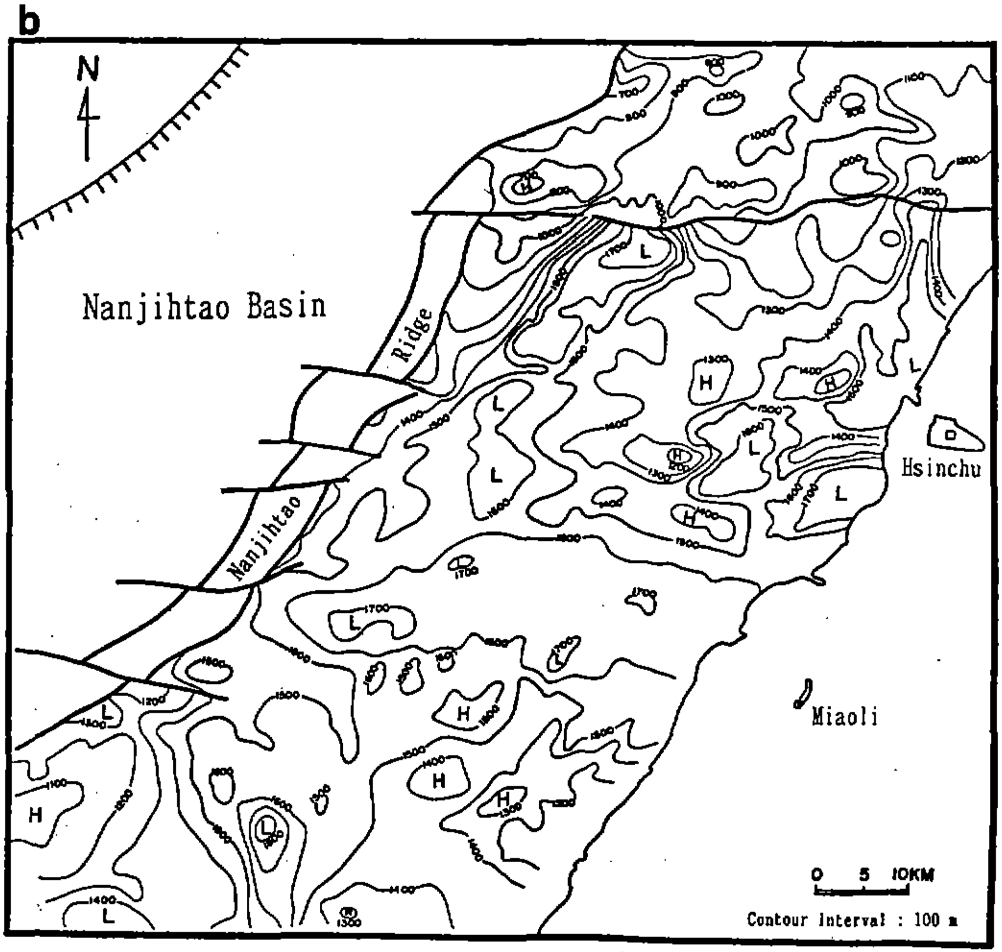


Figure 5. (Continued)

TECTONIC FEATURE

In this study, four diagnostic horizons concerned with major unconformities, or flooding plane surfaces are picked in the entire Northern Taihsi Basin. These four horizons are the Eocene Top, the Oligocene Top, the Kuanyinshan Sandstone Base and the Nanchuang Formation Top. The older underlying and younger overlying sequences are also picked partly, especially those near the highlands of the Kuanyin Uplift and the Penghu Uplift.

Time contour maps of three of the above mentioned horizons are completed. They are the Eocene Top, the Oligocene Top and the Nanchuang Formation Top (Figs. 6, 7, and 8). The Eocene and the Oligocene are regarded as major synrift sequence (beyond 2.7 km) and passive subsidence sequence (beyond 1.7 km) respectively on account of: (1) high similarity of structural pattern, (2)shingled prograding seismic facies on the ramp region of highlands such as the Kuanyin Uplift and the Penghu Uplift. On these highlands of the basin, there is an unconformity between the major phase and final phase of the synrift sequence. In regional geology, the sedimentary setting of the Kuanyinshan Sandstone-Nanchuang Formation is regarded as a typical regressive sequence (Huang, 1982) and provides good flooding plane surfaces (or facies boundaries) for good horizontal correlation. In order to get good illustration for the tectonic trend, azimuth diagrams for main faults of the Oligocene Top in the Northern Taihsi Basin and nearby highland are accomplished and shown in Figure 9.

Tectonic Analysis

In fact, the basement of the Northern Taihsi Basin is supposed to be Paleocene which is too deep to be investigated particularly in the central part of the basin. In rifting basin, the fault sets in synrift sequence could thoroughly exhibit the rifting direction. From the time contour map of the Eocene Top (Fig. 6) and the Oligocene Top (Fig. 7), it could be found that the tectonic settings of the Eocene are composed of five major parts as the following:

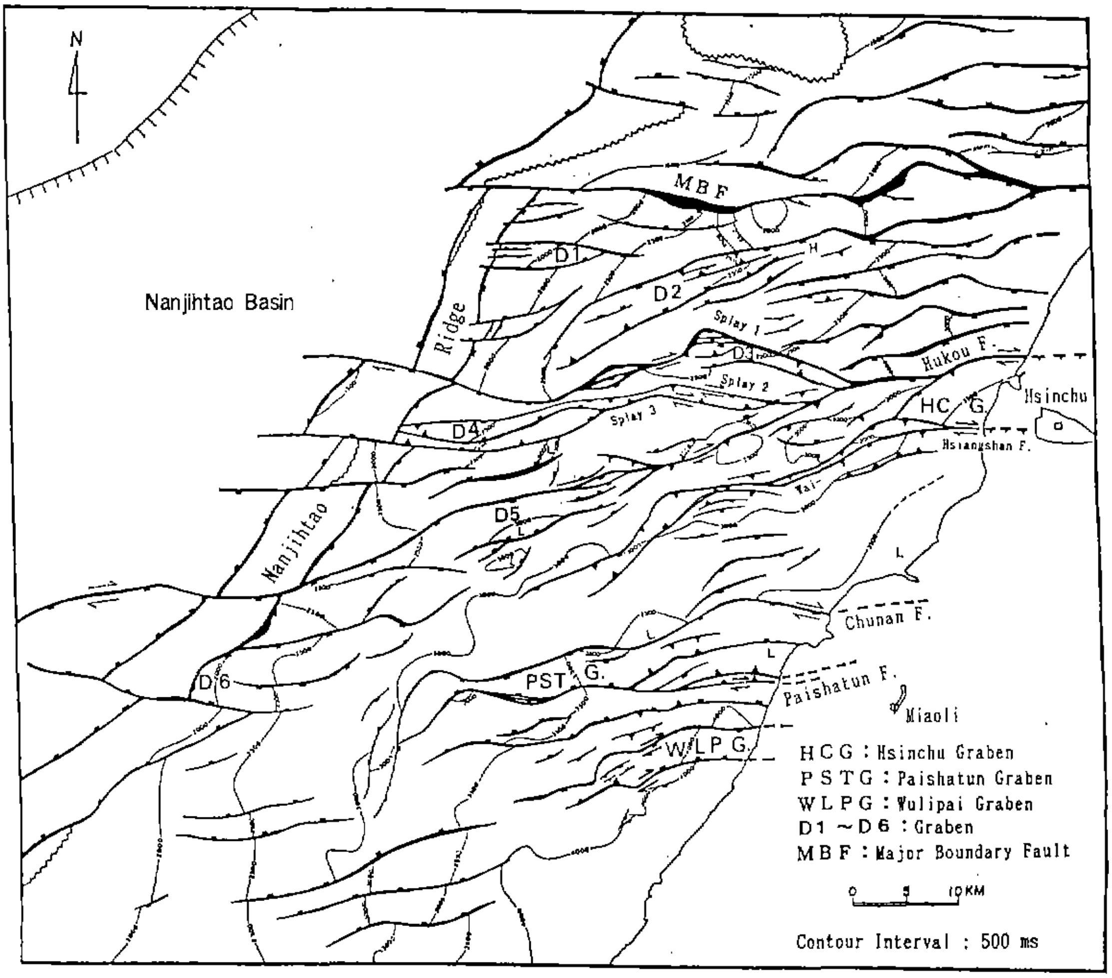


Figure 6. Time contour map of the Eocene Top.

- The depression part of the Northern Taihsi Basin is significant with horst-graben, the tectonic trend of which is about N79° E (Fig. 9a). Some major faults have passed through the Nanjihtao Ridge into the Nanjihtao Basin such as the Hukou fault and its fault splays.
- The average strike of major boundary faults of the Nanjihtao Ridge is N43° E (almost NE-SW, shown in Fig. 9b). This tectonic trend is matched with the trend of those basins such as the Nanjihtao Basin, the Tungyintao Basin, the Pengchiahsu Basins, the Taiwan Basin, and etc. in the offshore northern Taiwan and in the East China Sea (Hu *et al.*, 1990; Lee, 1987; Hsiao *et al.*, 1991; Wageman *et al.*, 1970).
- The average tectonic trend of stepped normal faults in southern edge of the Kuanyin Uplift is N81° E (almost E-W, shown in Fig. 9c).
- The tectonic trend of stepped normal faults in en échelon arrangement in the northern edge of the Penghu Uplift is N70° E (shown in Figs. 9d and 10). It reveals the fact that the structural feature is concerned with transtension or

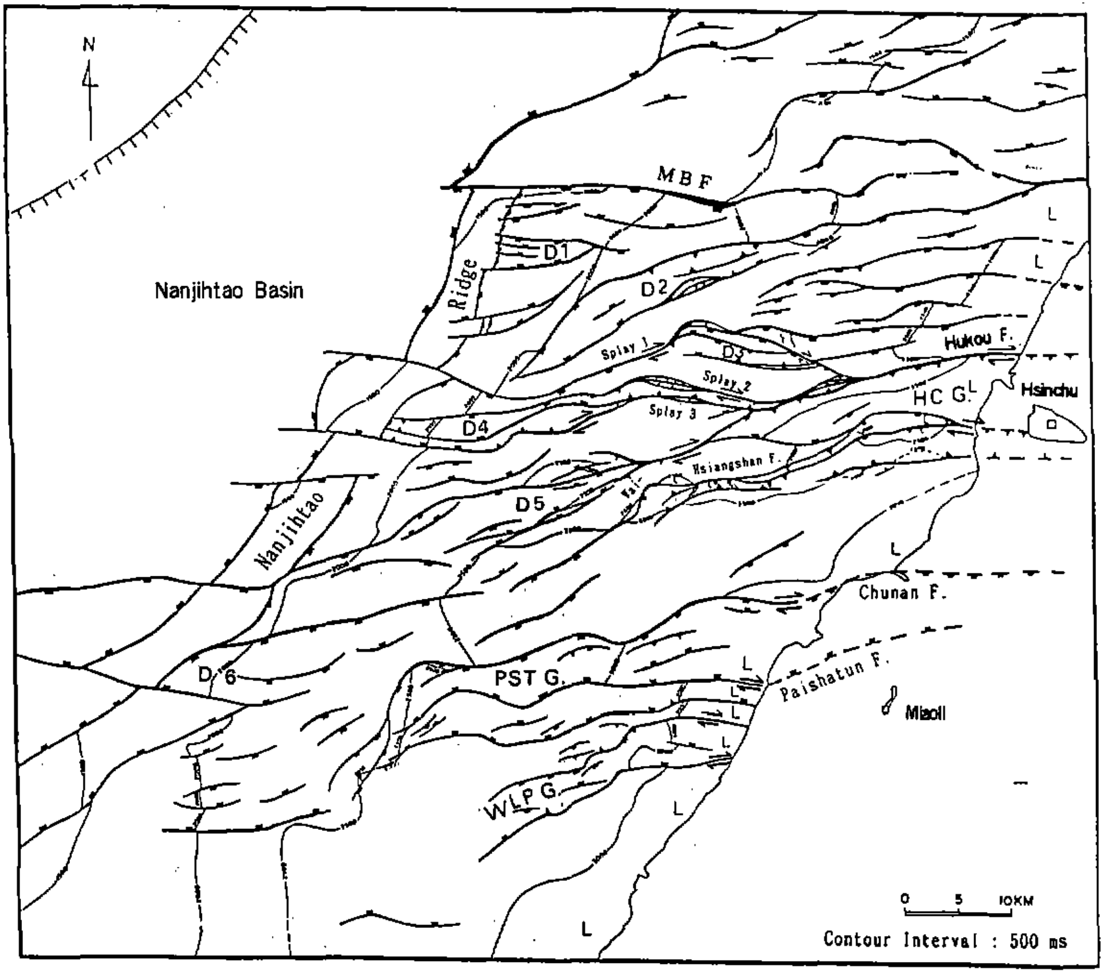


Figure 7. Time contour map of the Oligocene Top.

relay structure based on the concepts of Larsen's (1988) study. Therefore, the main block moving direction or rifting direction could be determined as toward north.

- Some small residual shuttle-like grabens with the similar tectonic trend of major horst-graben still existed near the east side of the Nanjihtao Ridge.

Above all, it could be found that there is a tectonic trend change between the Northern Taihsi Basin and the Nanjihtao Ridge. The tectonic regime resulted in the change of trend is worthy of an advanced analysis. In this viewpoint, this article just delineate the fact and will not focus on the cause of the trend change.

If we compare the fault patterns of the Oligocene Top(Fig. 7) with those of the Eocene Top (Fig. 6), most of the fault patterns are similar, except on two following different points:

- the appearance frequency of reverse faults in Oligocene is higher than that of Eocene;
- In the Penghu Uplift, there is an obvious structural feature of en échelon

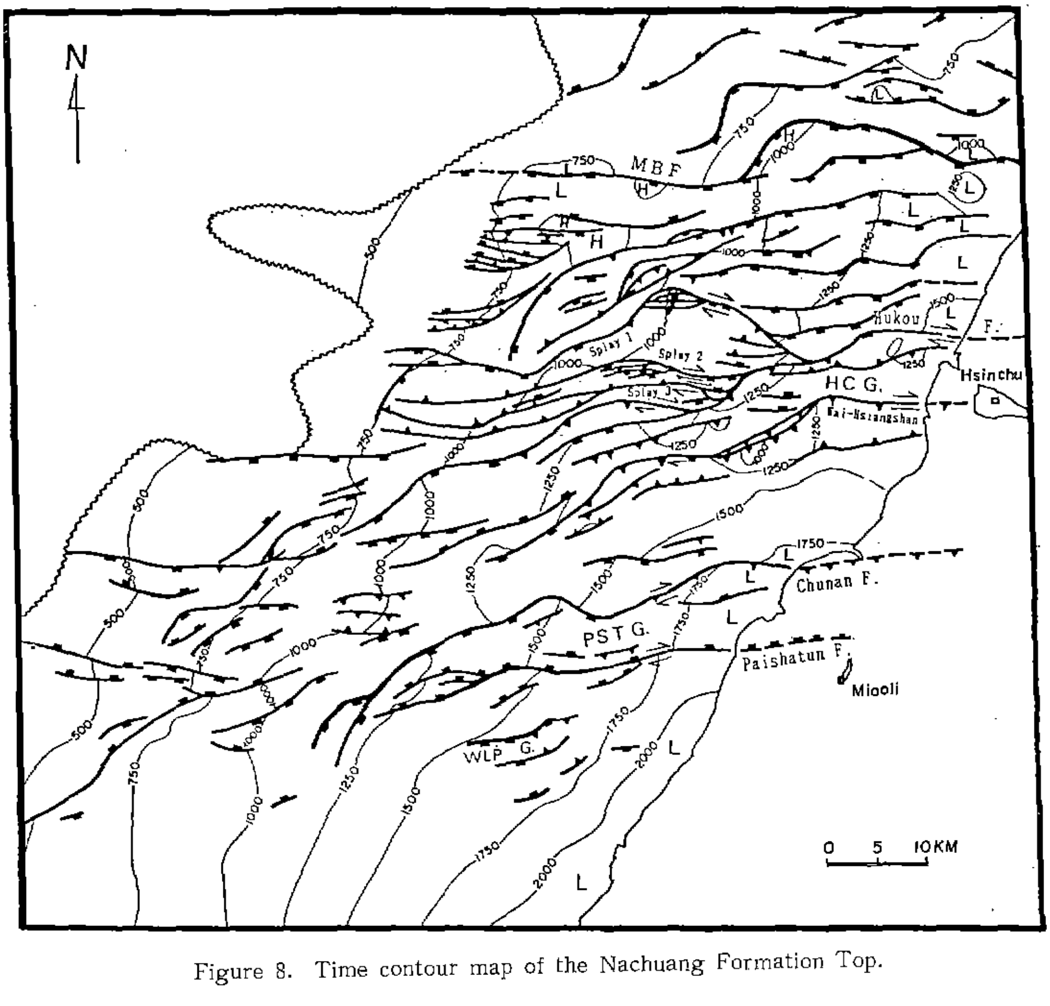


Figure 8. Time contour map of the Nachuang Formation Top.

stepped normal faults in the Eocene top, while in the Oligocene top this feature is less conspicuous or even diminished (Figs. 7 and 10).

It could be certain that the orientation of the Northern Taihsi Basin is near N79° E direction if we overlap together the three time contour maps. In tectonic analysis, one important feature demanding mentioning here is that a lot of minor thrust or reverse faults occurred in the Nanchuang Formation (postrift sequence) whilst apparent normal faults were maintained at the depth in the Oligocene and the Eocene (synrift sequence). These results suit well McClay's (1989) tectonic inversion model as shown in Figure 11. The original extensional or transtensional setting was deformed by later compressional or transpressional regime.

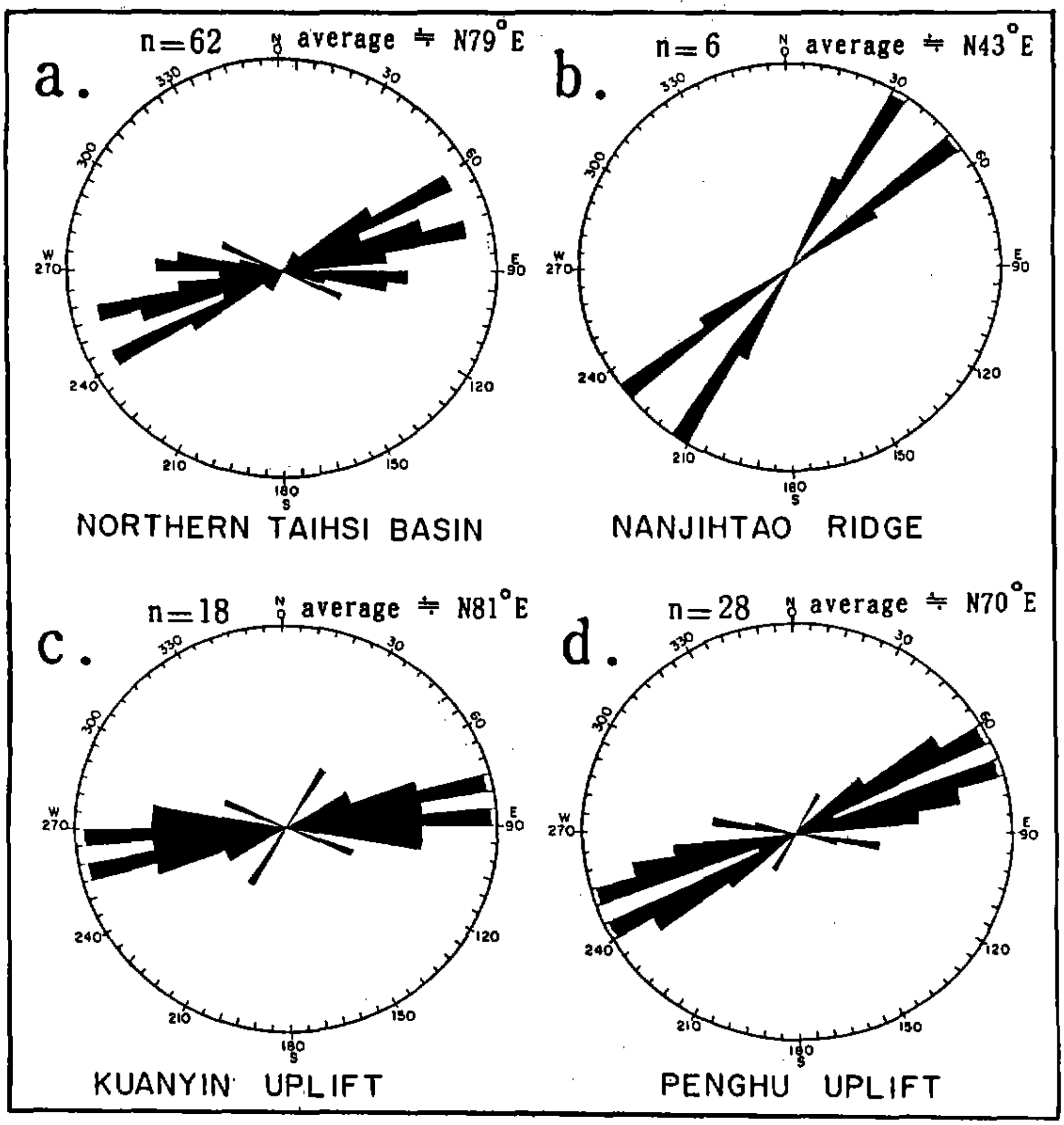


Figure 9. Azimuth diagrams of main faults of the Oligocene Top in the Northern Taihsi Basin and nearby highland region.

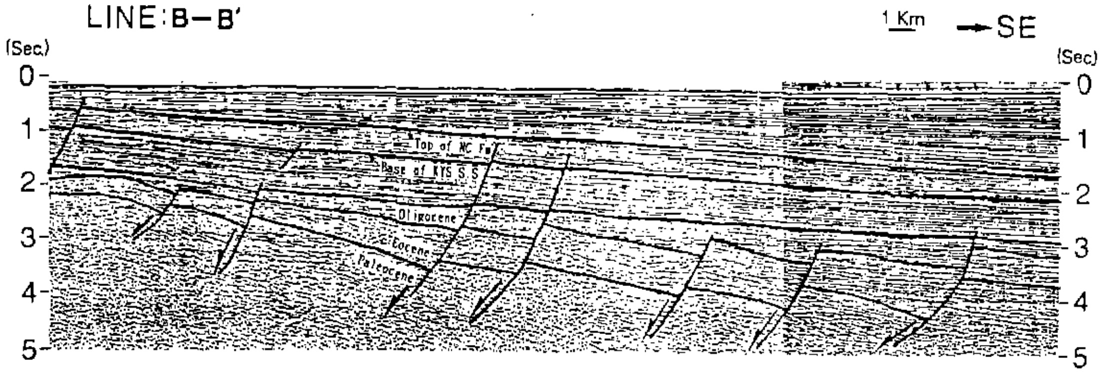


Figure 10. Seismic profile B-B' showing regular stepped normal faults pattern in Paleogene sequence whilst the overlying Neogene lack of large scale faulting.

Basic Models of Inverted Graben

In order to present good structural illustration, Figure 12 shows some basic inversion models derived from Letouzey (1990).

If as suggested by Ho (1982), Lee and Wang (1988) that the direction of stress release was from the southeast of Taiwan Island, the foreland basin or subthrust will be strained or inverted. In stress-strain regime, the stress could be divided into two components (such as N-S and E-W) in terms of the orientation of the Norhtern Taihsi Basin. The N-S component, with preferrence toward bulk contraction rather than strike-slip motion, will contribute to bending, narrowing, and eliminating the geometry of inverted graben by McClay's (1989) and Letouzey's (1990) models (shown in Figs. 11 and 12d). However, the E-W component will enhance the strike-slip motion rather than graben bulk contraction shown in Figure 12b. This structural feature will be discussed in detail later. As a matter of fact, although some authors have presented the paleo-stress direction, it is still difficult to understand the direction of dynamic stress during the Penglai Orogeny. It could be deduced that this basin has encountered at least two kinds of structural inversion including strike-slip motion and bulk graben contraction.

During late Miocene, strike-slip motion regarded as one of structural inversions fit the inversional model in Figure 12b enhanced by E-W component of the stress from the Penglai Orogeny. This is one independent sub-event in the early stage of the Penglai Orogeny, judging from the fact that a series of faults reactivated and stopped during late Miocene and since then it was covered with concordant overlying sequence. During this same stage, but for strike-slip motion, weaker graben bulk contraction caused by the other relatively smaller N-S component of inversion stress still linger on in the western part of the Hsinchu Graben (Figs. 13 and 14) and also in the local parts of the D4, D1, D2, D5 Grabens (Figs. 15, 16 and 17). It is also deduced that the E-W component was greater than the N-S component during late Miocene.

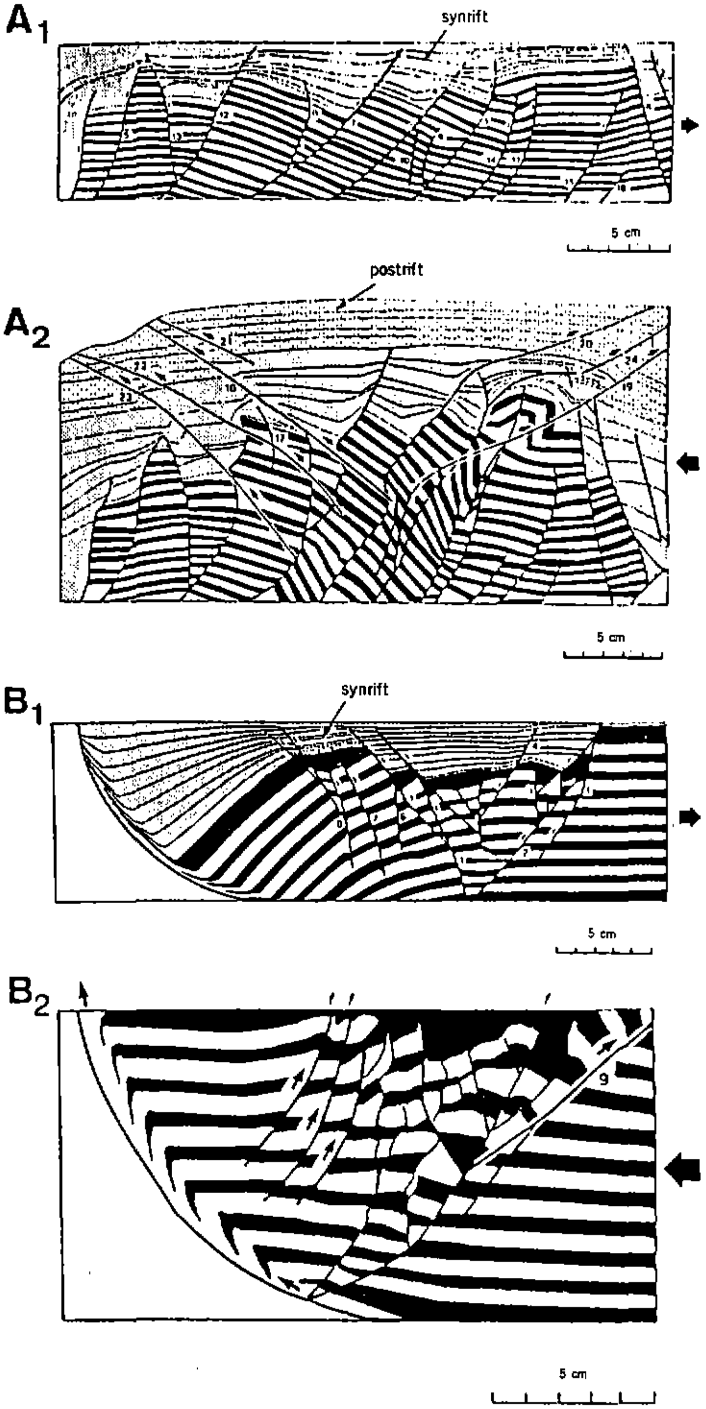


Figure 11. Two experimental models of tectonic inversion (McClay, 1989) are utilized to explain the tectonic features of the Northern Taihsi Basin. A1 and A2 are sand-mica and mica layered models with homogeneous extension and subsequent contraction. B1 and B2 are sand and clay layered models above simple listric detachment.

During Plio-Pleistocene (later stage of the Penglai Orogeny), another inversion event occurred and the previous one was superimposed or modified. According to the tectonic features, most of them matched models shown in Figures 11 and 12d, when basinal orientation or strike of horst-graben are taken into consideration together. The N-S component seems to be greater than the E-W one by the analysis of stress-strain regime. After late Pliocene, a series of anticlines commenced to take place along the faults controlling the figuration of each graben as $\sigma 1$ was not parallel to the orientation of horst-graben axis. For a typical example, the structure in Figure 18 was possibly inverted from the pre-existing rollover structure, and probably matched McClay's (1989) model shown in Figure 11b and termed as bulk contraction of inverted graben. This case also verifies that this feature is coincident with McClay's (1989) opinion that at high bulk contractional strain, initial low angle

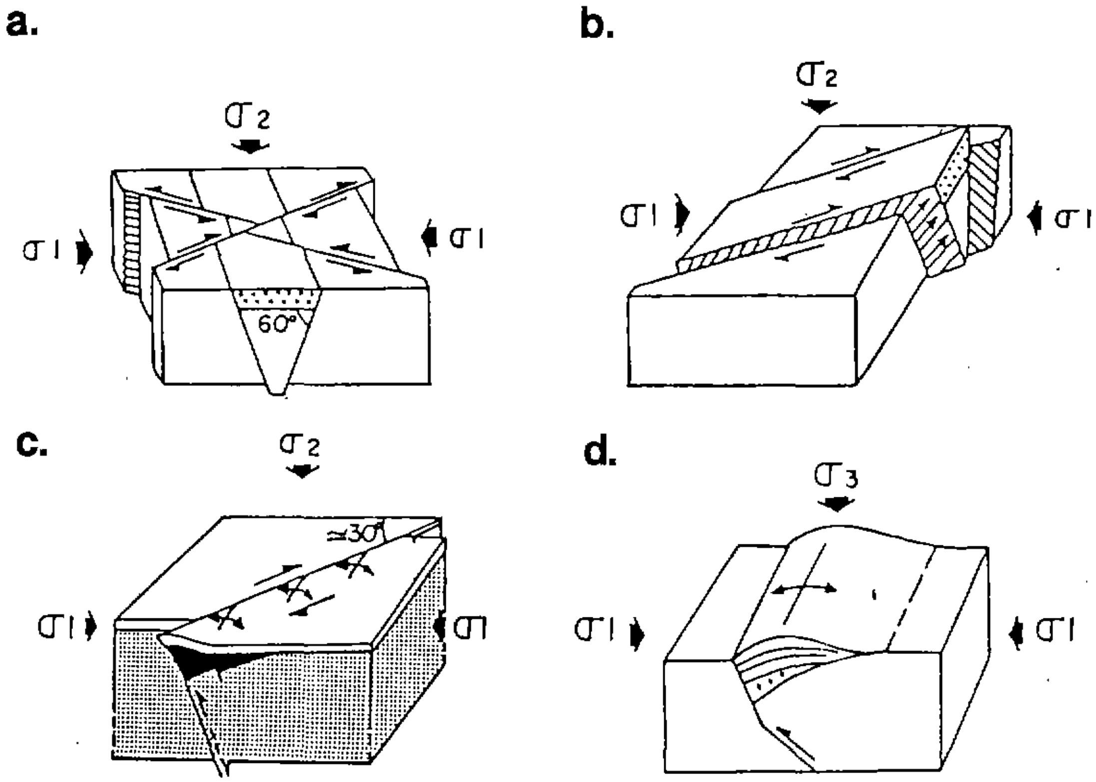


Figure 12. Four tectonic regime models from Letouzey(1990).
(a) The two normal faults bounding the graben are not suitably oriented for reactivation. New strike-slip fault will be created.
(b) Reactivation with strike-slip reverse movement along the fault planes take place for pre-existing normal fault with favorable orientation.
(c) In strike-slip tectonic regime, the pre-existing fault planes were reactivated with strike-slip or strike-slip reverse. Fold axis remains roughly perpendicular to $\sigma 1$.
(d) To a non-planar normal fault, the dependent part with dip 45° has optimum conditions for reactivation while the shallow part with high angle cannot easily be reactivated.

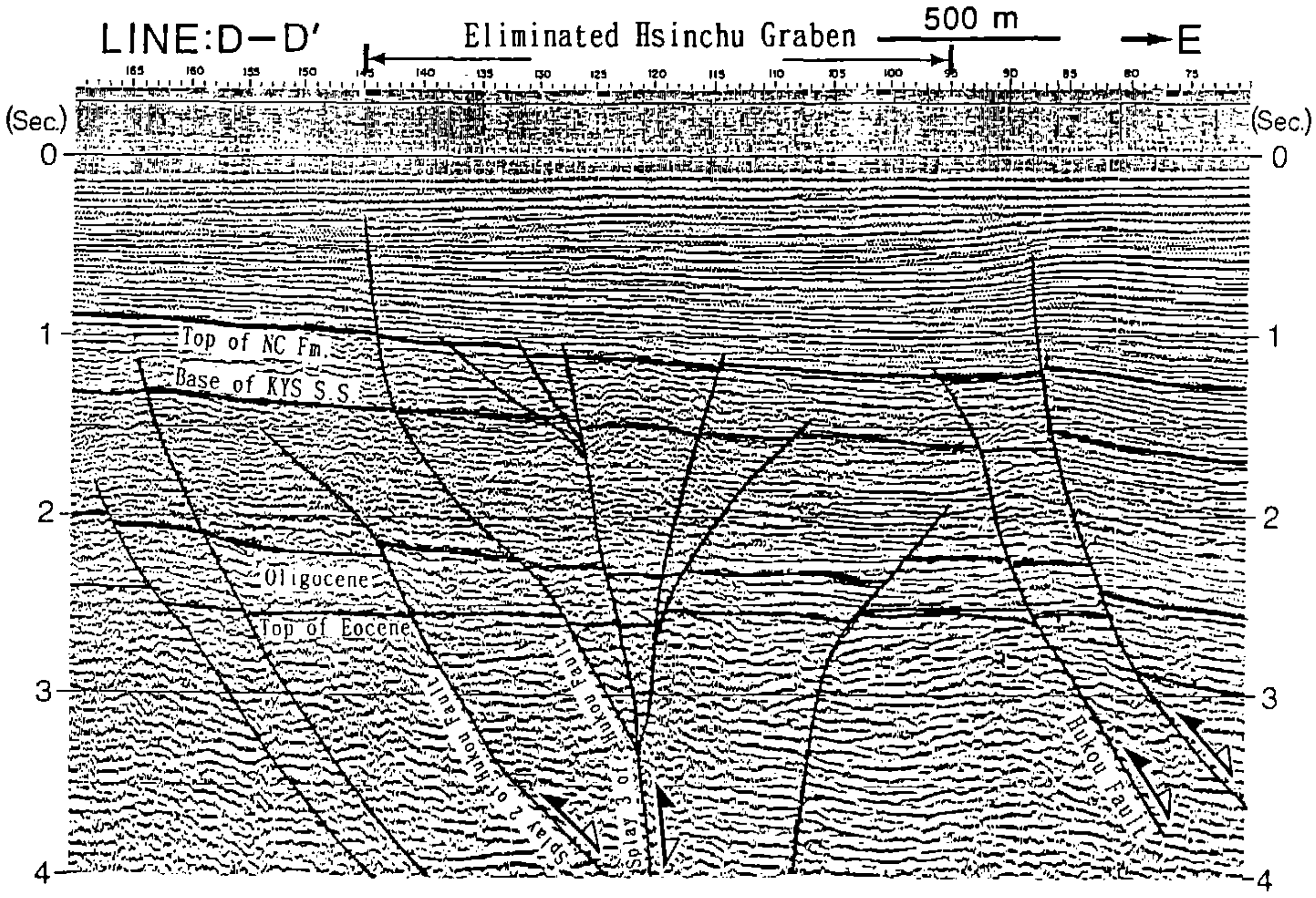


Figure 13. The pre-existing Hsinchu Grabaen is difficult to inspect due to tectonic inversion.

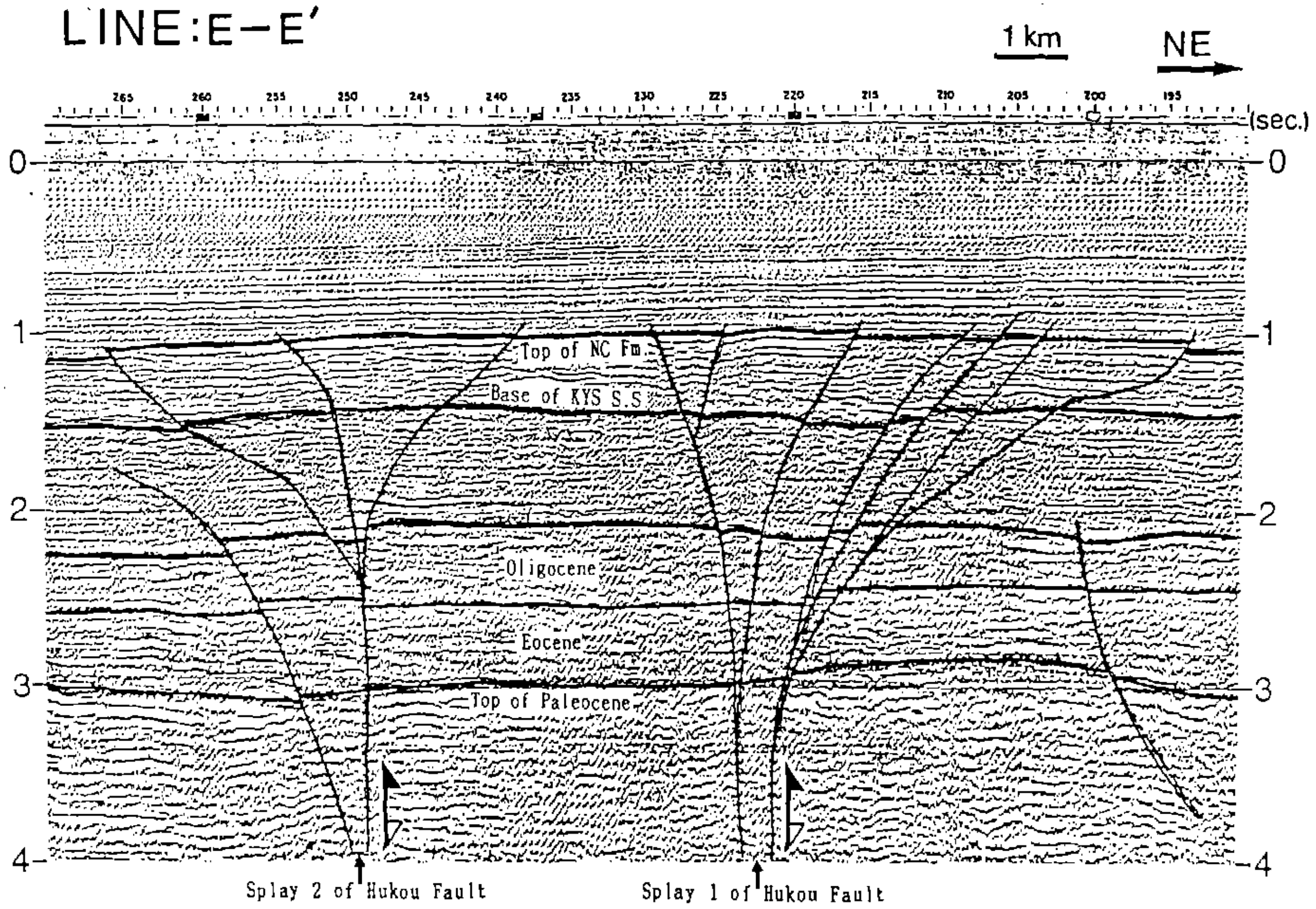


Figure 14. Two small scale positive flower structures regarded as the splays of the Hukuo Fault which is determined as strike-slip fault.

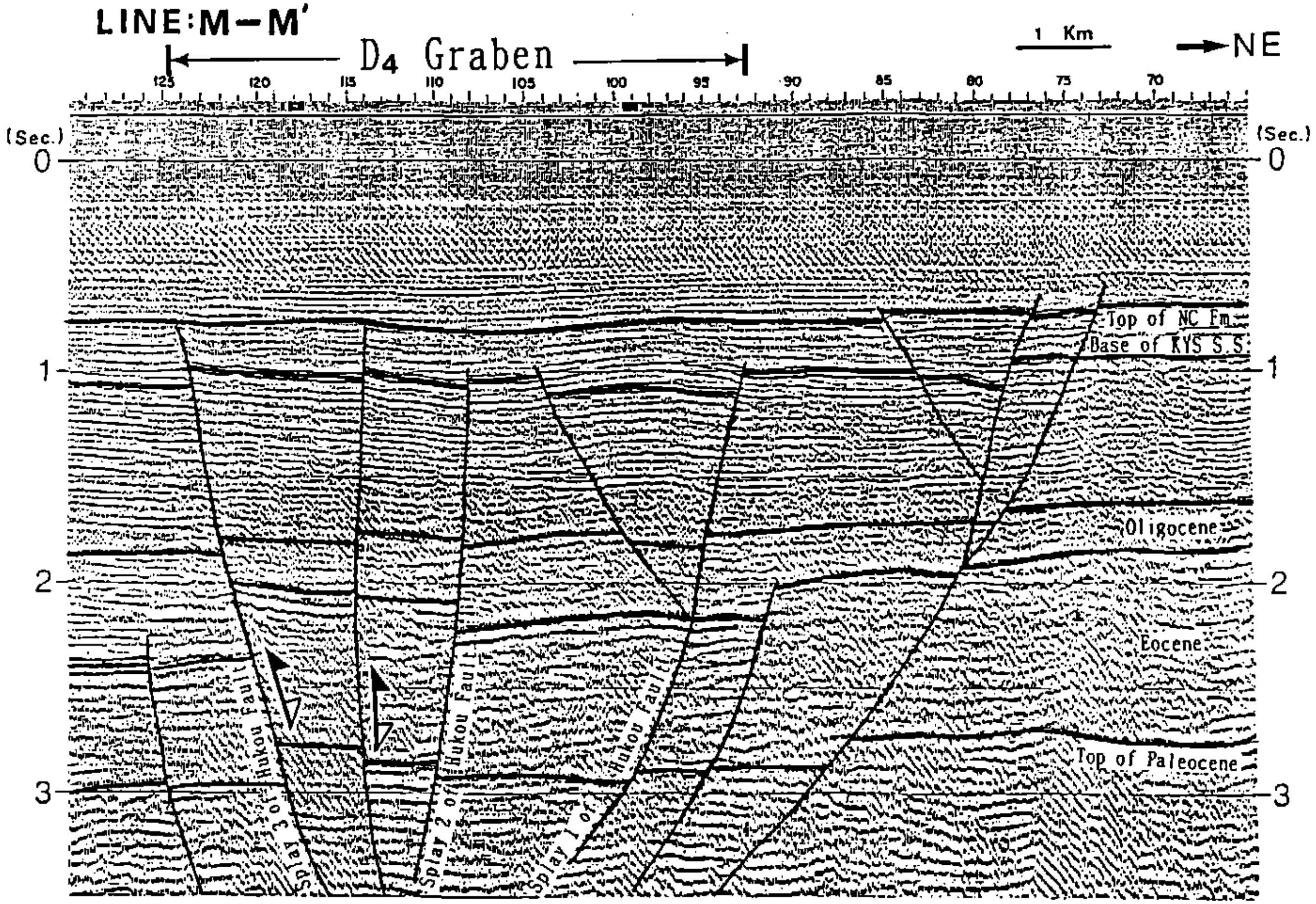


Figure 15. The D4 Graben is considered as an extending part of the Hsinchu Graben. Because the graben is located on the east ramp of the Nanjihtao Ridge. The thickness variation is greater than the other flat place in the Hsinchu Graben.

extensional fault becomes rotated into higher angle while the upper high angle part of extensional fault is bypassed by shortcut contractional fault. Therefore, those higher order tectonic elements such as synthetic or antithetic faults will posess high inversion probability rather than the major faults with higher fault angle.

From regional mapping on the tops of the Eocene, the Oligocene and the Nanchuang Formation, the authors believe that the compressional regime would be accompanied with pre-existing normal faults in an essentially transpressive tectonic pattern. This feature is illustrated in Figure 12c by Letouzey (1990).

Strike-slip Motion

There are several lines of evidence to demonstrate that the Northern Taihsi Basin suffered from widely oblique-slip motion or transtension.

- A series of positive flower structures as shown in Figures 13 & 14 are found in this basin. To a curved strike-slip fault, negative flower structure is caused by transtension whilst positive flower structure by transpression (Caselli, 1987; Harding, 1990; Jenyon, 1990). Up to present, except some pitfalls defining strike-slip fault, flower structures as well as the diagnostic criteria such as the presence of local compressional feature within a dominantly extensional setting are still major good features in defining strike-slip fault (Emmons, 1969; Roberts *et al.*, 1990). Very local compressional evidence in the curved part of pre-existing faults has also been manifested by Suppe's (1984) study that fault-propagation fold deformed and slipped along the old normal fault (i.e. The Waihsiangshan fault). Through correlation of these flower structures, it is considered that the strike-slip faults had taken place during late Miocene (the early stage of the Penglai Orogeny).
- The fault pattern of the Eocene top, the Oligocene top, and the Nanchuang Formation top in the junction between the D4 Graben and the Hsinchu Graben seems to be almost coincident with one of Letouzey's (1990) tectonic regime models (Fig. 12a). On plane view, the conjugated strike-slip faults resulted from the $\sigma 1$ perpendicular to possible Paleocene graben. The possible Paleocene graben is too deep to be detected as it is beyond the seismic resolution. Probably it could be guessed that there were pre-existing strike-slip fault acting as main boundary faults. Direct evidence is still needed to verify this viewpoint.
- Along the Hukou fault and its splay 3, thickness variation of Kuanyinshan Sandstone-Nanchuang Formation between hangingwall and footwall in the east ramp side of the Nanjihtao Ridge (Fig. 15) is much greater than that in offshore of the Hsinchu City (Fig. 13, eastern part of the Hsinchu Graben). The results are produced by strike-slip motion rather than graben bulk contraction. This phenomenum could be interpreted by one of Letouzey's (1990) model shown in Figure 12b so that the stress will transmit into basin center or even penetrate the Nanjihtao Ridge into the Nanjihtao Basin by such strike-slip

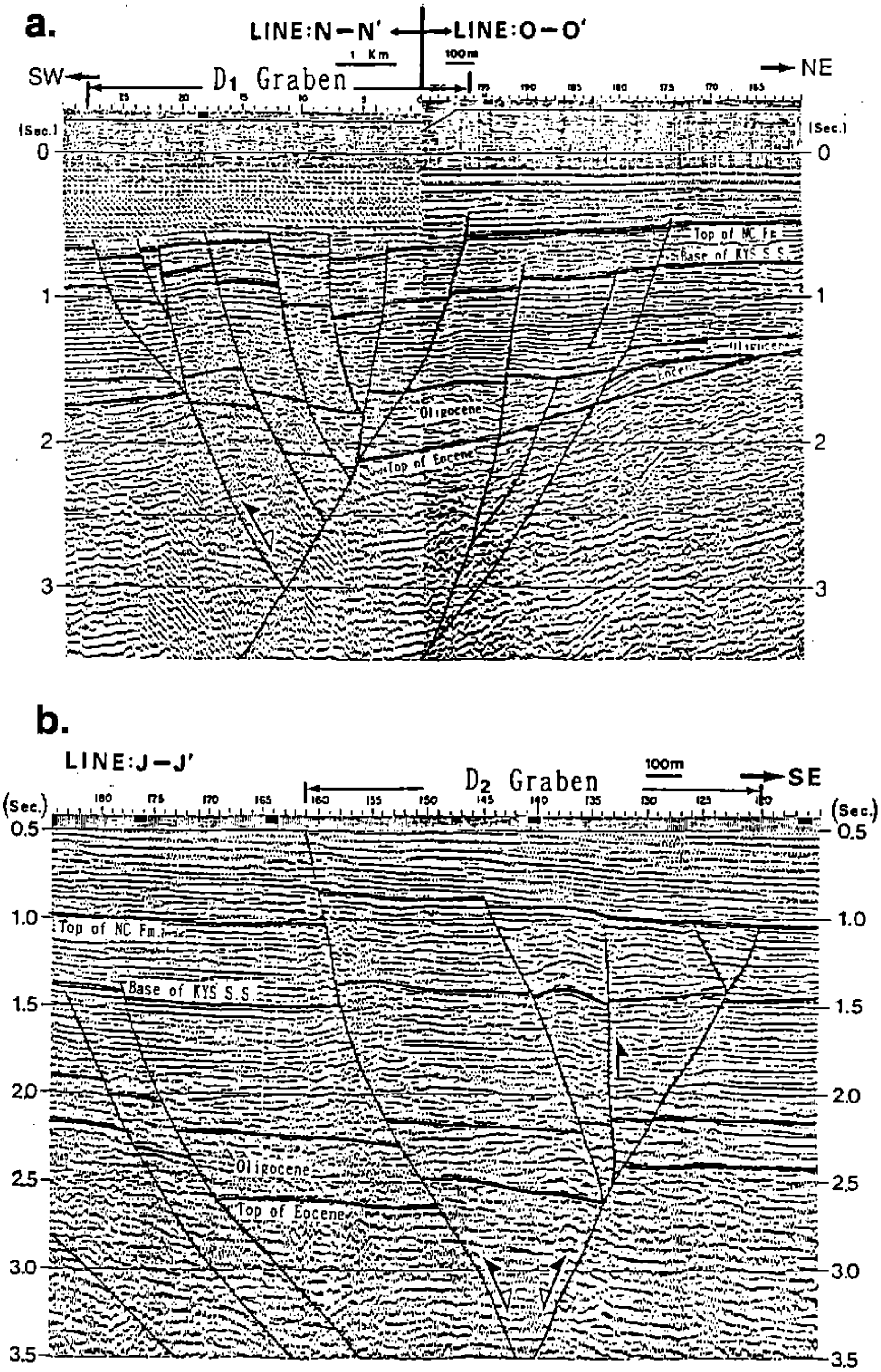


Figure 16. (a)The D1 Graben is a small extensional graben and still subjected to inversion.
(b) Morphology of the D2 Graben. Strong inversion occurred in the central part of the D2 Graben (Fig. 2).

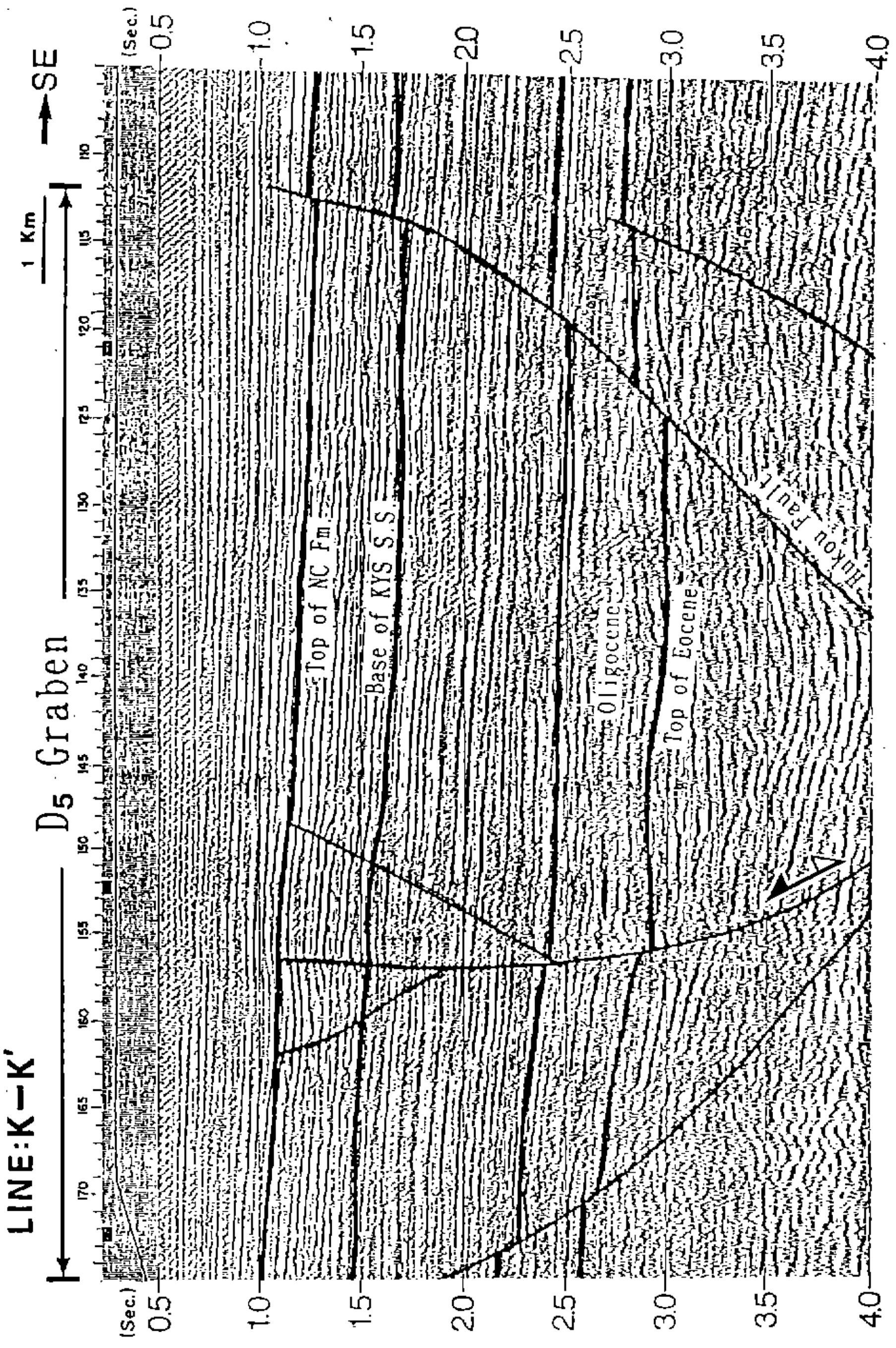


Figure 17. Morphology of the D5 Graben. Mild inversion took place during late Miocene.

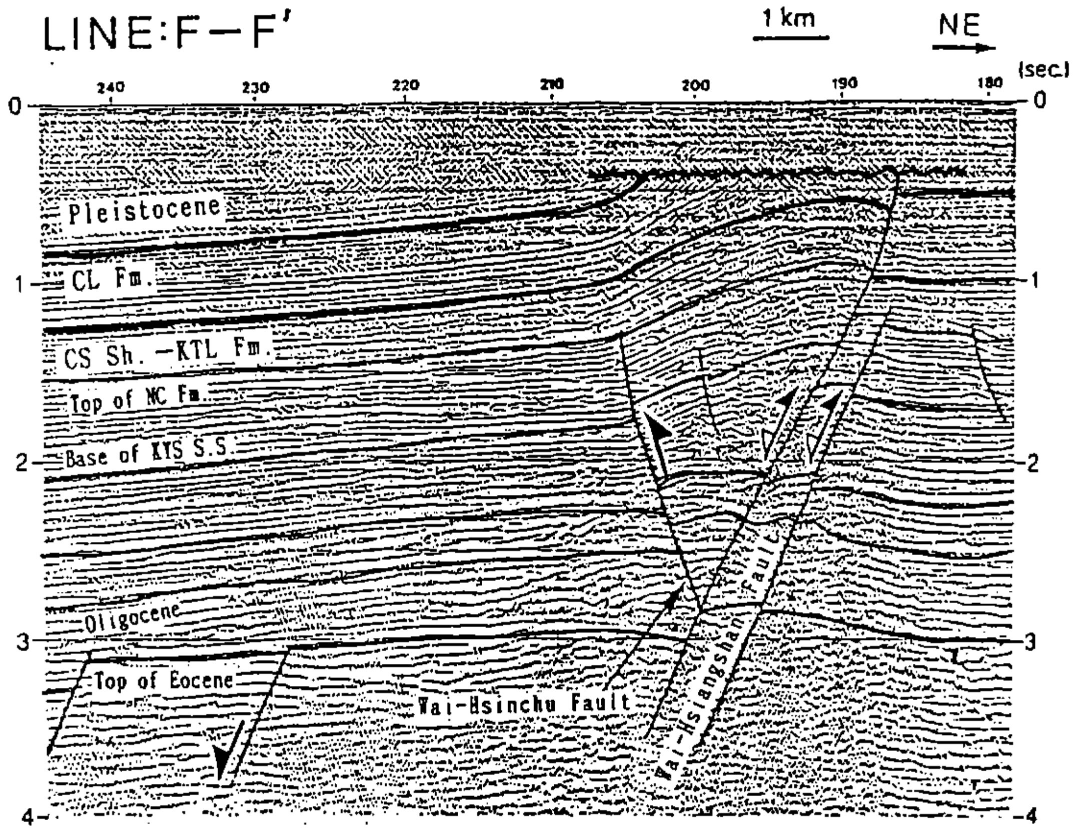


Figure 18. This antiform is one of the inversion features and could be considered that the pre-existing rollover and antithetic faults were inverted by the late Penglai Orogeny.

motion. If the latter graben bulk contraction in the east side of the Nanjihtao Ridge had sharply decreased as far away from the foreland basin, the thickness variation should have decreased westward.

By the application of Caselli's (1987) opinion, the Hukou fault, the Waihsiangshan fault, the Chunan fault and the Paishatun fault could be determined as strike-slip fault due to a series of minor reverse faults, or minor positive flower structures causing by the compression and transpression from the east side of the basin and increasing numbers of fault splays occurred in the curved part of these faults (Figs. 6, 7 and 8).

Extent of Tectonic Inversion

By comparing the Hsinchu Graben (including the D3, D4, D5 Grabens), the Paishatun Graben and the Wulipai Graben, it is found that the extent of inversion tectonics decreases both from the Kuanyin Uplift southward to the Penghu Uplift; and from Taiwan Island westward to the Nanjihtao Ridge. Therefore, the Hsinchu Graben is strongly inverted, whereas some part of the Hsinchu Graben is narrowed or eliminated, such as the features shown in Figures 13 and 19. The Paishatun Graben with more symmetrical geometry is subjected to moderate inversion shown in Figure 20. Minor thrust fault took place along the southern major boundary fault. Only mild or partial structural inversion took place in the Wulipai Graben where near the major boundary fault, compression within the graben is expressed on the seismic profile by gentle folding without obvious fault in the younger sequence overlying the middle Miocene (Fig. 21). Some Eocene residual grabens, including the D1, D2, D3, D4, D5 Grabens, still retain the inversion structure especially in the central part of these grabens (shown in Figs. 15, 16, and 17). The D5 Graben seems to be interconnected with the Hsinchu Graben by the major Hukou Strike-slip fault before late Miocene, and then the interconnected part was narrowed and even eliminated by strong tectonic inversion (Fig. 19).

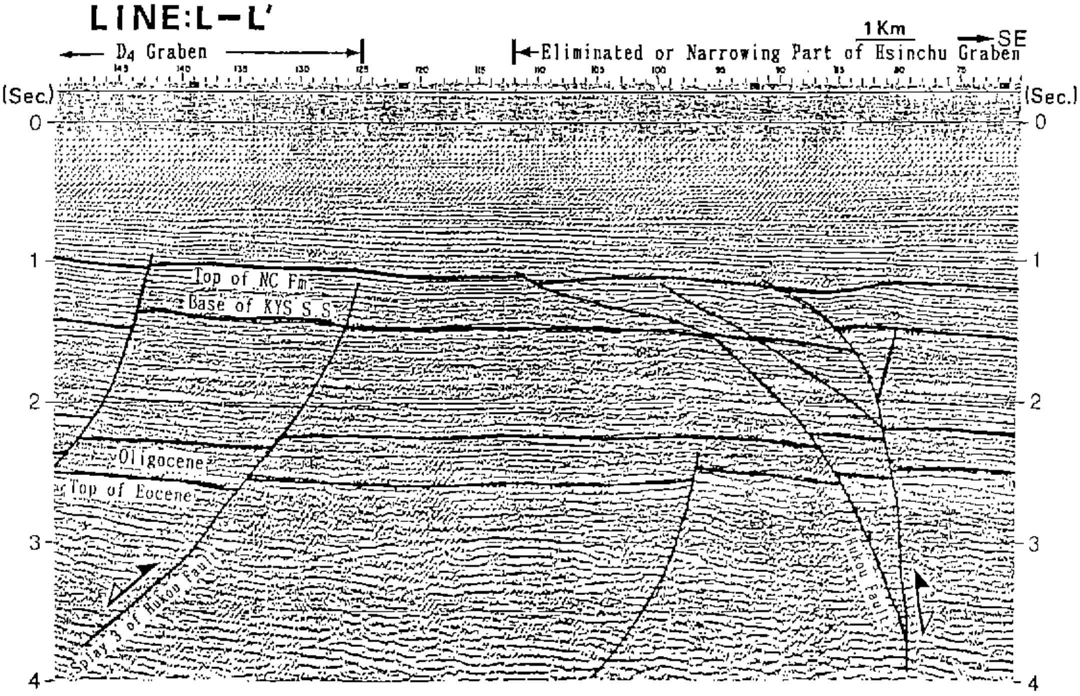


Figure 19. Inversion tectonics result in local narrowing or eliminating of the Hsinchu Graben.

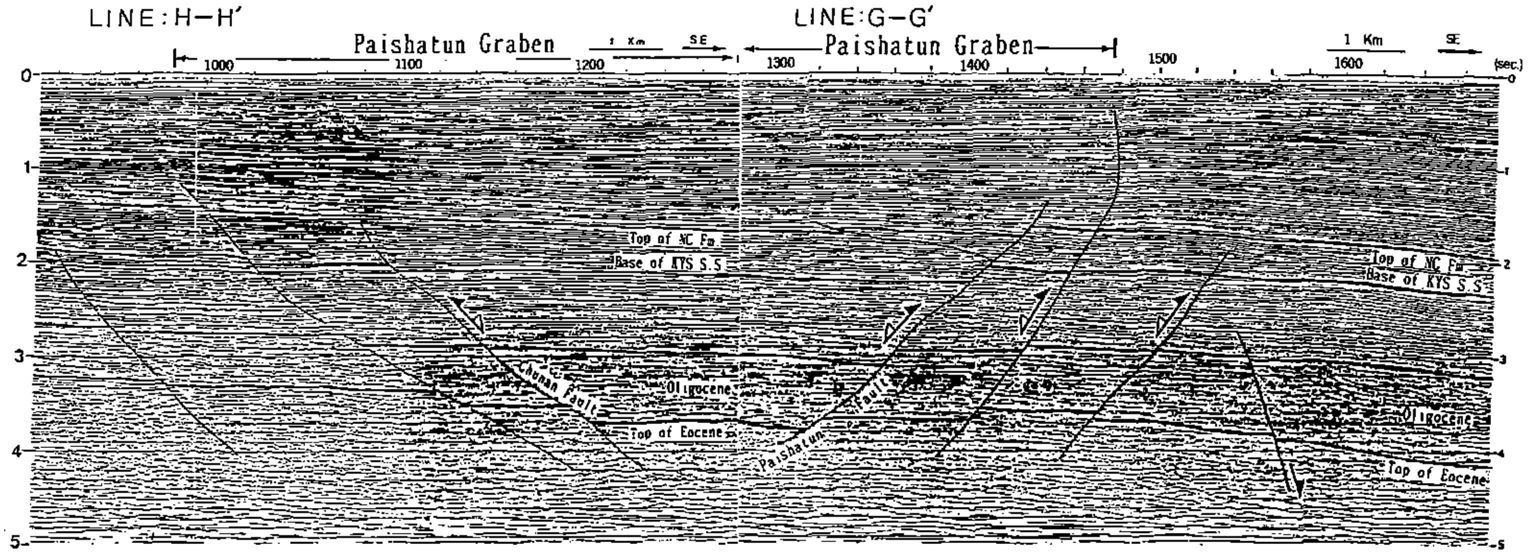


Figure 20. Morphology of the Paishatun Graben. The major boundary fault is moderately inverted.

BASIC BASIN MODEL AND BASIN EVOLUTION

Following the present reinterpretation of the tectonics of the Northern Taihsi Basin, we propose a simple basic model (Fig. 22) concerning the relationship between basin orientation and stress $\sigma 1$. Some authors such as Ho (1982) and Lee and Wang (1988) had pointed out that the major stress direction of the Penglai Orogeny is southeast. Although the dynamic stress direction is very difficult to determine in geologic time, for easy illustration we would firstly just consider two components E-W and N-S, in terms of major orientation or trend of the Northern Taihsi Basin. If the tectonic mechanisms and tectonic characteristics are clarified, we will then attempt to reconstruct the history of basin evolution.

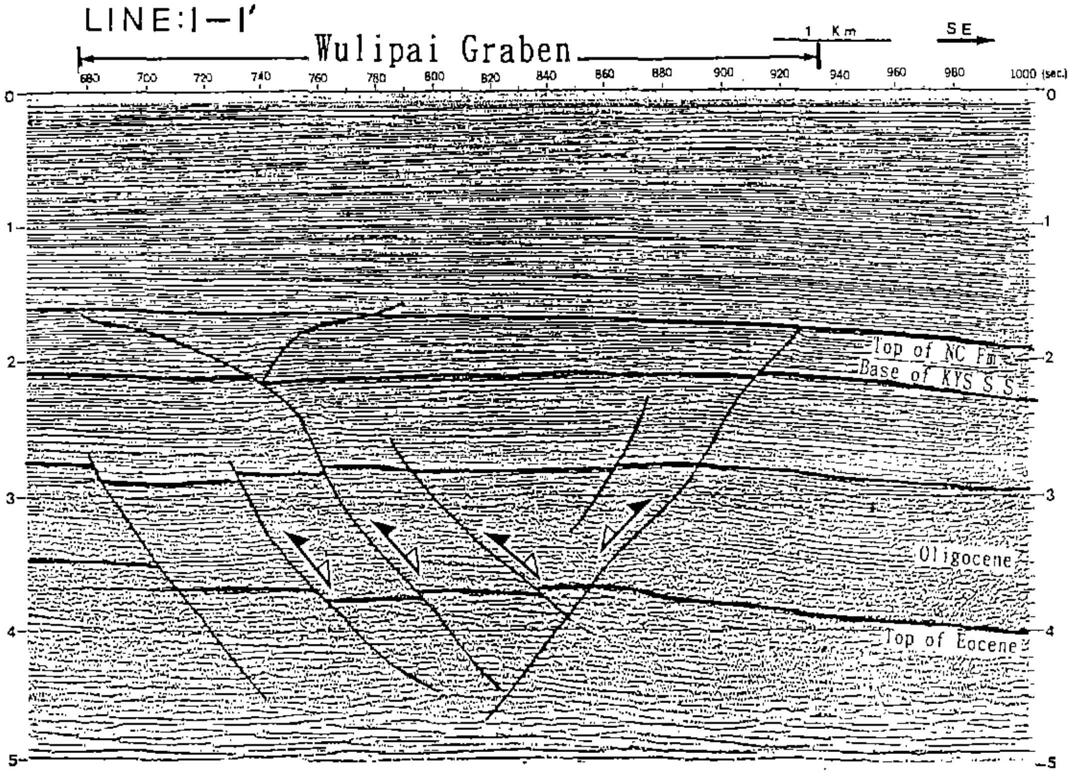


Figure 21. Morphology of the Wulipai Graben. The graben is also subjected to mild inversion.

Orientation of the Northern Taihsi Basin and Basin Model

It might be both surprising and interesting that the authors consider that the orientation of the Northern Taihsi Basin is near E-W or N79° E based on the major faults. One of the examples is shown in rose diagrams of the Oligocene Top (Fig. 9).

According to time contour maps of the Eocene Top, the Oligocene Top, the

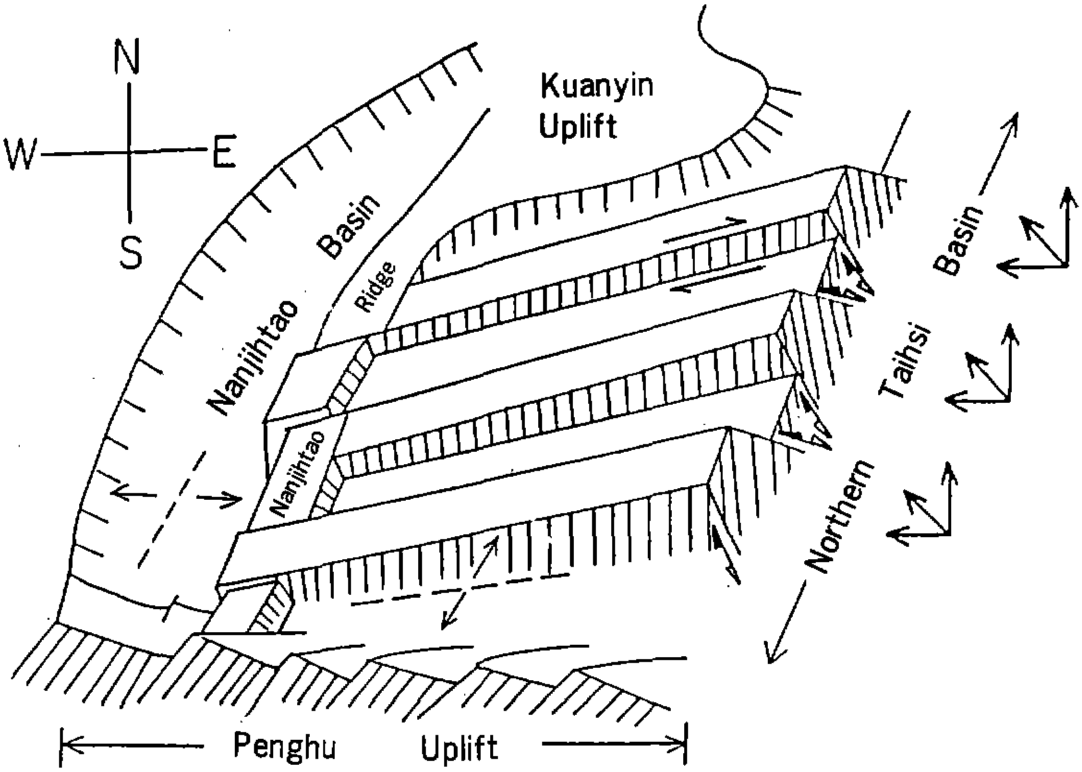


Figure 22. Basinal model of block diagram expresses the average N79° E tectonic trend of the Northern Taihsi Basin. (Dash lines show the rifting axis of the Northern Taihsi Basin during Eocene-Oligocene and the Nanjihtao Basin in Paleocene, respectively. Stress produced by the Penglai Orogeny is shown in the east side by arrowed lines.)

Nanchuang Formation Top (Figs. 6, 7 and 8, in this study) and the Mushan Formation Top, the Talu Shale Top (provided by OOPED and unpublished), the major trends of fault pattern in each of the above mentioned horizon highly coincided with one another. It could be deduced that the tectonic features of the upward postrift sequence would match the underlying synrift sequence so that the fault rejuvenation in postrift stage would take place along pre-existing main boundary faults occurring in synrift stage. Thus, tectonic inversion would take place along the pre-existing normal faults as well as their associations of synthetic or antithetic faults.

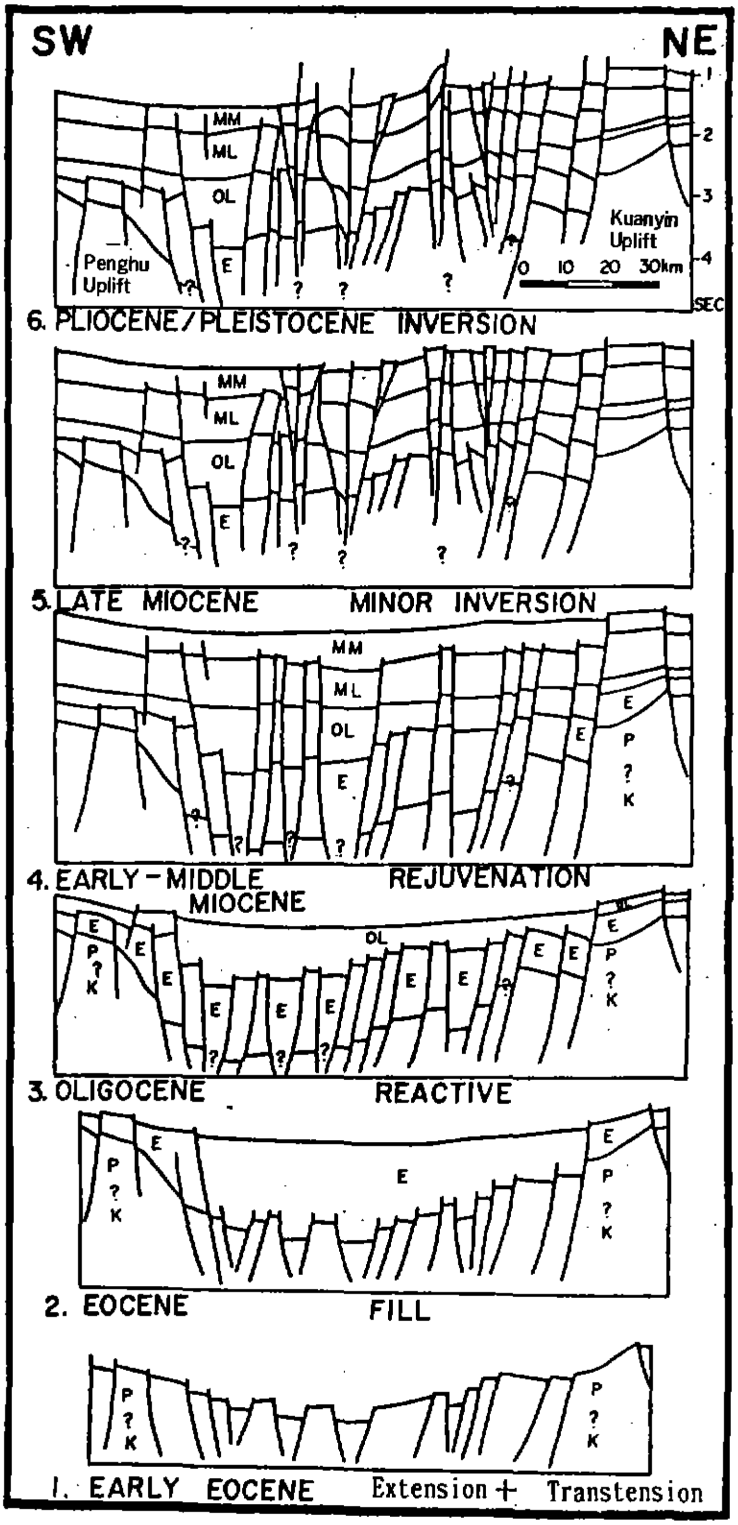
In the Northern Taihsi Basin, it is difficult to find the axis of a series of anticlines, or strike-slip fault, created by tectonic inversion parallel to NE-SW or the trend of the Nanjihtao Basin. However, if we combine all the tectonic features such as extension, transtension, and inversion structures together, it becomes reasonable to conclude that the geologic model in Figure 22 is more preferrable in outlining the Northern Taihsi Basin.

Evolution of the Northern Taihsi Basin

We hereby try to construct one simplified evolutional model (Table 1 and Fig. 23) for the Northern Taihsi Basin even though the evidence is still far from satisfactory. The Northern Taihsi Basin is mainly formed during Eocene to Oligocene as an extensional basin. By Hubbard's *et al.* (1985) concept for synrift basin, its synrift sequence could be subdivided into two rifting phases: fault controlled sequence and passive subsidence sequence. In this study, the Eocene is determined as fault controlled sequence (or isostatically adjusted sequence by Hsü's 1958 concept). The Oligocene is a passive subsidence sequence. Seismic profile B-B' in Figure 10 shows this extensional tectonics.

TABLE 1. *Evolution of the Northern Taihsi Basin*

Age	Major Tectonic and Depositional Features
1. Late Cretaceous-Late Paleocene	horst-graben?
2. Early Eocene	N79° E horst-graben Extension faulting Transtension faulting
3. Eocene	Major faulting and Fault controlled sequence
	—— Unconformity ——
4. Oligocene	Reactive faulting; Passive subsidence sequence
	—— Unconformity ——
5. Early-Middle Miocene	Regional subsidence Fault rejuvenation; Postrift sequence
	—— Tectonic regime change ——
6. Late Miocene	Compression and transpression Strike-slip motion and minor graben bulk contraction (E-W component > N-S component)
7. Pliocene/Pleistocene	Graben bulk contraction and probable association with transpression motion (N-S component > E-W component) Anticline, reverse fault, graben narrowing of eliminating



6. PLIOCENE/PLEISTOCENE INVERSION

5. LATE MIOCENE MINOR INVERSION

4. EARLY-MIDDLE MIOCENE REJUVENATION

3. OLIGOCENE REACTIVE

2. EOCENE FILL

1. EARLY EOCENE Extension + Transtension

Figure 23. Tectonic evolution of the Northern Taihsi Basin.

Before Eocene, the Paleocene setting is difficult to be outlined especially in the center part of the basin due to poor resolution in deeper seismic reflection. But according to the regional geology, it could be assumed that the proto-Paleocene Basin did not exist or just existed as a small scale rifting basin like the geometry of the Nanjihtao Basin. After the deposition of thick Eocene sediments, the Paleocene was buried to the much deeper part of the basin and became undetectable except in the vicinity of the Kuanyin Uplift and the Penghu Uplift.

The extension of the Northern Taihsi Basin probably began in early Eocene or much earlier and reached its peak of development in Eocene and ended in Oligocene. At the end of Oligocene, the synrift sequence was generally stopped and replaced by the widespread regional subsidence. The thick Neogene sequence responded to sea level change and covered the whole area. From late Miocene, the basin started to be affected by compressional tectonics resulting from the collision between the Eurasian Plate and the Philippine Sea Plate so that the Northern Taihsi Basin was partly transformed to foreland setting especially nearby Taiwan Island. Therefore, inversion structural style such as strike-slip motion or graben bulk contraction would be controlled by $\sigma 1$ released from orogenic belt as well as the favourable orientation of horst-graben axis. Fundamentally, the Northern Taihsi Basin initially developed under tensional-transtensional setting and inverted by later compressional-transpressional deformation.

During Paleocene, the tectonic trend of the major synrift sequence of the Nanjihtao Basin is NE-SW, but in early Eocene, the extensional axis of the Northern Taihsi Basin seemed to be determined as N79° E. Up to present, it is still difficult to imagine what caused the regional rifting axis change? The Eocene is regarded as the thickest isostatically adjusted sequence or major synrift sequence (beyond 2.7 km). The tectonic feature is significant with horst-graben. These grabens are shown in Figure 2. Towards the end of the fault controlled sequence, the Oligocene is termed as the passive subsidence sequence and most of the faults were reactivated from the pre-existing Eocene major faults. In comparison with the Taiwan Basin, the Oligocene deposits of the Northern Taihsi Basin is much thinner (1.7 km) than that of the Taiwan Basin (4 km).

The widespread eastward thickening lower-middle Miocene sequence was caused by the large regional scale subsidence and alternated by global sea level changes. During the postrift stage, the major tectonic event was the small scale fault rejuvenation.

Until late Miocene, there was a great contrasting change in tectonic regime due to the effect of the Penglai Orogeny. The tectonic regime changed from extension or transtension into compression or transpression. During the early stage of the Penglai Orogeny (late Miocene), the E-W component of the movement stress was over the N-S component and the tectonic structure is dominant with oblique-slip faults due to inversion of the pre-existing main boundary faults such as the Hukou fault and its splays, the Waihsinchu, and the Paishatun faults. The strike-slip faults play an important role in transmitting the stress far away from the foreland basin, or even into the Nanjihtao Basin. During the late stage of the Penglai Orogeny (Plio-

Pleistocene), the N-S component of the movement stress seemed to be over the E-W component, so that the major strain could not propogate far away than the previous strike-slip motion. Therefore, the dominant inverted features are antiforms (Fig. 18), and reverse faults (Fig. 20) along the pre-existing faults, that controlled the figuration of each graben. Furthermore, strong inversion caused graben narrowing or eliminating (Figs. 11 and 19).

In conclusion, the Northern Taihsi Basin was located on the foreland of Taiwan Island, and naturally suffered from the inversion tectonics on account of the susceptible orientation of basin axis.

CONCLUSIONS

In Cooper *et al.* (1989), Ziegler expressed the opinion that in some cases a clear boundary between compressional intraplate and plate margin deformation cannot be defined if the foreland is transsected by inverted grabens which extend into the orogenic belt (e.g., Dauphinois, Western Alps). With similar N79° E transsecting (as above mentioned) into the orogenic belt of the Taiwan foreland area, it is the reason why the Northern Taihsi Basin is attributable to inverted basin and was not readily recognized.

The formation of the Northern Taihsi Basin initiated with extension and transtension in early Eocene or much earlier, reached its peak of development in Eocene, and ended in Oligocene. The lower-middle Miocene is considered as postrift setting with small fault rejuvenation. From late Miocene, the tectonic regime underwent a great change. Compression and transpression superimposed on this basin such that the original extensional or transtensional setting was deformed by these inversional stresses. In consideration of the relationship between the orientation of horst-graben axis and direction of each component in inversion stress ($\sigma 1$) produced by the Penglai Orogeny as well as timing, the inversion tectonics are divided into two major groups that include:

- strike-slip motion reactivated from pre-existing main boundary fault as the stress (E-W > N-S component) was parallel to the trend of the graben. The process seems to be prevalent during the early stage of the Penglai Orogeny. The original major boundary faults in synrift sequences were reactivated into strike-slip faults with minor and obvious reverse faults in the lower-middle Miocene sequence while at the depth of the Eocene and the Oligocene apparent normal faults were still retained.
- Bulk contraction of inverted graben was caused by compression associated with transpression as stress $\sigma 1$ was not parallel to the trend of the graben (N-S > E-W component). The process and inversional events were dominant in the late stage of the Penglai Orogeny and in the vicinity between the Northern Taihsi Basin and Taiwan Island. Antiforms or reverse faults with strong inversion probably were created from pre-existing rollover structures or antithetic and synthetic faults with lower fault angles and higher orientation angles.

Comparing each graben, it will certainly be found that the extent of inversion generally decreases both from the Kuanyin Uplift toward the offshore of the Tachia City and from Taiwan Island toward the Nanjihtao Ridge. The eastern part of the Hsinchu Graben was strongly inverted and its graben space was narrowed or eliminated locally. The Paishatun Graben was moderately inverted while the Wulipai Graben and the residual grabens near the east side of the Nanjihtao Ridge were just mildly or partially inverted.

Above of all, it could be concluded that the Northern Taihsi Basin is attributable to a typical inverted basin with complicated tectonic evolution. During Eocene to middle Miocene, this basin was still characterized by rifting system. Since late Miocene, the original extensional or transtensional setting of the Northern Taihsi Basin was inverted or deformed by later compressional or transpressional regime from the Penglai Orogeny.

ACKNOWLEDGMENTS

We would like to express our deep appreciation to the OOPED and the Taiwan Petroleum Exploration Division of the Chinese Petroleum Corporation for providing us with the related subsurface and seismic data.

Our thanks also extend to Dr. Kenneth J. Hsü, Dr. J. H. Hung and Dr. K. M. Yang for their kind guidance and discussions, and Mr. Y. C. Torng for help in the computer processing of isopachs.

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台灣北台西盆地的構造逆轉及盆地演化

黃旭燦　陳瑞瓊　紀文榮

節要

北台西盆地是整個台西盆地最深的部份，也相當於晚新生代台灣前陸盆地的北部位置。蓬萊運動期間北台西盆地爲了抵抗歐亞板塊及菲律賓海板塊的碰撞及同時因爲此碰撞受觀音高區的阻擋，而受到構造逆轉的作用。

北台西盆地的構造走向幾乎是東西向（N79°E），不同於具東北－西南走向的台灣海域盆地如東引島盆地、南日島盆地、彭佳嶼盆地及台灣盆地。什麼樣的構造機制主宰了北台西盆地的構造特性？這可能仍是一個謎，可能是涉及具不同張裂方向的張裂構造系統。限於缺乏直接強烈的地質證據，暫不討論此一問題。一系列標準型地塹－地壘構造證實這盆地可能在始新世至漸新世已受過盆地張裂作用。

從始新世至中新世中期，這個盆地的構造作用力始終維持在張裂系統中，然而從中新世晚期開始，由於受到蓬萊運動的作用力在前淵盆地釋出的影響，北台西盆地的構造作用力有了基本的改變。

從中新世晚期開始，具東西走向的地塹－地壘的北台西盆地開始受到構造逆轉的作用，包括兩類型較早期橫移斷層作用及較晚期的地塹的整體收縮。

分佈廣且具典型的逆轉構造特徵是小而且明顯的逆斷層出現在後張裂層序（即下部～中部中新世地層），然而在較深部的正斷層仍保留了“假正斷層”。這假正斷層在幾何形貌上是正斷層，在過程上是逆斷層，通常大部份的逆轉特徵是沿地塹邊緣介於主地塹斷層及順傾斷層或逆傾斷層之間發育。具有較低角度且與作用力方向有較良好交角的構造如順傾斷層及逆傾斷層將優先受構造逆轉的作用。

比較了幾個主要的地塹，可以發現構造逆轉的特徵是由觀音高區往大甲外海的方向，以及由台灣島往南日島脊的方向逐漸減弱。新竹地塹的東側部分受到最強的逆轉，整個地塹的體積有局部變窄、消失的現象；白沙屯地塹屬於中度逆轉；而五里牌地塹及一些位於南日島脊兩側的殘存小地塹僅受到溫和或是輕微的逆轉。

北台西盆地張裂形成於始新世早期至漸新世或是比始新統更早的地質年代。於始新世期間發展至最高點，而逐漸結束於漸新世。經過了中新世早期～中期的主斷層回春作用。在中新世晚期即蓬萊運動的初期，與張裂特性非常不一樣的擠壓及橫向擠壓應力使得北台西盆地受到構造逆轉的作用。