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A Preliminary Study of Seismic Stratigraphy of the Late Cenozoic Sequences in the Tainan Basin off Southwestern Taiwan

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ABSTRACT

This study investigates the late Cenozoic strata in the Tainan basin off southwestern Taiwan. The nature and development history of late Cenozoic sequences are discussed in terms of seismic stratigraphy. Multichannel seismic profiles more than 330 *km* long were acquired and processed, including 4 dip profiles and 3 strike lines. The quality of the seismic profiles range from fair to good.

Seismic profiles show that late Cenozoic strata are relatively conformable stratigraphic successions from which Pleistocene and Pliocene seismic sequences are defined. The seismic reflection configurations of the late Cenozoic sequences are characterized by parallel, subparallel and divergent patterns. The parallel pattern suggests that sediments accumulated at a relatively uniform rate on a shallow shelf within the study area. The divergent reflection pattern and the external wedge-shape of the sequences indicate lateral changes in depositional rates and progressive tilting of the shelf facies. Seismic facies analysis indicates that late Cenozoic sediments were deposited mainly in the fluvial-nearshore environments. The regional trends of the Pliocene and Pleistocene sequences represent relatively smooth parts of the shelf without the characteristic shelf-slope breaks. The shelf breaks in the Pliocene and Pleistocene sequences are probably situated farther seaward than today's shelf edge.

Velocity models indicate an interval velocity ranging from 1,800 *m/s* to 4,000 *m/s* suggesting that the late Cenozoic sequences are composed mainly of sands and shales. Vertical distribution of the interval velocity shows that the velocity of the sequences increases with depth as a result of compaction (i.e. depth of burial).

Analyses of seismic sequences, seismic facies and velocity suggest that the Pleistocene and Pliocene sequences developed into a clastic wedge. The sequences form parts of the South China continental margin which has undergone tilting and subsiding during the past ten or more million years.

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1. INTRODUCTION

Purpose

This study investigates the late Cenozoic strata of the Tainan basin using seismic stratigraphic techniques. Emphases are placed on description of seismic characteristics of reflections within the sequences, elucidation of the major unconformities and analysis of the seismic velocity. Specifically, the objectives of this study include (1) determination of the depositional environment, (2) understanding the processes related to sedimentation and tectonics and (3) discussion of the relationship between lithology and seismic velocity.

Study Area

The seismic survey was done in the northeastern part of the Tainan basin off southwestern Taiwan (Fig. 1). The Tainan basin is one of the Tertiary basins along the southern Chinese continental margin. The name of the Tainan basin was first proposed by Sun (1982). The Tainan basin has an area of about 46,000 km^2 of which about 90% is offshore. The northern part of the Tainan basin is generally covered by water with normal depths shallower than 200 m, however, close to the southeastern margin, the water reaches up to 3,000 m in depth.

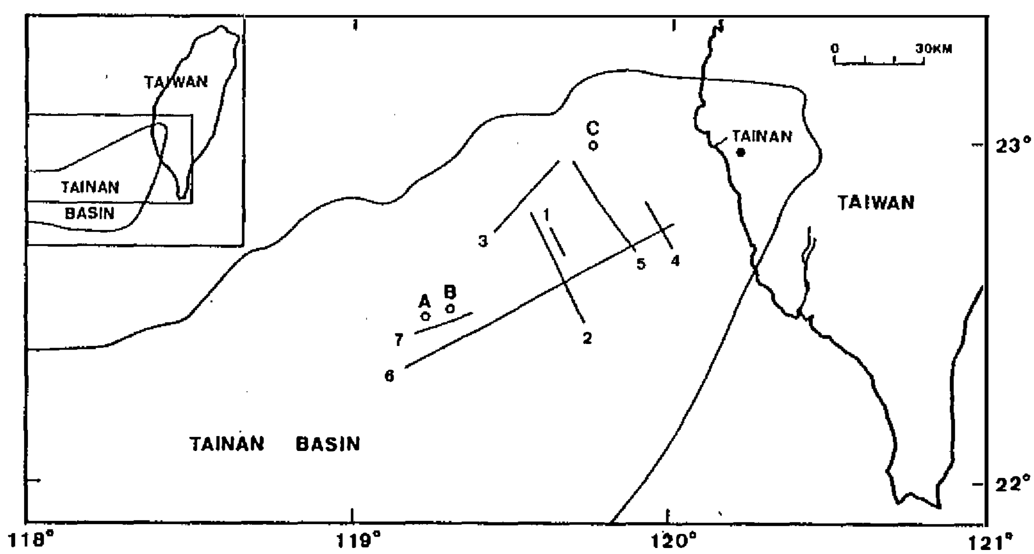

Fig. 1. Map showing the seismic grid covering the study area in the Tainan basin off southwestern Taiwan. The seismic lines are numbered 1 to 7. Note that wells A, B and C are included for seismic correlation.

Seismic Data

Multichannel seismic reflection profiles 330 *km* long were acquired using the facility on board R/V Ocean Researcher I during cruises in the years 1988 and 1989. The seismic energy source was an air gun. The length of the streamer about 760 *m*. The recording device used was the 24 channel DFS-V floating gain digital system. The sampling period was 2 *ms* and the record length per shot 5 *sec*. Field seismic data were then processed using the DISCO system (Digicon's Interactive Seismic Computer) at the Geophysical Data Processing Center of the Chinese Petroleum Corporation. Finally, a set of 12 fold migrated seismic profiles were completed.

As shown in Fig. 1, the seismic survey lines are composed of 4 dip lines trending *NW-SE* and 3 strike lines in a *SW-NE* direction. Apparently, the survey lines are distorted from the original one which is designed with equal line spacing passing through the A, B and C wells. The main reasons for distortion are operational difficulties such as the malfunction of navigational positioning systems and bad weather conditions caused by typhoons.

Well Data

Wells A, B and C within the study area belonging to the Chinese Petroleum Corporation, are integrated into the interpretation of the seismic data. Wells A, B and C are renamed because of confidential reasons. Only the Miocene, Pliocene and Pleistocene sequences recorded in the well logs concern us here. Table 1 summarizes the geologic age, formation depth, thickness and seismic reflection time for the wells. Wells A and B are located north of line 7. Well data indicates that the average thickness of the Pliocene sequences is around 1,000 *m*. Cored samples indicate that Pliocene sequences are characterized by the nannofossil zones of NN11-NN18. In conjunction with synthetic seismograms, the depths of two-way travel time for the reflections at the base of the Pliocene sequence are determined to be about 2.0 *sec*. The overlying Pleistocene sequences show a similar thickness of about 1,000 *m* and are characterized by the nannofossil zones of NN19-NN21. Synthetic seismograms suggest that the reflections occurring at the base of the Pleistocene sequence are about 1.2 *sec* (two-way travel time). Well C is located at the northeast corner of the survey area. Well data indicate that the Pliocene sequence is approximately 1,300 *m* thick. Two-way travel time for the reflection at the base of the Pliocene is about 1.8 *sec*. The Pleistocene sequence is 610 *m* thick. The reflector at the base of the Pleistocene occurs at about 0.9 *sec* (two-way travel time).

Table 1. The composite well data of the Tainan basin based on the data from three exploratory wells in the study area.

Epoch \ Well	Depth (m)			Thickness (m)			Reflection Travel Time (sec)		
	A	B	C	A	B	C	A	B	C
Pleistocene	151-1080 (NN19-NN21)	159-1252 (NN19-NN21)	290-900	929	1093	610	1.1	1.3	0.9
Late Pliocene	1080-2033 (NN15-NN18)	1252-2007 (NN16-NN18)	900-1550	953	815	650			
Early Pliocene	2033-2173	2067-2340 (NN11-NN15)	1550-2130	40	273	647	2.0	2.0	1.8
Miocene			2103-2593	1277	885	1277	2.8	2.6	2.8
			2595-3529						
	2173-3450 (NN1-NN3)	2340-3195 (NN1-NN3)	3529-4050 (NN1-NN3)						

Stratigraphic Framework

Tainan basin is mainly filled with thick Neogene sediments; the depocenter is about 50 *km* off the city of Kaohsiung (Hu, 1988). A composite stratigraphic column in the Tainan basin is shown in Table 2. Generally, the basement of the Tainan basin is Cretaceous in age. Well data indicate that the Cretaceous bedrock is mainly composed of fine to coarse-grained sandstones interbeded with shales. Late Oligocene strata unconformably overlie the Cretaceous basement. The lower part of the Late Oligocene sequence is composed mainly of shallow marine sandstone. The upper part is dominated by shales and siltstone. In general, Miocene sequences unconformably overlie the late Oligocene rocks. The Miocene deposits are mainly comprised of shallow marine shales and siltstones. The Pliocene sequence unconformably overlies the Miocene and/or older rocks. The Pliocene sediments are mainly composed of siltstone and shale. The Pleistocene and younger sediments are mainly comprised of shales with minor amounts of silt and sand. The Pleistocene sequence is unconformably underlain by the Pliocene sequence. The maximum thickness of the Pleistocene and younger deposits reaches up to 3,000 *m* on the sloped areas of the basin.

It is noted that the late Tertiary sequences are mainly separated by regional unconformities (Hu, 1988). The unconformable surfaces between Pleistocene, Pliocene and Miocene are either irregular and uneven erosional surfaces or nearly parallel contacts with no marked erosional features.

Table 2. The composite stratigraphic successions of the Tainan basin (after Hu, 1988).

Period	Epoch	Age	Lithology	Fossil	Depositional Environment
Tertiary	Pleistocene		Schales Silts	NN19-NN21	Shallow to deep marine
	Pliocene		Shales Siltstones	NN11-NN18	Shallow marine
		late	Shales	NN11	
	Miocene	middle	Shales, Siltstones	NN7-NN10	Shallow marine
		early	Siltstones, Shales	NN4	
	Oligocene	late	Shales Sandstones Thin beds of limestones Shales	NN1 NN23-NN25	Shallow marine
Cretaceous			Shales Siltstones Fine to coarse grained sandstones	Spores Pollens	Marshes Lakes

2. METHOD

Standard procedures for the stratigraphic interpretation from a set of seismic data are given by Mitchum *et al.*, 1977. Figure 2 is a flow chart diagrammatically showing the procedures for stratigraphic interpretation of the late Cenozoic strata in the Tainan basin. In general, step 1 integrates the available geologic data from the Tainan basin and well logs from wells A, B and C with the seismic data. For example, Formation boundaries from well data are projected into the seismic sections. Step 2 includes the recognition of seismic sequences from the seismic profiles using reflection termination criteria aided by age correlation with the well data. The structural analysis of the Pliocene and Pleistocene seismic sequences are also included. Step 3 is the detailed mapping of seismic facies units within sequences. Seismic parameters are mapped and correlated to well data where possible. Seismic velocity analysis is also performed. Finally, the seismic data are interpreted in terms of depositional environments, sedimentation processes and lithology.

3. SEISMIC SEQUENCE ANALYSIS

Mitchum, Vail and Thompson (1977) define (p.53) a depositional sequence as "a stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or

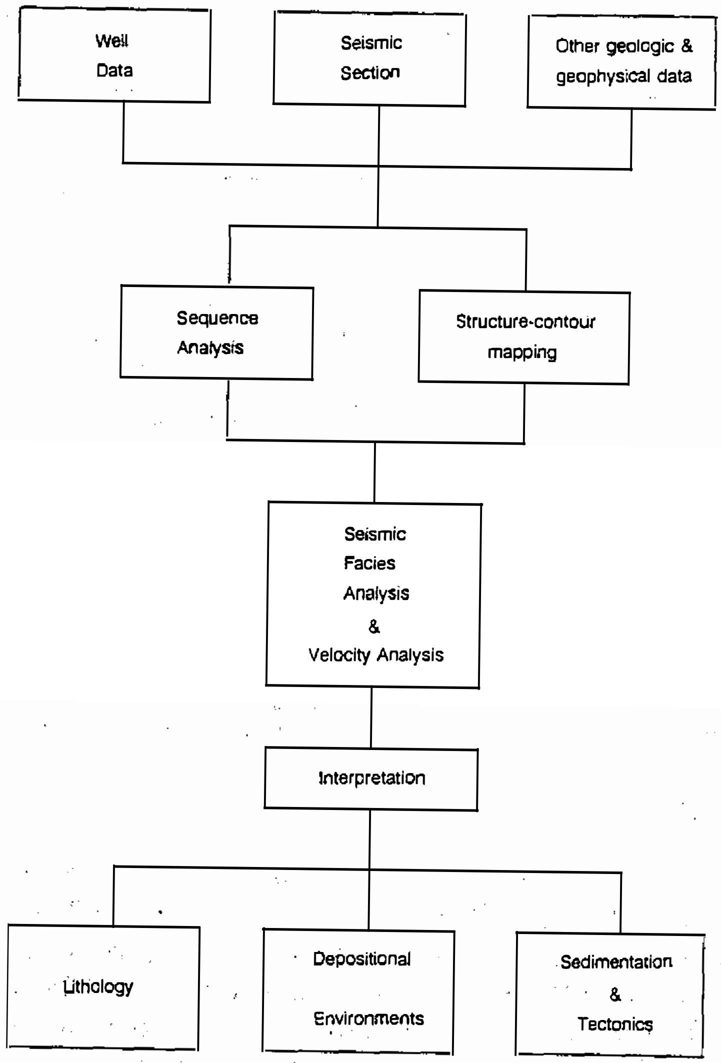

Fig. 2. A flow chart diagrammatically showing the procedures for seismic stratigraphic interpretation of the late Cenozoic strata in the Tainan basin.

their correlative conformities". Thus the mapping of unconformities from the seismic sections is the key to identification of the seismic sequences, and if fossil information from well data are known, the geologic ages of the seismic sequences are also determined. Apparently, the regional unconformities that separate unconformable strata of Miocene, Pliocene and Pleistocene coincide with the seismic sequence boundaries. In terms of seismic sequence analysis, the irregular erosional surfaces mentioned in the section concerning stratigraphic framework can be taken as a discordant sequence boundary and the nearly parallel contacts as a concordant sequence boundary (Mitchum *et al.*, 1977, Fig. 2, p.58). Examining the characteristic reflection configurations and correlating the sequence boundaries and geologic ages with the well data, we identify two major seismic

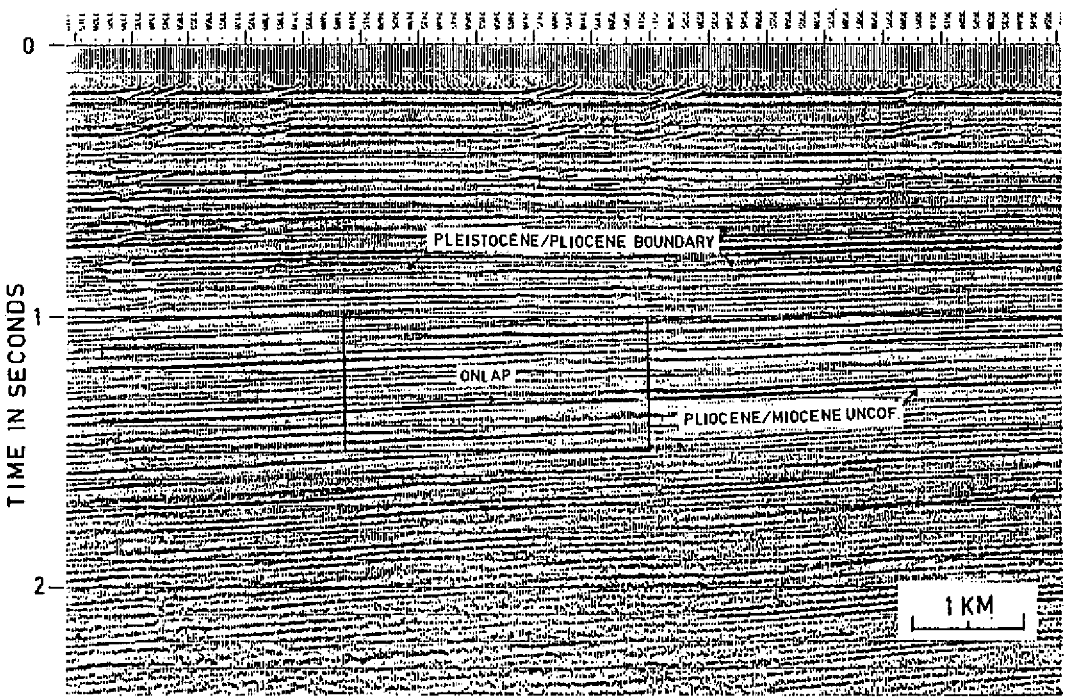

Fig. 3. The bounding surfaces between late Miocene and Pliocene sequences are mostly concordant and sometimes low angle onlaps (line 3).

sequences Pleistocene and Pliocene from the seven seismic profiles. The seismic characteristics of these two sequence boundaries are described as follows.

Late Miocene/Pliocene sequence boundary: It is characterized by strong amplitude and good continuity. The bounding surfaces are mostly concordant and sometimes low angle onlaps (Fig. 3).

Pliocene/Pleistocene sequence boundary: It is characterized by strong to weak amplitudes and good continuity. The bounding surfaces are mostly concordant but sometimes truncations (Fig. 4).

We may extrapolate from these sequence boundaries where the reflections are conformable, thus the sequence unit mapping is completed and the Pleistocene and Pliocene seismic sequences are defined on the seismic profiles. For example, sequences interpreted for dip line 2 and strike line 7 are shown in Fig. 5 and Fig. 6, respectively.

Structure-contour maps of the base of the Pliocene and Pleistocene sequences and the present-day sea floor in the study areas are prepared in order to examine the regional trends of the sequences and discuss the sequential development of the seismic sequences.

As shown in Fig. 7, the base of the Pliocene sequence generally dips in a southeasterly direction towards the ocean side and strikes in a NE-SW direction

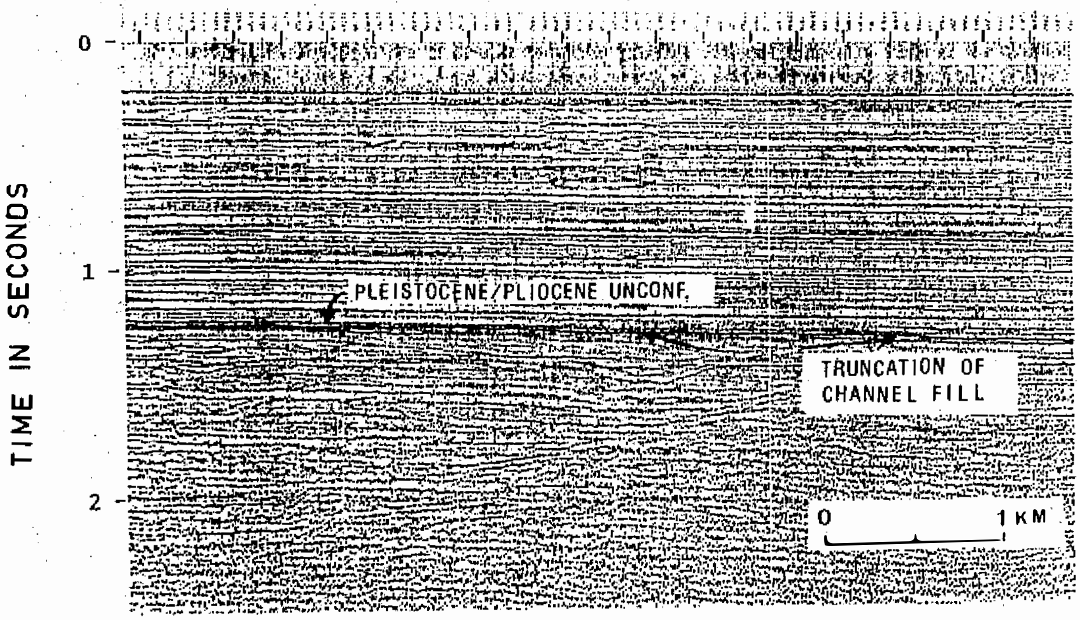

Fig. 4. Strike line 7 indicates that truncations by channel-cut occured at the sequence boundary separating the Pliocene from the Pleistocene.

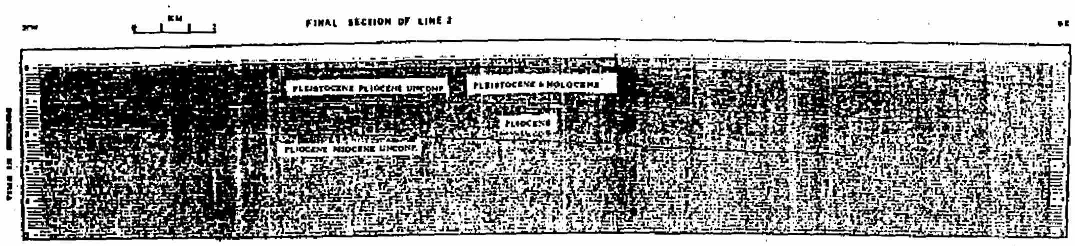

Fig. 5. The *NW-SE* trending dip line 2 showing the Pleistocene and Pliocene sequences characterised by parallel and subparallel reflections. As one unit, both sequences are represented by a divergent pattern showing progressive tilting and thickening towards the ocean.

paralleling the South China continental margin. The contour intervals range from 1,200 *ms* (1,200 *m*) to 2,500 *ms* (3,000 *m*). Clearly, the base of the Pliocene sequence deepens progressively from the continental side towards the deep ocean with an average dip angle of 4.1 *degrees*. The dip angle is close to the present day average dip angle of a continental slope (Shepard, 1973). However, we believe that the dip angle is a result of the combined processes of tilting and subsidence of the passive continental margin of South China. This interpretation is heavily based on ideas which suggest that subsidence is a major process in the development of passive continental margins (McKenzie, 1978; Steckler and Watts, 1978; Royden and Keen, 1980); and that sediments

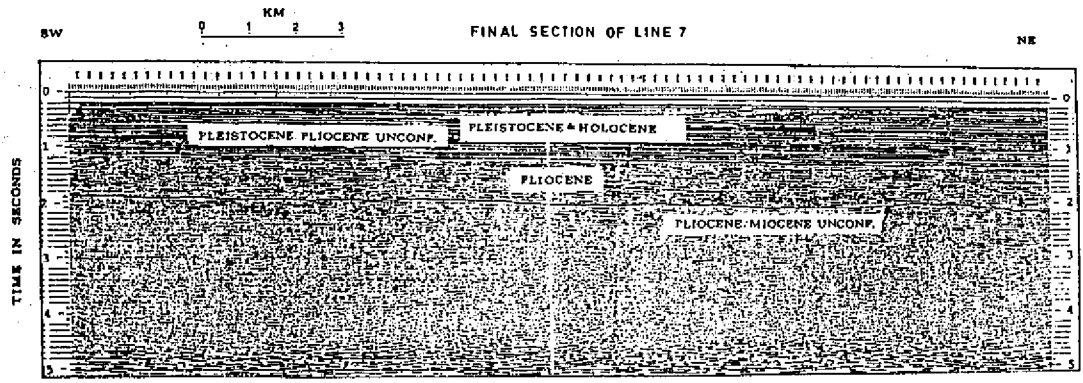

Fig. 6. Strike line 7 showing the Pleistocene sequence characterized by parallel strata, strong and continuous reflections; the Pliocene sequence characterized by strong but discontinuous reflections.

accumulated on the passive margins may reach up to a maximum thickness of 14 *km* and may contain shallow shelf deposits from base to top of a thick sedimentary wedge (Pitman III and Golovchenko, 1983). This explanation is also supported by the the seismic facies of parallel and divergent reflections within the Pliocene sequence as will be discussed in the seismic facies section. In other words, the Pliocence base was deposited on broad continental shelf areas of the South China margin and later tilted and deepened through evolution of the South China margin.

Similar to the structure of the Pliocene base, the base of the Pleistocene sequence mainly dips southeastward onto the ocean side and strikes generally along the coastline of Mainland China (Fig. 8). The contour intervals range from 800 *ms* (800 *m*) to 1,900 *ms* (2,200 *m*). The average dip angle is about 2.2 *degrees* which is greater than the dip angle of today's average continental shelf but smaller than that of the average continental slope. We suggest that the dip angle of the Pleistocene base has also resulted from the continued processes of subsidence and tilting operating in the passive continental margin. However, the magnitude of the tilting of the Pleistocene base is less than that of the Pliocene base. This interpretation is aided by the seismic facies of parallel or subparallel reflections within the Pleistocene sequence as discussed in the seismic facies section.

The present-day sea floor structure in the study areas shows more complex structural patterns than those of the Pleistocene and Pliocene bases (Fig. 9). It is noted that the structural contours of the sea floor dip in two directions. One is the southwest-facing slope and the other dips in a southeasterly direction. However, the general trend curves which implies structural control, the uplift of Taiwan in Recent times seems to be a candidate. It is noticed that the 300 *ms* (225 *m*) contour line approximately separates the structure map into two parts;

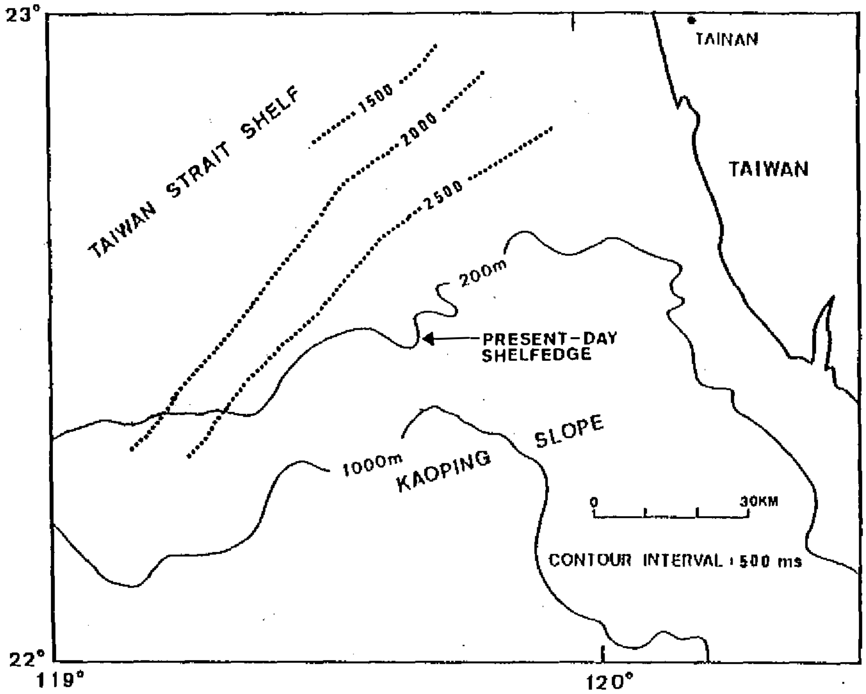

Fig. 7. The structure-contour map for the base of the Pliocene sequence. The Pliocene base dips towards the deep ocean with an average dip angle of 4.1 *degrees* along the South China continental margin. Note the present day upper slope (200 ~ 1,000 *m* depths) is shown for reference of geographic position. The gradients of the upper slope range from 2 to 3 *degrees*.

the shallow part which is characterized by the depths between 150 to 225 *m* (200 to 300 *ms*) with an average dip angle at about 0.3 *degrees* representing a typical continental shelf topography and the other is the deep, steeper region which is characterized by depths greater than 300 *m* and slope angles greater than 4 *degrees*. This area belongs to the continental slope. Clearly, present-day sea floor topography is determined by seismic data in the study areas including the shelf and the upper slope and the shelfbreak which is defined as the place at the outer edge of the shelf with a marked change of gradient (Vanney and Stanley, 1983). It is worthwhile to note that seismic data indicates a shelf break occurring about 225 *m* in depth in the study area which is somewhat different from the shelfbreak of about 200 *m* in depth around Taiwan as suggested by Boggs and others (1979). In addition, the position of the shelfbreak in this study is different from that of Boggs *et al.* (1979). These discrepancies, due to the two different methods seismic and echo-sounding can be resolved by later systematic seismic profiling and hydrographic surveys. As a whole, the regional trends of the bases of Pliocene and Pleistocene represent parts of the smooth shelf without having the characteristic shelf-slope breaks. Hence, the Pliocene

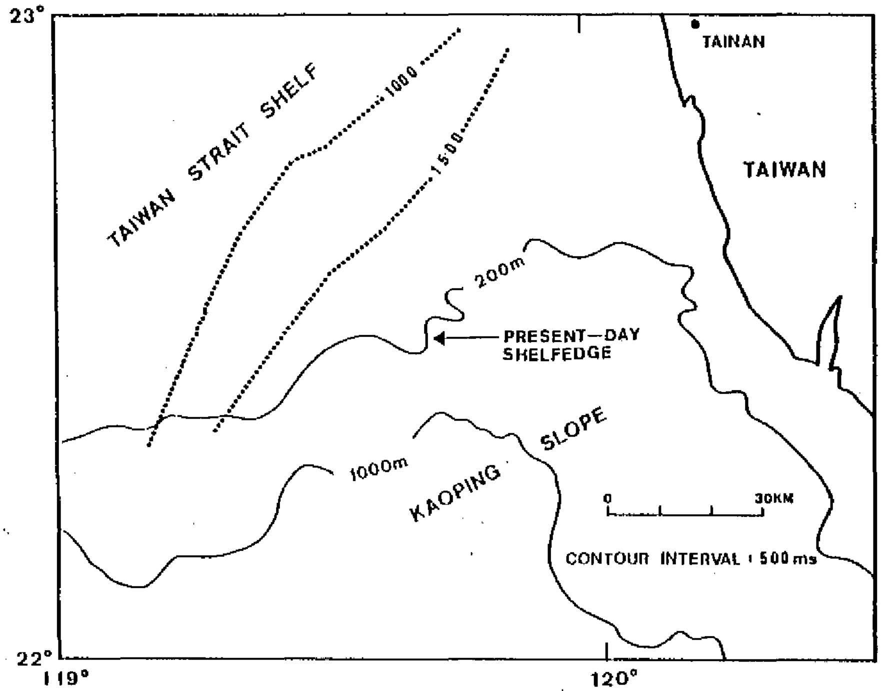

Fig. 8. The structure-contour map showing that the Pleistocene base dips oceanwards with an average dip angle of 2.2 *degrees* along the coastline of Mainland China. Note the present day upper slope (200 ~ 1,000 *m* depths) is shown for reference of geographic position. The gradients of upper slope range from 2 to 3 *degrees*.

and Pleistocene sequences are mainly platform facies deposited on the shallow continental shelves; later these sequences have tilted and deepened through the evolution of the passive South China continental margin. The paleo-shelfbreaks of Pliocene and Pleistocene sequences were probably situated farther away from today's shelf edge.

4. VELOCITY ANALYSIS

Velocity measurements are commonly used to determine the lithology of the strata, for example, Gardner and others (1974) pointed out that there exists a close relationship between interval velocity, rock density and lithology. Although well data and published stratigraphic studies indicate that the late Tertiary strata of the Tainan basin are mainly composed of sands and shales, it is used here to examine the properties of seismic velocity within the sequence units and to discuss the relationship between lithology and seismic velocity.

Estimates of interval velocity using Dix's Formula (Dix, 1955) is carried out for construction of velocity models for the late Cenozoic sequences. This method depends heavily on the accurate determination of the stacking velocity.

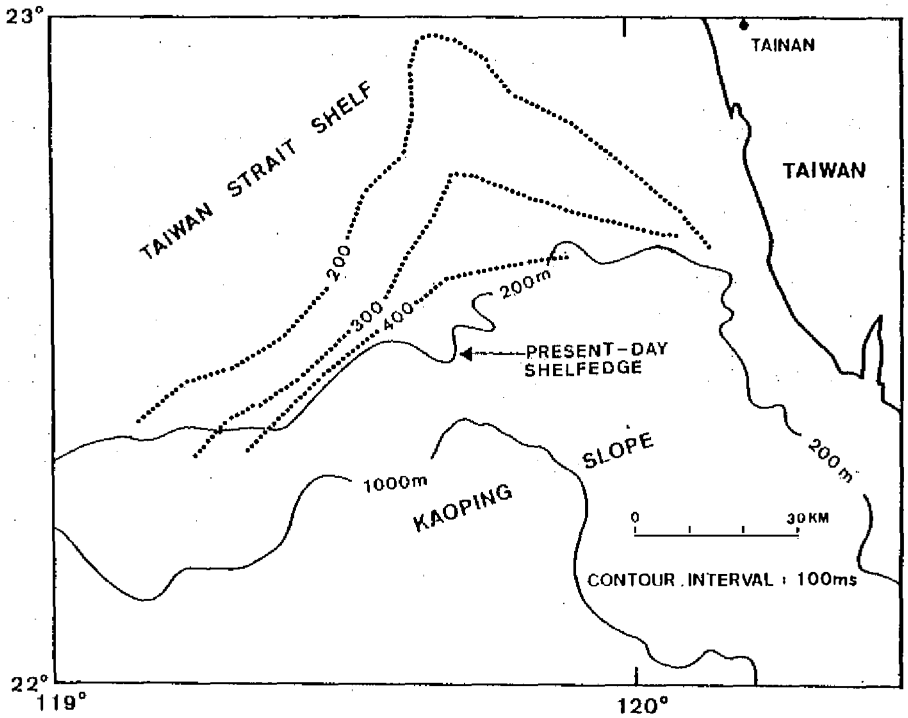

Fig. 9. The structure-contour map of today's sea floor. The structural contours of sea floor dip in two directions. The general trend curves which implies structural control of the uplift of Taiwan in Recent times. Note the present day upper slope (200 ~ 1,000 *m* depths) is shown for reference of geographic position. The gradients of upper slope range from 2 to 3 *degrees*.

For example, the velocity spectrum of the CDP 6770 (line 3) shows that deep reflectors have relatively broad velocity contours and result in poor estimates of the stacking velocity (Fig. 10). We understand that the quality of velocity determination is limited by the short distance of the offset (max 700 *m*) in our 24 channel acquisition system.

Interval velocity models are prepared for the seismic sections in order to examine vertical variations in velocity. For instance, velocity models for dip line 2 and strike line 7 are shown in Fig. 11. In general, the interval velocity of the sequences range from 1,800 *m/sec* to 4,000 *m/sec*. The Pliocene sequence is characterized by interval velocities ranging from 2320 *m/sec* to 3,520 *m/sec*. Interval velocities of the Pleistocene fall in an interval of 2,020 to 2,470 *m/sec*. As expected the values of the interval velocity indicate that the lithology of late Cenozoic strata in the study area is dominated by sandstones and shales as determined from Gradner's graph of velocity-density relations in rocks of differing lithology.

Vertical distribution of the interval velocity indicates that the older under-

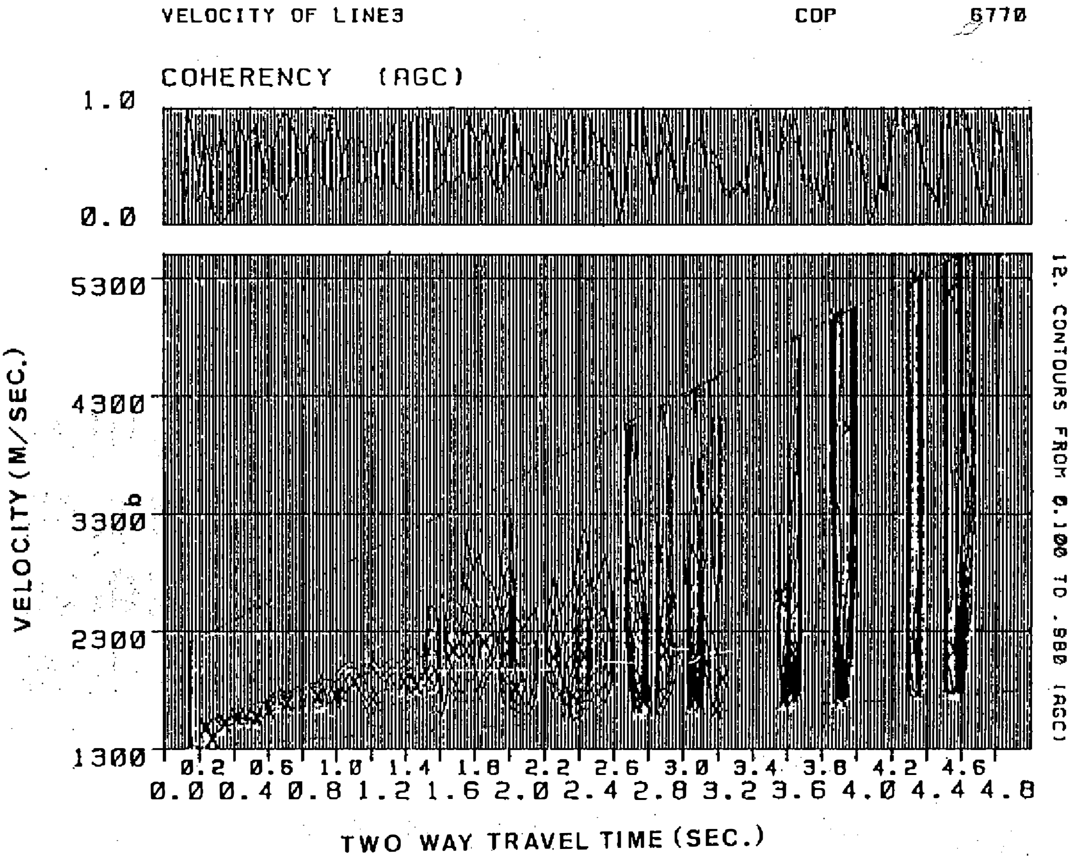

Fig. 10. A velocity spectrum showing the deep reflectors have relatively broad velocity contours and result in poor estimate of the stacking velocity.

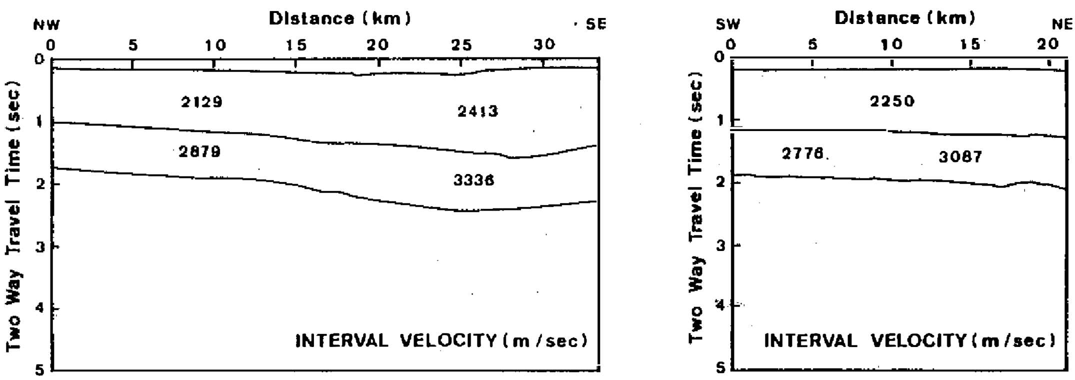

Fig. 11. The velocity models for the dip line 2 at left and strike line 7 at right. Vertial distribution of velocity shows that the velocity increases with depth. The interval velocities range from 2130 m/s to 3340 m/s indicating the lithology probably comprising sands and shales.

lain Pliocene sequence has an interval velocity greater than that of the younger and overlying Pleistocene sequence. This suggests that the seismic velocities of the late Cenozoic sequences for the Tainan basin respond mainly to the compaction (depth of burial) because the velocity of most Tertiary clastic rocks generally increases with depth due to compaction (Sheriff, 1980). Thus the late Cenozoic sequences in the study area follow similar trends to that of most Tertiary clastics. It is realized that this velocity interpretation is preliminary. Further detailed velocity analyses will be performed in the future.

5. SEISMIC FACIES ANALYSIS

Based on the seismic criteria for interpretation of the depositional framework of clastic facies units (Sangree and Widmier, 1977; Brown and Fisher, 1979), the seismic facies for the Pliocene and Pleistocene sequences are mapped. In order to map the distribution of the seismic characteristics of the sequences, the fractional code used for seismic facies mapping (Ramsayer, 1979; Kirk, 1985) is applied here. The basic elements of the fractional code include the upper boundary character (A), the lower boundary character (B) and the internal reflection character (C) of a seismic sequence which are abbreviated and plotted on a map as $\frac{A-B}{C}$. The most common seismic reflection patterns in the study area are shown in Fig. 12.

Seismic facies for the Pliocene sequence are shown in Fig. 13 for which three groups of seismic facies are recognized :

(1) Area I is characterized by the $\frac{T-O}{D}$ pattern and distributed mainly in the northwestern part of the seismic survey area (line 3).

(2) Area II is characterized by the $\frac{C-C}{P}$ pattern and distributed in the central and eastern parts of the seismic survey area.

(3) Area III is characterized by the $\frac{T-C}{CHF}$ and $\frac{T-C}{SUBP}$ patterns and distributed in the western part of the seismic survey area.

It is noted that the Pliocene sequence is mainly represented by parallel and subparallel reflections which are commonly characterized by high to medium amplitudes and good continuity.

A seismic facies map of the Pleistocene sequence is shown in Fig. 14 of which four groups of seismic facies are recognized:

(1) Area I is characterized by the $\frac{T-O}{D}$ pattern and distributed in the northwestern part of the seismic survey area.

(2) Area II is characterized by the $\frac{T-C}{CHF}$ pattern and distributed in the northeastern part of the seismic survey area.

(3) Area III is characterized by the $\frac{T-C}{D}$ pattern and distributed in the central part of the seismic survey area.

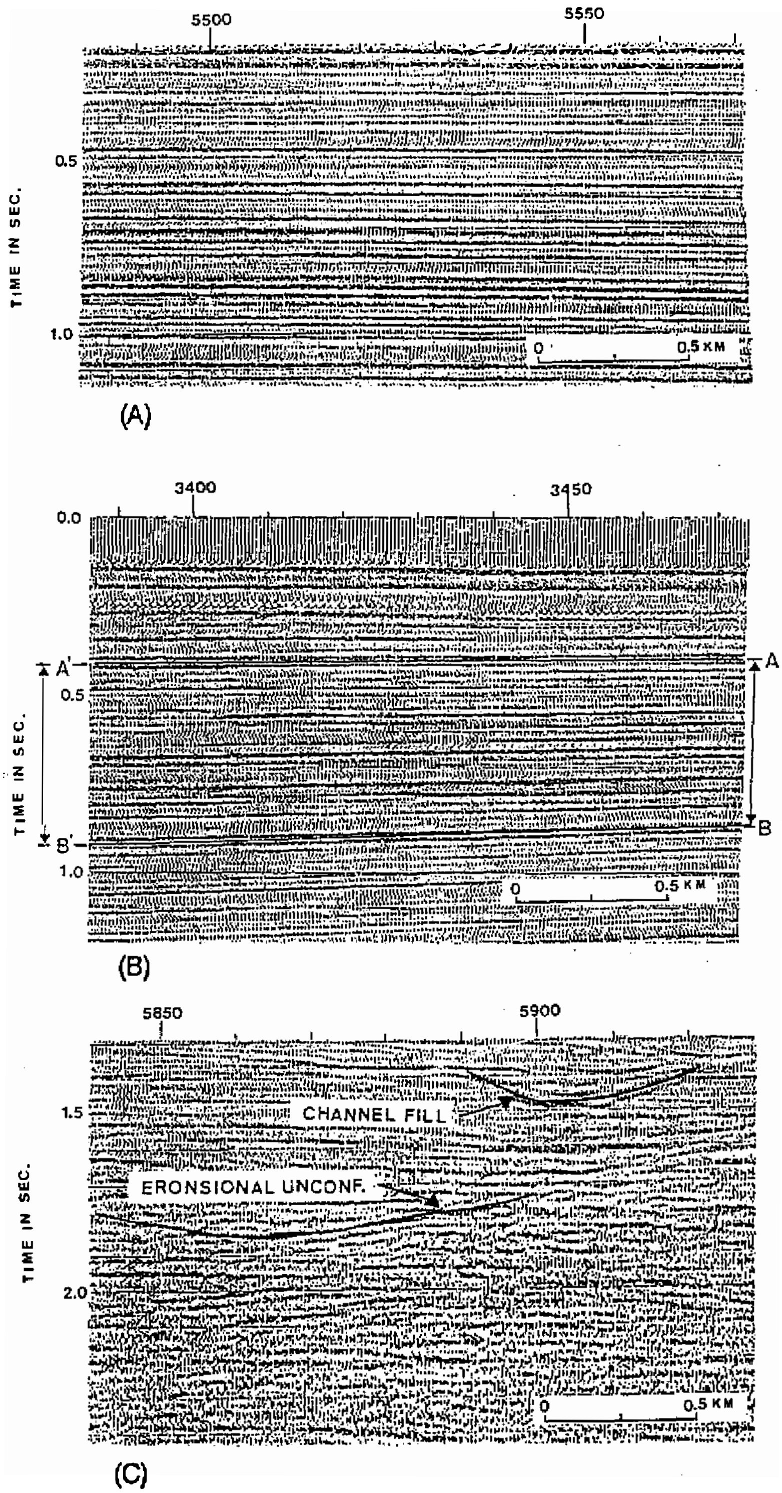

Fig. 12. Three common seismic reflection patterns: (A) parallel, (B) divergent and (C) erosional truncation are recognized in the late Cenozoic sequences in the study area.

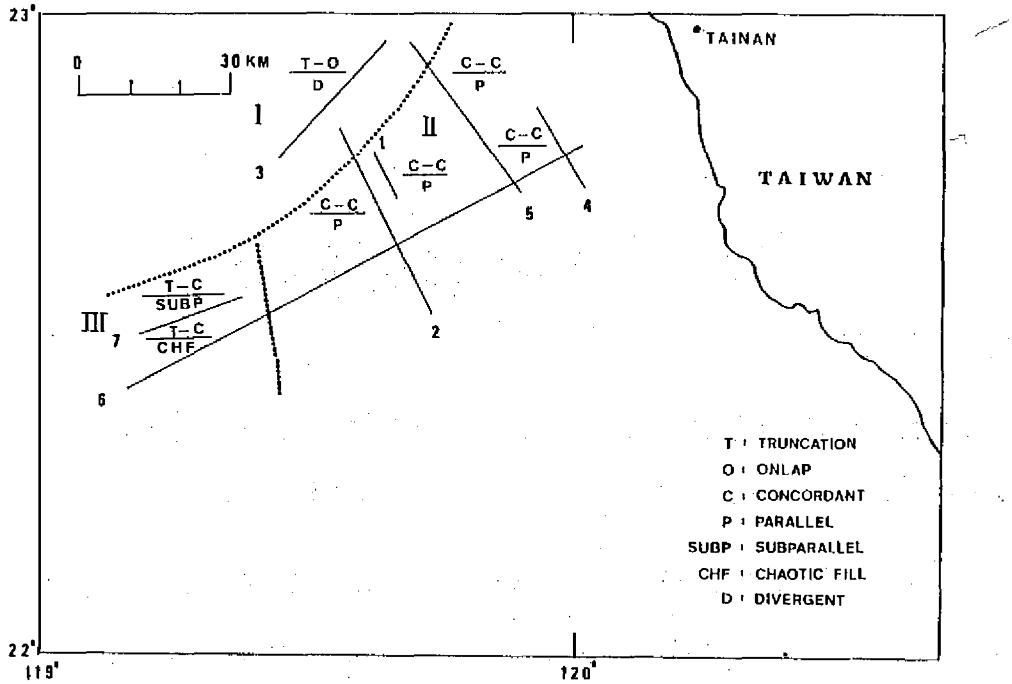

Fig. 13. Seismic facies of the Pliocene sequence is expressed in the fractional code pattern. The Pliocene sequence is mainly represented by the parallel and subparallel reflections with high to medium amplitudes and good continuity.

(4) Area IV is characterized by the $\frac{T-C}{P}$ pattern and distributed in the western part of the seismic survey area.

In general, the Pleistocene sequence is mainly represented by divergent reflections which are commonly characterized with strong to weak amplitudes and good to fair continuity.

In terms of regional stratigraphic interpretation, specifically, determining the depositional environment, the characteristic parallel or subparallel patterns suggest that late Cenozoic sediments of relatively uniform sedimentation rates accumulated on the shelf. The divergent configurations and the wedge-shaped external forms suggest that lateral changes in depositional rates for shallow-water shelf facies and progressive tilting of the late Cenozoic sequences. Strong and continuous reflections for parallel configurations imply nearshore environments for the late Cenozoic sequences in the study area; and the subparallel pattern, strong and discontinuous reflectors and erosional truncations suggest fluvial-nearshore environments. However, it is premature to further determine the subenvironments of the shelf facies within the sequences without available core samples or detailed representations of well logs to serve as necessary constrains for determination of depositional environments.

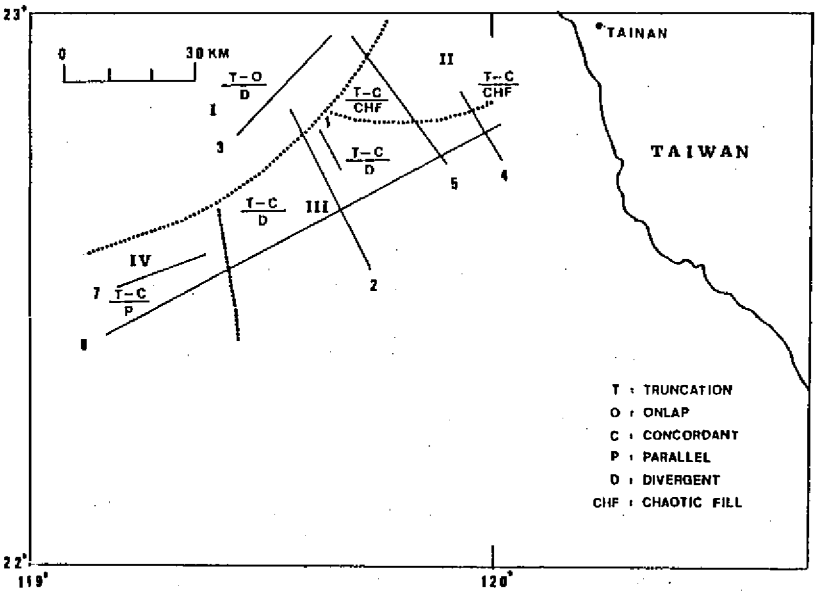

Fig. 14. Seismic facies of the Pleistocene sequence is represented by the fractional code pattern. The Pleistocene sequence is characterised by divergent reflections with high to medium amplitudes and fair to good continuity.

6. CONCLUSIONS

Preliminary analyses of seismic sequences, seismic facies and velocity indicate that the Pleistocene and Pliocene sequences form as a thick clastic wedge. The sequences are parts of the South China continental margin which has undergone tilting and subsiding during the past ten million years or more. Further determination of the shelf facies subenvironments for the sequences and reconstruction of the paleo-geography of the sequences by locating the positions of the paleo shelfbreaks are needed to better understand the nature and development history of the late Cenozoic sequences within the Tainan basin. Clearly, systematic seismic surveys over the study areas will be pursued in the future.

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台灣西南外海台南盆地新生代後期地層之震波地層學研究

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摘要

本研究以震波地層學來討論台灣西南外海台南盆地新生代後期地層之性質及其發展歷史。總共在海上作業完成參佰多公里長的多頻道震測剖面，其中有四條傾角測線，三條走向剖面，其品質介於尚可與優之間。

由震波剖面確認新生代後期地層具有相當地整一性，並定出更新世及上新世的震波序列。新生代後期地層之震波結構特徵爲平行、次平行及發散狀。平行震波結構意謂著具有相當一致沈積速率的淺海沈積物，堆積在研究區域的大陸棚上，而發散結構及楔形的外觀指出陸棚上之部份沈積相其沈積速率有側向變化及漸進的向外海傾斜。震波相分析指出，新生代後期之沈積物主要在近海環境生成。上新世及更新世之區域構造代表著相當平緩的大陸棚部份而無明顯的棚－坡分界點。上新世及更新世之棚－坡分界點推測應遠於現今大陸棚界之位置。

由震波速度模式得知層速度介於 1,800 公尺／秒及 4,000 公尺／秒之間，推測新生代後期地層以砂、頁岩爲主。層速度的縱向變化指出速度隨著深度而增快，爲反應壓實作用（深埋作用）。

由震波序列、震測相及速度分析結果認爲，上新世及更新世兩個沈積序列發展成一個楔形碎屑沈積岩體。其爲中國南部大陸邊緣的一部份，自壹仟多萬年以來，持續受大陸邊緣傾斜及下陷作用影響。