STRATIGRAPHIC AND STRUCTURAL ANALYSES
OF THE PENYU BASIN, MALAYSIA

By

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PREFACE

This thesis is primarily a general survey of the stratigraphic and structural frameworks of the Tertiary Penyu basin in the South China Sea. In the study, concepts of plate tectonics are utilized to explain basinal evolution, not only of the Penyu basin but also of other basins of the region. Of significant importance in terms of hydrocarbon potential is a thick development of a sedimentary section in the basin.

The author would like to express his most sincere gratitude to the Government of Malaysia for sponsoring a program that made it possible for him to pursue graduate training at the Oklahoma State University and to his colleagues at the Geological Survey of Malaysia for their continuous encouragement.

The author extends to CONOCO his sincere gratitude for providing for this study company reports on the Penyu and Pari wells, seismic profiles, and base maps used in exploration of their offshore concession off the coast of the Peninsula Malaysia. In addition, CONOCO made the final drafting of isopach and structural maps and reproduced the illustrations. A special thanks, therefore, goes to Dr. Arthur O. Beall, Jr., as the company representative and adviser, who not only has provided the data but also has been very generous with his time in making criticisms and suggestions during all phases of the study.

Consistent guidance was received from Dr. John W. Shelton from the time the study was in its embryonic stage to the final phase of writing.

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CHAPTER I

ABSTRACT

The Penyu basin is a complex, intracratonic basin on the northern Sunda Shelf. The basin formed during Oligocene when the region was under influence of extensional stresses caused by arching effect of the continental plate. The basin is characterized by numerous faults which trend east and/or southeast. Most faults were contemporaneous with deposition, and four of them, Faults "A", "B", "C", and "D" define the extremities of the basin. Because the faults are thought to have formed under similar tectonic stress fields, the different trends may represent the influence of older structural elements and of basement composition.

Basinal subsidence began during Oligocene, and continental units, representing the initial phase of sedimentation, are more than 12,000 feet thick in the deeper part of the basin. Active subsidence of the basin continued during deposition of 6000 to 10,000 feet of coastal sediments, which are as young as Late Miocene. Transgressions were widespread during Pliocene to Recent when some 2000 feet of marine units were deposited.

Folds and domal features, which are numerous within the basin, and some faults were formed by differential basinal subsidence, differential compaction, mild compressive stress, reverse sense of fault movement, and/or paleotopography.

Much of the younger sediments, particularly at the Pari well area, represent immature source rock. However, in areas of thick development of sediments, some 10,000 feet is within the liquid window. Generation of hydrocarbons is possible at depths below 12,000 feet.

Folds and domal features together with stratigraphic pinch-outs and unconformities provide abundant traps for hydrocarbons.

CHAPTER II

INTRODUCTION

Location

The area of study is part of the South China Sea, or the northern Sunda Shelf, east of the Peninsula Malaysia between 2° 30' and 4° 45' north latitude and 103° 18' and 105° 00' east longitude. It comprises an area of about 16,000 sq. miles (Fig. 1). The Penyu basin, which is defined by total thickness of sediment greater than 5000 feet, is the westward extension of the Boundary trough, also known as the West Natuna basin (Fig. 2).

Previous Investigations

Regional Studies

Knowledge of regional geology of the northern Sunda Shelf prior to 1960 was confined to the work of van Bemmelen (1949). When the interest for petroleum began to focus upon the area 10 to 15 years ago, extensive geophysical and geological investigations of both offshore and onshore areas were undertaken by oil companies, educational institutions, and government agencies. As a part of these studies, the Geological Survey of Malaysia has conducted reconnaissance and detailed geological mapping of the mainland and the offshore islands, where different rock types and lithologies range in age from Cambrian to

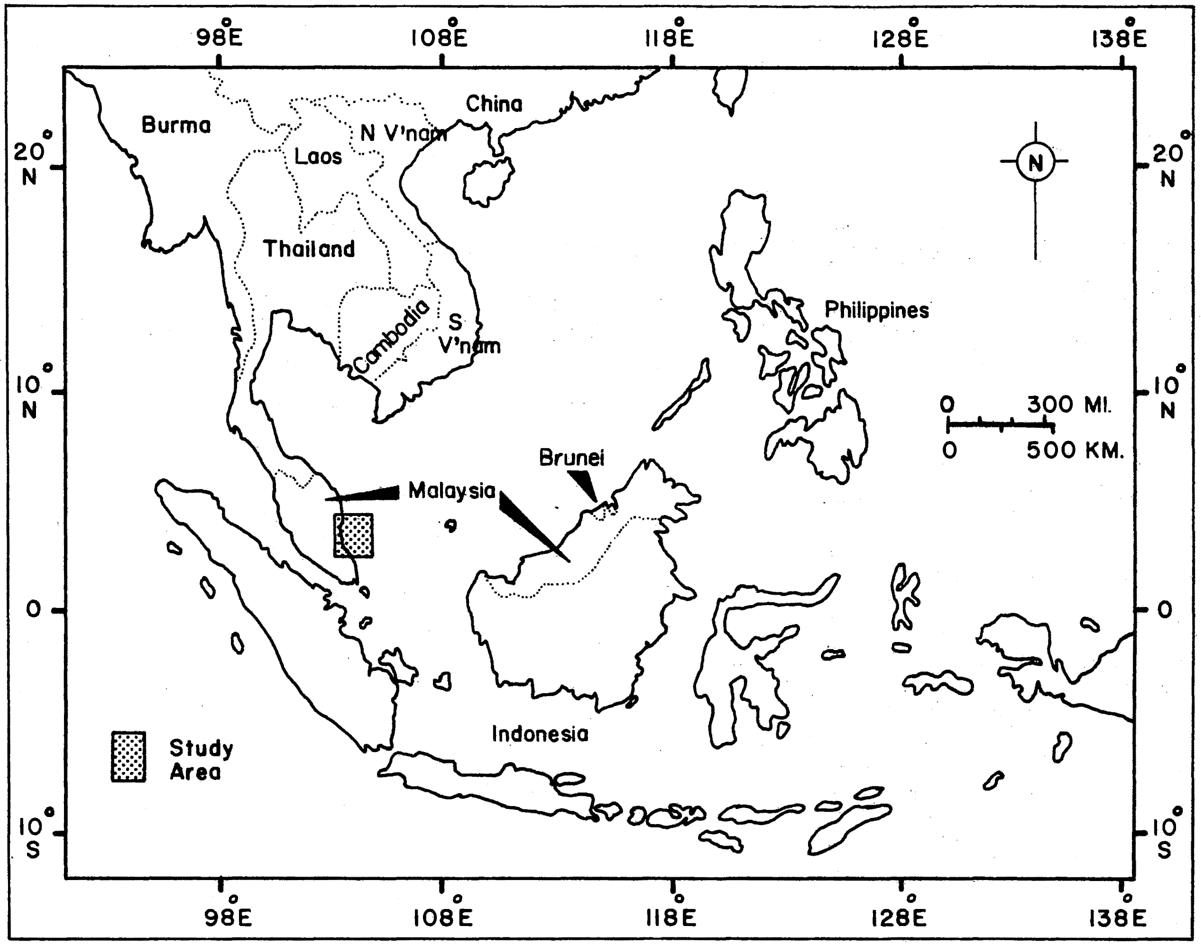


Fig. 1. - Index map of Southeast Asia showing location of the study area.

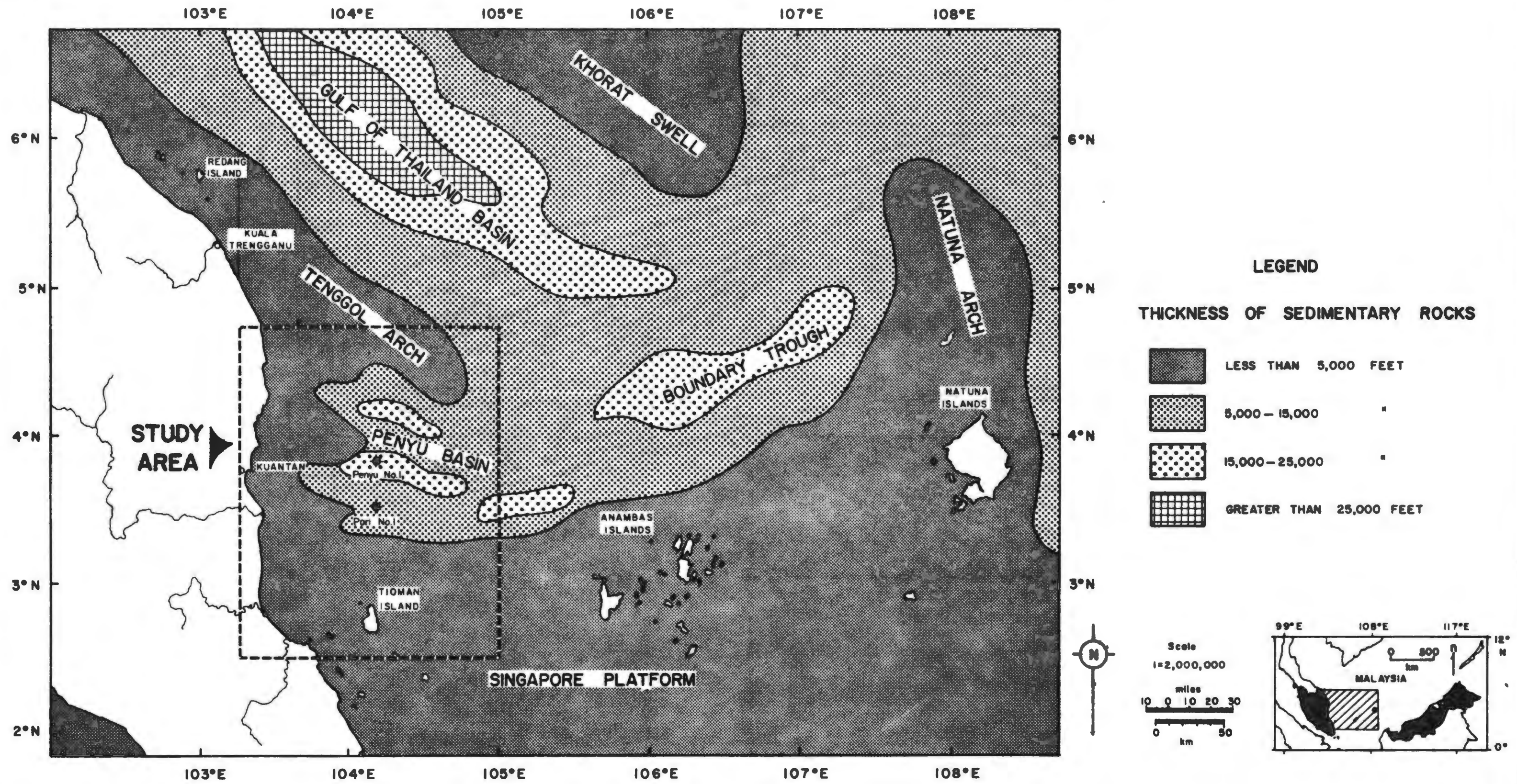


Fig. 2. - Generalized thickness of sedimentary rocks in Tertiary basins between the mainland (Malaysia) and Natuna island (Indonesia), modified in part after unpublished CONOCO report and Haile (1973).

Recent. Of interest to the petroleum industry are the relatively undisturbed Jurassic-Cretaceous sedimentary rocks on the mainland, which were deposited in a fluvio-deltaic-lacustrine environment (Senathi Rajah, 1969) (Fig. 3).

Haile (1970, 1973) conducted geological studies of the Tambelan, Anambas, and Natuna islands and noted the occurrences of igneous rocks and metasediments of Jurassic-Cretaceous age and unmetamorphosed Tertiary sediments (Fig. 3).

Parke *et al*. (1971) determined the regional structural framework of the northern Sunda Shelf from continuous seismic and magnetic surveys. They mapped three major sedimentary basins where sediments exceed 7000 feet in thickness. The basins are Gulf of Thailand basin, which includes the Gulf of Thailand basin proper, the Boundary trough, and the Penyu basin (Fig. 2), Mekong basin, and Brunei-Saigon basin. Ridge- or swell-like features separate the basins, and folds, faults, unconformities, and diapiric structures are present within them. Parke *et al*. (1971) suggested that these basins were formed during Late Cretaceous.

Dash *et al*. (1970, 1972), using seismic reflection and refraction methods, made similar geophysical studies in the vicinity of Natuna and Tioman islands.

Ben-Avraham *et al*. (1973), from geophysical analysis of the regional structural framework of the entire Sunda Shelf, recognized three major structural units: the northern Sunda Shelf basinal areas, the Singapore platform, and the Java Sea basinal areas. They also indicated that the distribution and shapes of the basins are determined by numerous faults.

Hutchison (1973), Katili (1971, 1973), Pupilli (1973), and Murphy (1974) tectonically analyzed the region and proposed geological evolution of the Sunda Shelf and the Indonesian island arc in the framework of plate tectonics. Murphy (1974) further proposed that Sunda Shelf basins have continental crusts. Achalabhuti (1974) is of the opinion that crustal units forming the basement rocks of the basins consist of granitic and metasedimentary rocks of Mesozoic and/or Late Paleozoic age.

Local Studies

Intensive geophysical investigations have been conducted by a group of companies, with CONOCO as operator, in the Penyu basin and the nearby areas during the last 7 years. These investigations were culminated with the drilling of two wildcat wells, CONOCO Penyu No. 1, reaching a depth of 8823 feet, and CONOCO Pari No. 1, with total depth of 7315 feet.

Objectives

The major objective of this study is to determine the stratigraphic and structural frameworks of the Penyu basin, utilizing isopach maps, structural maps, and structural cross sections. Data utilized in the study are:

1. Sixteen continuous seismic reflection profiles providing fairly uniform areal coverage (Fig. 4).
2. Unpublished reports on two wildcat wells, CONOCO Penyu No. 1 and CONOCO Pari No. 1.

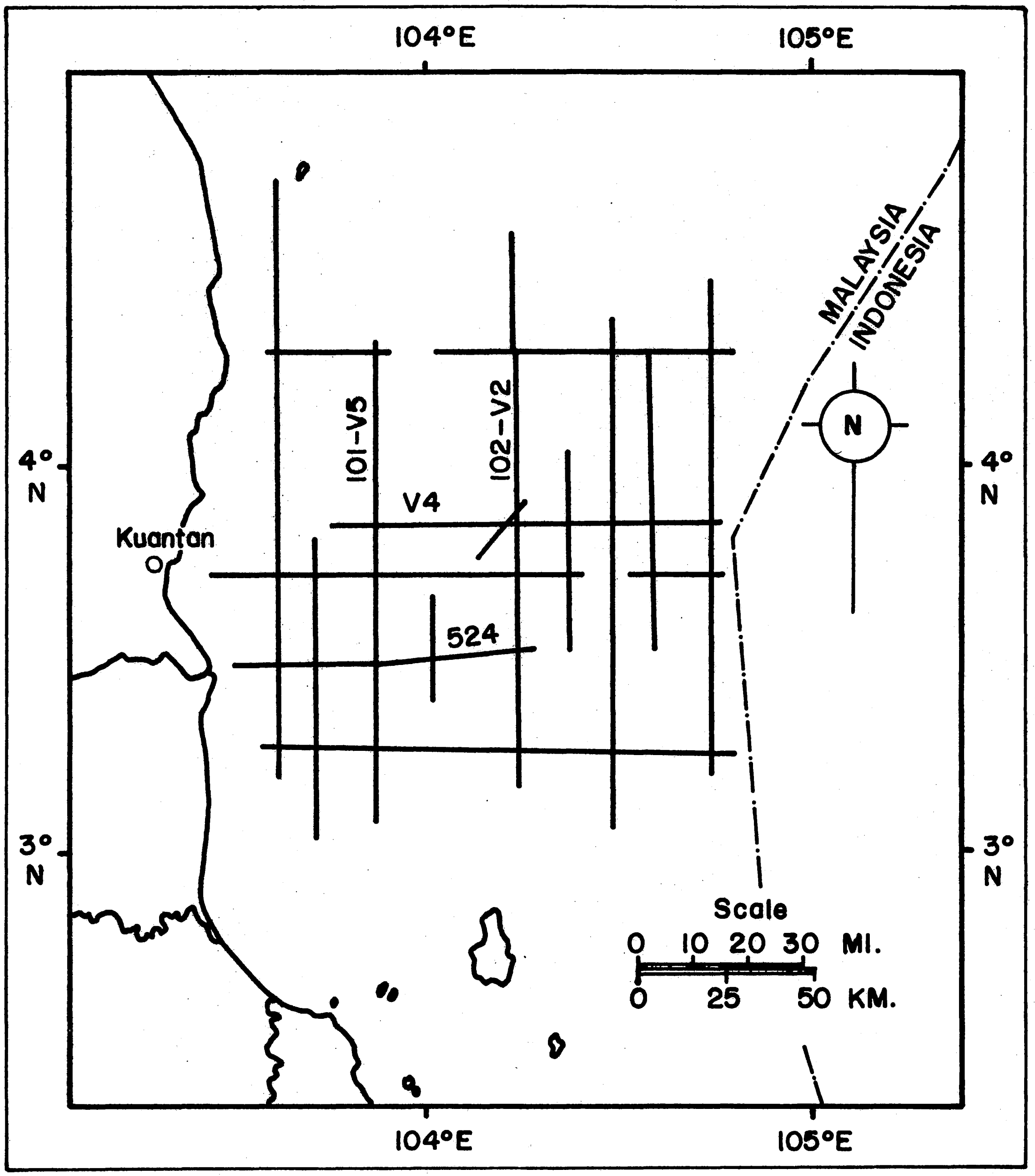


Fig. 4. - Index map of the Penyu basin showing locations of selected seismic lines. Numbered lines correspond to locations of key structural cross sections.

3. Published reports and maps representing regional studies of the Sunda Shelf and mainland.

A secondary, corollary objective of the study is to evaluate, on the basis of source-rock studies, the hydrocarbon potential of the basinal area.

Methods

After three prominent unconformities were recognized from electric, sonic, and lithologic logs of the Penyu and Pari wells, they were correlated with prominent acoustic reflections on seismic profiles along which the wells were drilled. These acoustic reflectors were then correlated and traced along the other seismic profiles which form a grid pattern (Fig. 4).

The quality of these reflectors varies considerably, and to aid in assessing the reliability of results, the reflector qualities have been arbitrarily classified into two categories: poor-to-fair and good-to-excellent (Figs. 5-7). In the first category, seismic signals are generally weak and diffuse, and in many cases they present some difficulties in the identification of reflectors and in determination of their continuity. Where such characteristics exist, the selection of reflectors is considered somewhat questionable. The second category represents much stronger and more intense seismic signals, and the selection of reflectors is considered reliable.

The subsea elevations of the three seismic reflectors were estimated by conversion of two-way transit, or reflection, time. The average curve of time-depth data from the two wells was used to determine the true depth of the seismic reflectors (Fig. 8). It is assumed

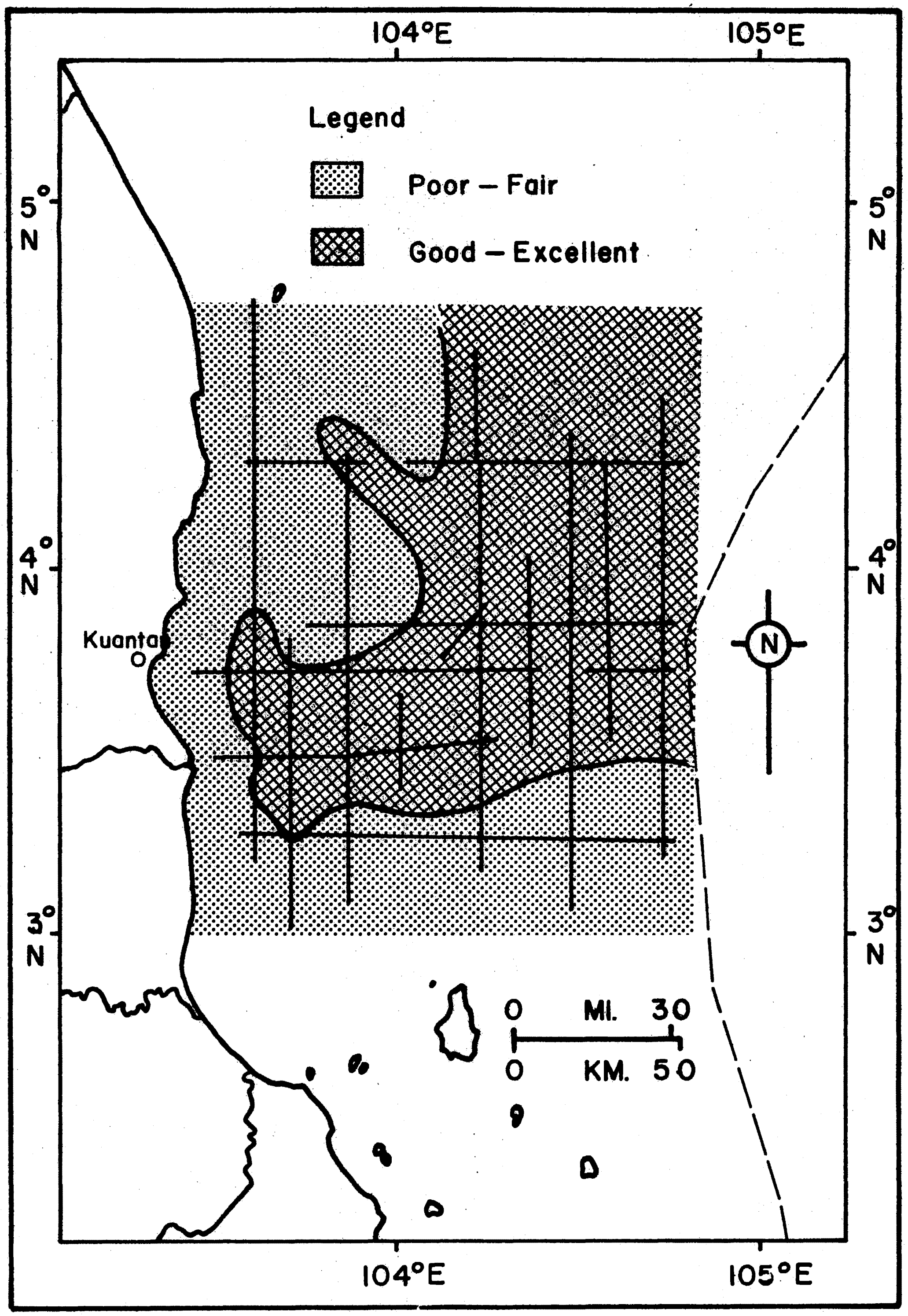


Fig. 5. - Quality of Reflector I, Penyu basin.

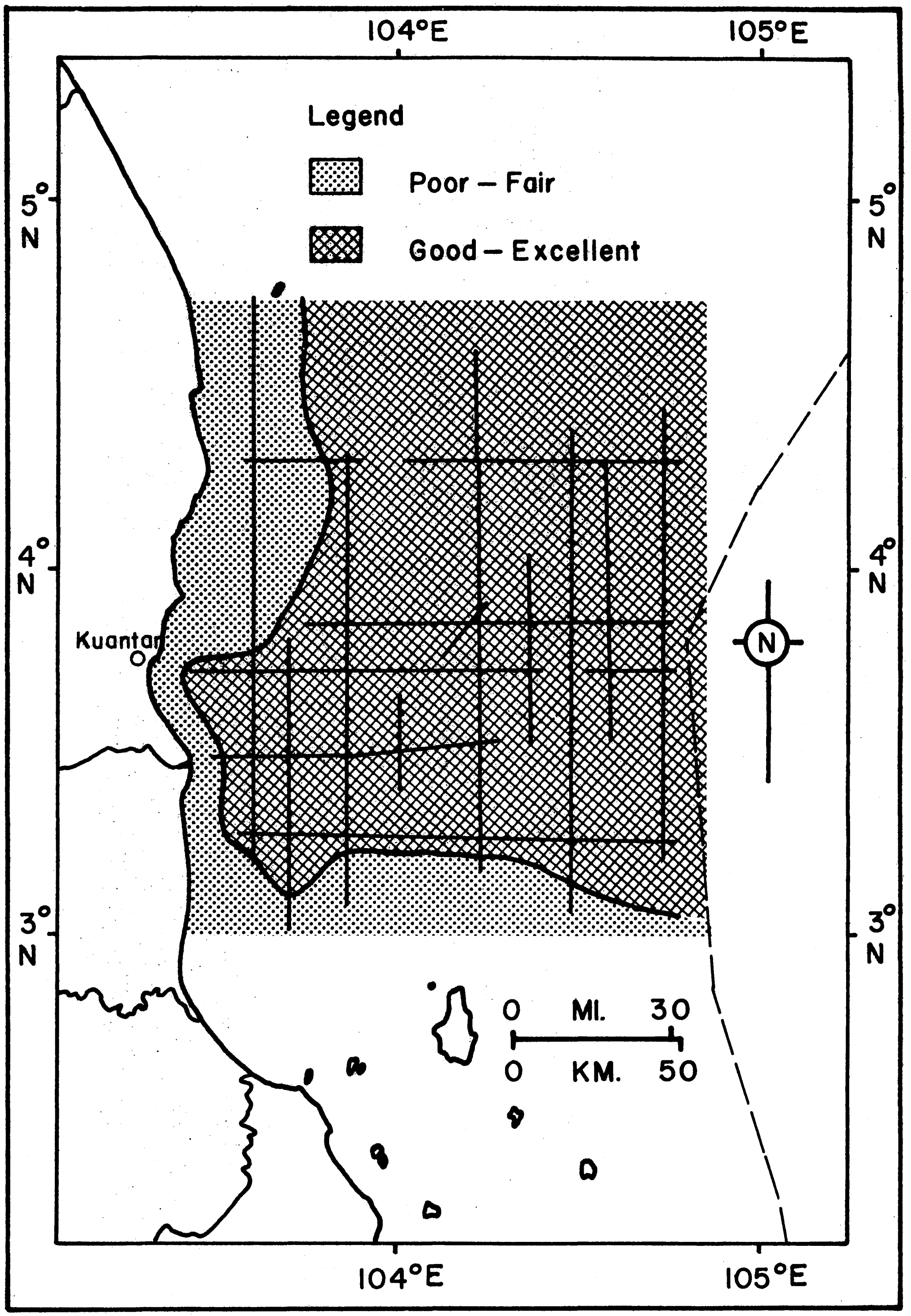


Fig. 6. - Quality of Reflector II, Penyu basin.

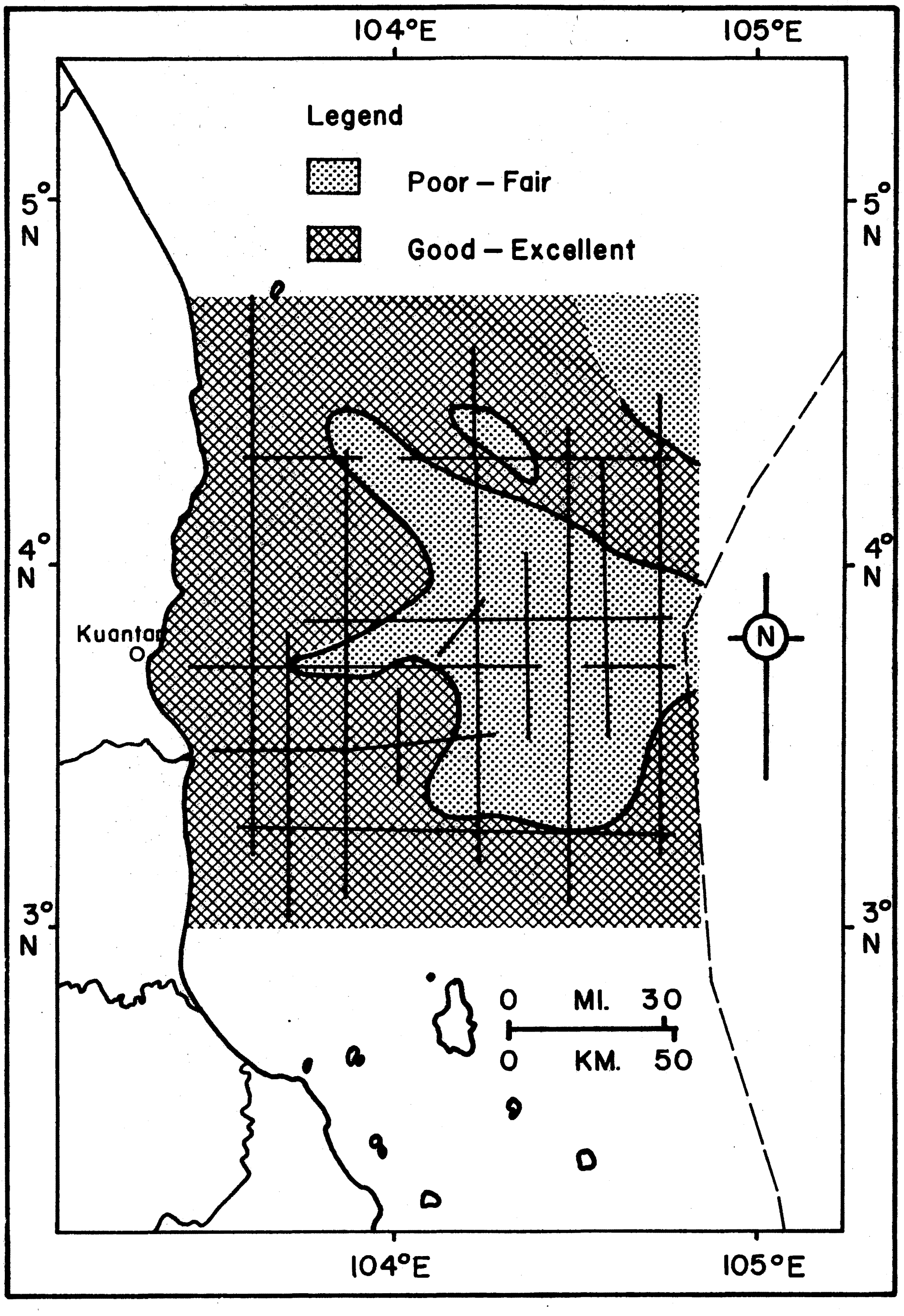


Fig. 7. - Quality of Reflector III, Penyu basin.

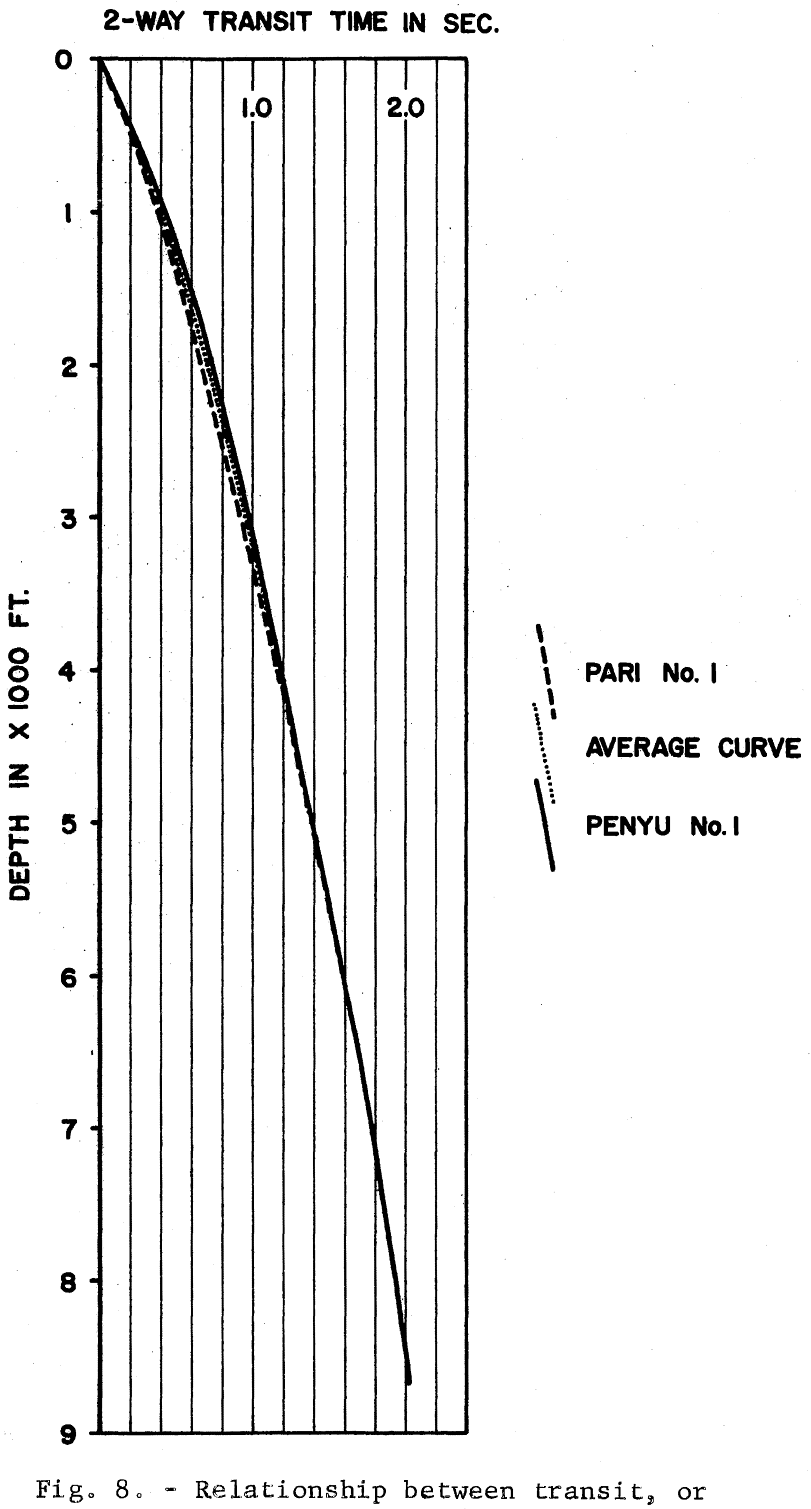


Fig. 8. - Relationship between transit, or reflection, time and depth, CONOCO Penyu No. 1 and CONOCO Pari No. 1.

that velocity of 13,300 feet/sec. within the sedimentary section at a depth of 8000 feet remains constant with depth.

The elevations of the three reflectors were utilized in preparing two isopach and two structural maps. Four structural cross sections were constructed along key seismic profiles.

Interpretation of environments of deposition was made primarily from various well data and secondarily from the regional stratigraphic framework.

CHAPTER III

STRATIGRAPHY

Seismic Reflection Profiles

The acoustic stratigraphy of the Penyu basin is characterized by three prominent and regionally traceable reflectors. These acoustic reflectors, designated informally as Reflectors I, II, and III in descending order, are correlatable with three unconformities recognized at CONOCO Penyu No. 1 and CONOCO Pari No. 1 wells. Because continuity of these reflectors generally is remarkably good, they apparently represent regional erosional surfaces.

Reflector I

Reflector I is generally less prominent than the other two reflectors. It is remarkably flat, although slight arching is present in the central part of the basin (Figs. 9-12). No fault is known to offset the reflector.

The thickness of the sedimentary column between the reflector and the sea bottom ranges from approximately 1000 feet on the west side of the basin to 2000 feet near the basinal center. Short-range foraminifera identified in the section suggest that the reflector represents the boundary between Upper Miocene and Pliocene units.

Reflector II

This reflector represents a very prominent reflecting surface which can easily be identified and traced. Based on the identification of microfossils, the reflector corresponds to an unconformity separating upper Middle and Upper Miocene beds.

The subsea elevations of the reflector at the Penyu and Pari wells are 7400 feet and 5400 feet, respectively. Depths within the basin range from 1000 feet on the west and south flanks to 11,000 feet in the center of the basin (Fig. 13); maximum thickness between Reflectors I and II is about 9000 feet (Fig. 14). Sharp changes in thickness of the interval in parts of the basin are caused by differential basinal subsidence during active sedimentation (Figs. 9-12).

Reflector III

This reflector apparently represents a surface which separates intervals of contrasting lithologies and ages. The base of basinal fill corresponds to this reflector (Figs. 9-12). It appears from structural profiles that both brittle and ductile materials (granitic and metamorphic rocks of Paleozoic and/or Mesozoic age) constitute the basement rocks.

Depth of the reflector is approximately 1000 feet on the west and southwest flanks of the basin and about 22,000 feet in the center (Fig. 15). On some seismic profiles sharp changes in elevation may involve as much as 11,000 feet.

Two sub-basins of the Penyu basin are recognized from the thickness of sediments between Reflectors II and III, which is greater than 12,000 feet (Fig. 16).

Borehole Data

The sedimentary section of the basin is divided informally into Sequence C, Sequence B, and Sequence A, in ascending order. Each sequence corresponds to a seismic interval (Fig. 17). The lithologic features and ages of the sequences are based on unpublished CONOCO data and reports.

CONOCO Penyu No. 1

Sequence C. The sequence is partially represented by the interval from 7400 feet to total depth at 8823 feet. The lithology of sedimentary units beneath the unconformity corresponding to Reflector II is predominantly siltstone, with red or multicolored mudstone and fine-grained, argillaceous sandstone, units of which are generally very thin (Fig. 18). Quartz, micas, carbonaceous material, feldspars, and rock fragments are common constituents of the siltstone and sandstone units, and carbonate and clay minerals are present as common matrix materials. Plant fragments of indeterminate types have been noted. The occurrence of one specimen of *Cicatricosisporites* cf. *dorogensis*, which is virtually restricted to Upper Cretaceous and older sediments (Muller, 1966), has been noted, and on the basis of this specimen, the age of the sequence initially was tentatively considered to be Late Cretaceous. However, Oligocene-to-Early Miocene is thought to be the probable age of the sediments. Tertiary volcanic tuffs and flows, such as the Kuantan and Segamat basalts in scattered exposures on the mainland and the Midai volcanics on the Sunda Shelf (Fig. 3), are not present in the section. Because unpublished data indicate that Oligocene volcanics

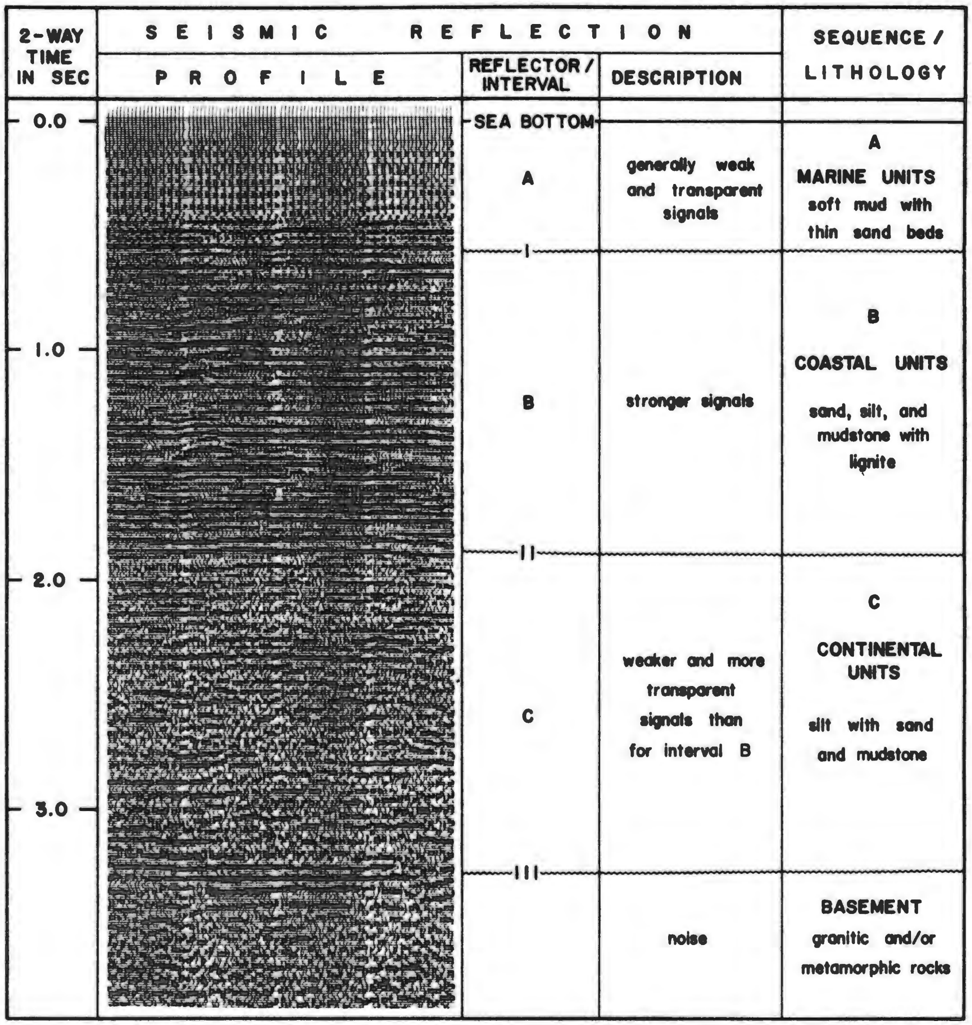


Fig. 17. - Typical seismic profile of the Penyu basin relating reflectors and general lithofacies.

are present northeast of the study area and because no volcanics were encountered in the Penyu well, sediments below the unconformity, Reflector II, are thought to be Late Tertiary in age, probably Early Miocene. Sequence C represents a thick sedimentary section, and the age of the sequence is probably Oligocene to Early Miocene. The solitary specimen in the Penyu well is therefore considered to be reworked.

Sequence B. Lithologies representing this sequence at a range in depths of 1500 to 7400 feet include interstratified coarse- to fine-grained sand, silt, multicolored mudstone, and lignite beds (Fig. 18). Lignite units are well developed between 2000 to 4000 feet. Sand units, which consist primarily of quartz, are generally coarser grained and better sorted in the upper part of the sequence than in the lower part.

Age of the sequence is based on numerous occurrences of Florschuetzia levipoli, which is a Medial to Late Miocene pollen.

Sequence A. The predominant lithology of this sequence, represented by the 1100 feet between depths of 400 and 1500 feet, consists of gray to brownish gray, poorly laminated and unconsolidated mud, with minor development of silt and sand units (Fig. 18). Several species of foraminifera have been identified within the section. Cribrolinoides curta, the most diagnostic short-range foraminifer, indicates a Pliocene-Recent age.

CONOCO Pari No. 1

Basement. Basement rock, encountered at 7100 feet and penetrated for 215 feet to total depth at 7315 feet, is composed predominantly of

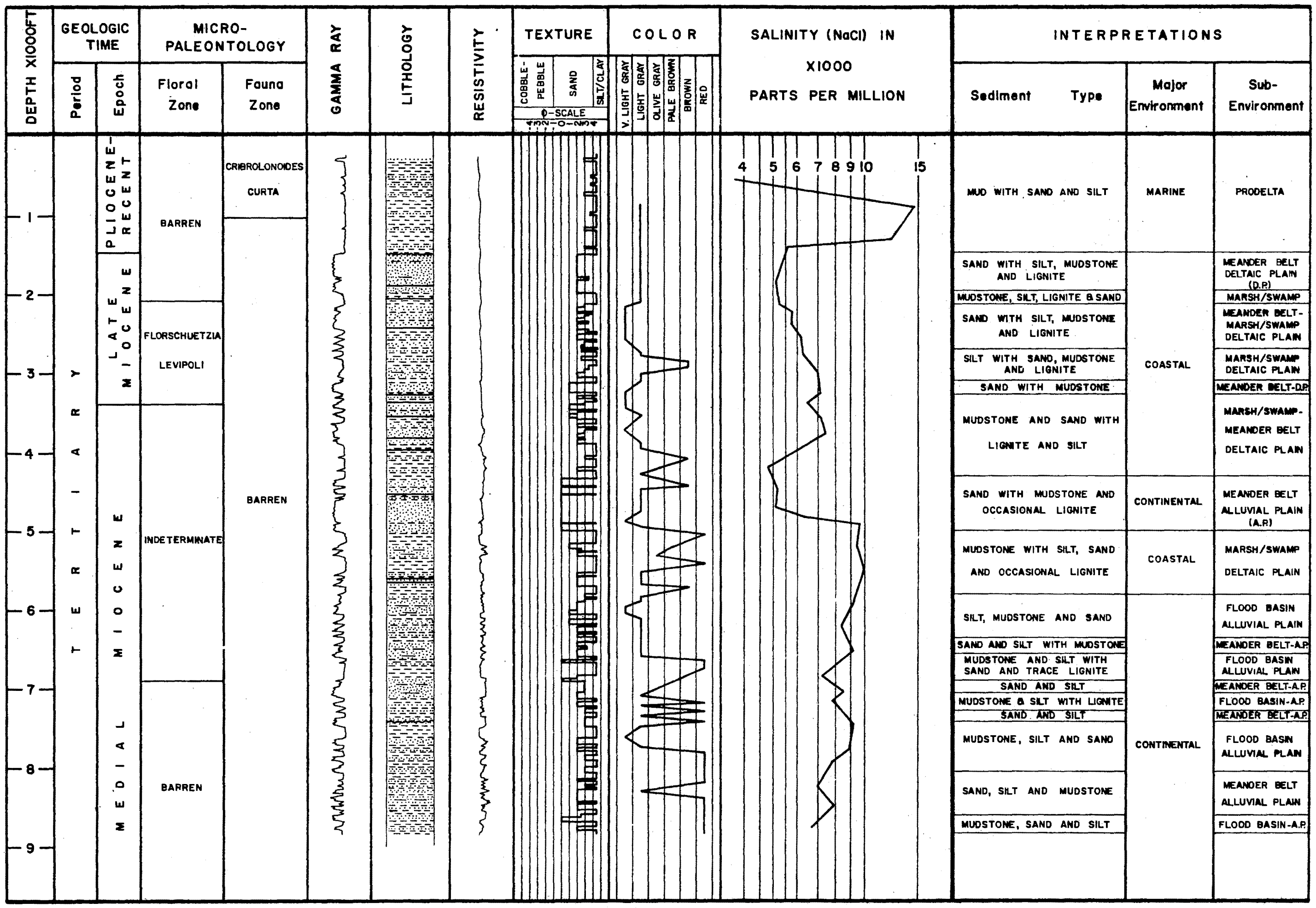


Fig. 18. - Interpretive log of CONOCO Penyu No. 1.

dark gray, calcareous argillite, dissected by numerous calcite veinlets. Petrographically, the rock is primarily composed of quarts with secondary micas, chert, zircon, and iron oxides. The matrix is extensively replaced by diagenetic carbonate.

The age of the basement is indeterminate by paleontologic methods.

Sequence C. Sequence C, from 5400 to 7100 feet, is composed of interbedded sand, silt, and multicolored mudstone, with rare occurrences of lignite beds (Fig. 19). Well preserved and stratigraphically significant plant palynomorphs have been identified within the predominately argillaceous section of the sequence. Among the more important palynomorphs identified are Florschuetzia levipoli, Crassoretitriletes vanraadshooveni, Jandufouria seamrogifomis, Magnastriatites howardi, Graminea sp. (grass pollen), Hystrichosphaeridium sp., and Pediastrum sp.. The age of the sequence is Early to Medial Miocene.

Sequence B. Sequence B comprises the 3900 feet of sediments from 1500 to 5400 feet. Sand and multicolored mudstone with silt and well developed lignite beds are the dominant lithologies of the section (Fig. 19). Arenaceous foraminifera, Trochammina sp. and Haplophragmoides sp., and palynomorphs, Florschuetzia meridionalis, and Dacrydium sp., have been identified within this section. On the basis of Florschuetzia meridionalis, the age of the sequence is assigned to Medial to Late Miocene.

Sequence A. The general lithology of this sequence, which extends from 400 feet down to 1500 feet, consists of soft gray mud with some fine- to very fine-grained sand and an occasional lignite bed (Fig. 19).

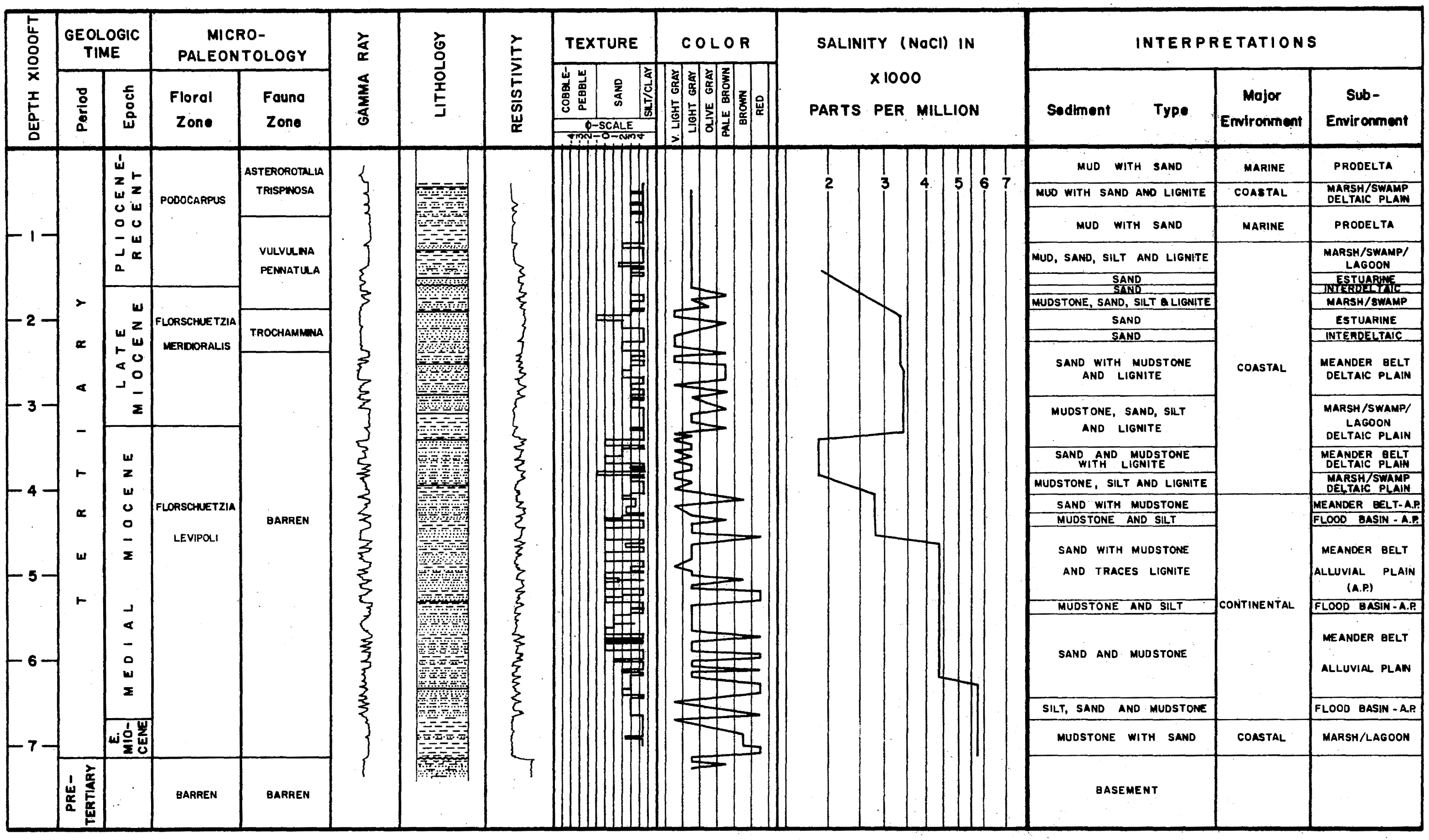


Fig. 19. - Interpretive log of CONOCO Pari No. 1.

Calcareous benthonic foraminifera--*Asterorotalia trispinosa*, *Pseudorotalia schroeteriana*, and *Vulvulina penatula*--have been identified in some units of this Pliocene-Recent sequence.

Environments of Deposition

The major environments of deposition of sediments of the Penyu basin recognized from the study of well data include continental, coastal, and marine environments (Figs. 18-19).

Coastal environments evidently existed initially with deposition of some 400 feet of Lower Miocene lagoonal mudstone, with the abundant brackish-water flora in Sequence C in Pari No. 1. Regression apparently continued, and thick development of continental deposits indicates that the rates of deposition and basinal subsidence were essentially the same.

Formation of some 800 feet of Middle Miocene deltaic beds in the Penyu well is thought to represent a local transgression which temporarily interrupted continental deposition. During a regional transgression, a thick sequence of upper Middle Miocene to Upper Miocene coastal sediments was deposited. Good development of lignite beds in the sequence probably represents luxuriant swamp-marsh conditions.

A regional sea withdrawal was followed by indeterminate amount of erosion during Pliocene over an extensive area. The most significant marine invasion prior to the Recent occurred during Pliocene, and with the exception of local deposition during periodic sea withdrawals, marine environments have been the dominant depositional conditions during Pliocene-Recent.

Correlation

Seismic Correlation

A typical seismic profile is accompanied in Figure 17 by a general interpretation of environments of deposition. On this profile relatively poor seismic signals characterize sequences of marine and continental sediments, and relatively good seismic signals characterize the interval of coastal sediments.

The relationship of the frequency of transmitted signals to lithologic homogeneity and/or stratification of units of different lithologies probably governs signal transmission and signal reflection. In the Penyu basin, the gross lithologies of the marine and continental sediments are mudstone and siltstone, respectively. Vertical lithologic continuity exists within these marine and continental sections, and breaks in seismic velocity are minimal in number. Therefore, seismic records are rather transparent because of the absence of reflectors. Conversely, the lithology of the coastal sediments is not continuous vertically. Significant contrast in velocity within the units of different lithologies results in generation of seismic signals at lithologic boundaries.

Well Correlation

Lateral continuity of continental, coastal, and marine sediments between the wildcat wells of the Penyu basin is illustrated in Figure 20. Thicker development of the continental units in the Penyu No. 1 is thought to represent more rapid rates of sedimentation in response to basinal subsidence. The apparent uniform distribution of upper

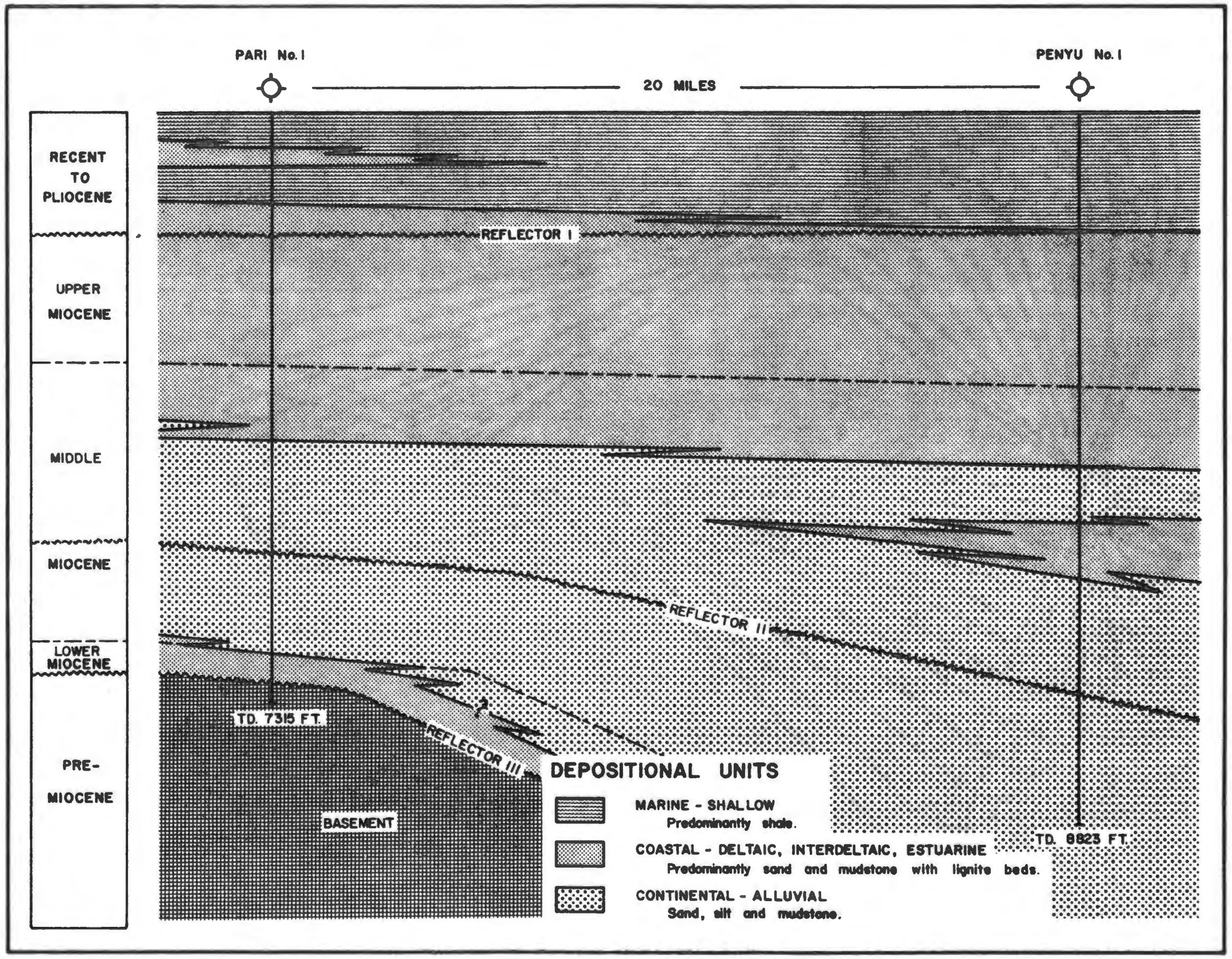


Fig. 20. - Generalized stratigraphic section of major depositional units and major seismic events in CONOCO Penyu No. 1 and CONOCO Pari No. 1.

Middle Miocene-to-Upper Miocene coastal sediments is probably related to regional basinal subsidence and relatively stationary coastlines. Eustatic changes in sea level during Pliocene to Recent may be responsible for the interfingering nature of the marine and coastal sediments.

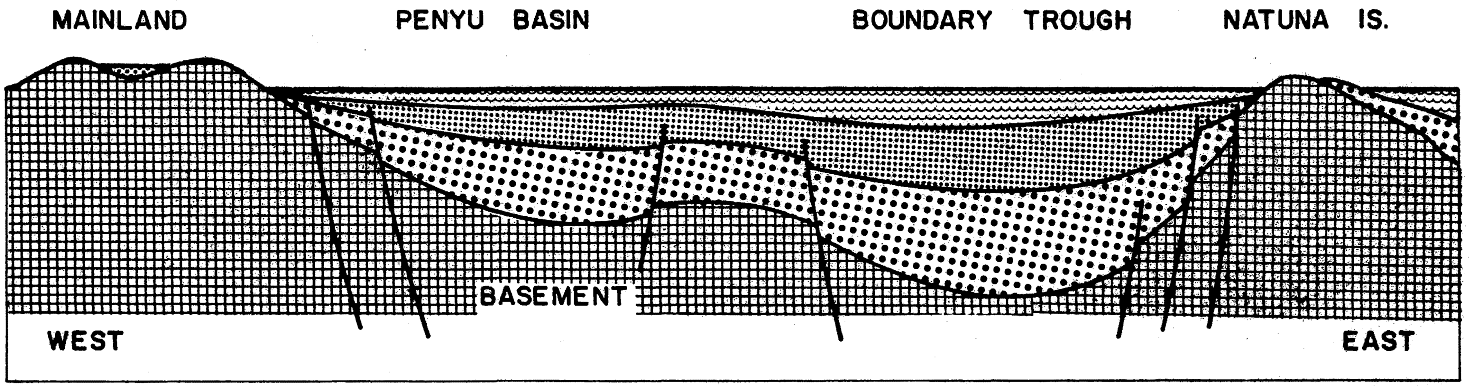
Regional Correlation

Several subsurface formations, ranging in age from Oligocene to Recent, have been recognized in the Boundary trough east of the Penyu basin (Pupilli, 1973). These are, from older to younger, Lumpur, Gabus, Barat, Arang, and Muda Formations.

The Lumpur, Gabus, and Barat Formations, Oligocene to Early Miocene in age, consist of sand, silt, and multicolored mudstone units, with an occasional occurrence of conglomeratic beds. Carbonaceous material is common in these formations. The formations are generally massive and somewhat indurated, with calcareous cement in the Gabus units.

The Arang Formation consists of alternating carbonaceous sands and mudstones and local development of lignite beds. Paleontologic data suggest an Early-to-Medial Miocene age. The Muda Formation, which contains disseminated carbonaceous matter, is composed predominantly of gray-green plastic mud of Medial Miocene to Recent age.

Units of similar lithologies and ages have been identified in the Penyu basin. In view of the continuity of the Penyu basin and the Boundary trough, it is thought that the continental, coastal, and marine units of the Penyu basin may extend to the east and correlate, respectively, with the Lumpur-Gabus-Barat Formations, the Arang Formation, and the Muda Formation of the Boundary trough (Fig. 21). The



	MAINLAND	PENYU BASIN	BOUNDARY TROUGH	NATUNA IS.
≋	—	Marine Units	Muda Fm	—
▒	Lacustrine Units	Coastal Units	Arang Fm	—
⁘	—	Continental Units	Lumpur – Gabus – Barat Fm	Natuna Ss.

Fig. 21. - Diagrammatic east-west stratigraphic cross section between the mainland and Natuna island. Certain data from Chung *et al.* (1968), Haile (1970), Pupilli (1973).

Natuna Sandstone of continental origin (Haile, 1970), on Natuna island, is thought to be the eastern extension and equivalent of the Lumpur-Gabus-Barat Formations. To the west on the mainland, the Miocene-Pliocene lacustrine units (Chung *et al.*, 1968; Gobbette *et al.*, 1973) may represent a western lithologic equivalent of the Lower-to-Middle Miocene Arang Formation.

CHAPTER IV

STRUCTURAL GEOLOGY

Subsea contours on top of the basement, Reflector III, indicate that structure of the study area and, in particular, the Penyu basin is very complex. The area is characterized primarily by block faulting which divides the bifurcating Penyu basinal area into sub-basins and separates it from relatively flat and stable areas (Fig. 15).

Penyu Basin

The Penyu basin, which is tectonically an intracratonic basin, is generally characterized by faults, including horsts and grabens, and folds (Fig. 15). Although most minor features, such as disharmonic folds, drape folds, and reverse-drags or rollovers, are not presented on structural maps, they are present on some seismic profiles. The basin is approximately 50 miles wide and at least 80 miles of its length are within the study area.

Faults

Generally, east- and northwest-trending faults are the most conspicuous structural features of the Penyu basin. From seismic profiles, all faults are interpreted to be normal. Most faults are contemporaneous, or growth, faults, and the range in throw is wide (Figs. 9-12, 15).

Other types of faults may be present in the Penyu basinal area, but their recognition is not readily possible from seismic cross sections. In view of the presence of numerous Mesozoic left-lateral wrench faults on the mainland and the nearby regions, it is conceivable that such faults may exist in the study area. Reverse sense of movement along major faults is indicated by the presence of drape structures, with the uplifted segment overlying the downthrown block.

Four faults are structurally important in the evolution of the basin and in definition of basinal extremities. These faults are, from north to south, Faults "A", "B", "C", and "D" (Fig. 15).

Fault "A". This fault, trending northwestward on the northeast side of the basin, separates the Penyu basin from the Tenggol arch on the north. The fault is recognized for a distance of approximately 60 miles in the study area, and it extends beyond the area into the Boundary trough. In plan view, the fault shows a generalized S-shaped configuration, with bifurcation at both ends to form several fault blocks.

Seismic cross sections indicate that Fault "A" is a growth fault which was very active during Oligocene-to-Early Miocene sedimentation. By end of Medial Miocene, total throw exceeded 12,000 feet, with maximum displacement near the center of the fault arc. Fault movement finally ceased during Medial to Late Miocene after a period of mild activity.

Fault "B". Fault "B" comprises at least two fault segments which trend northwestward. Total length of the fault is not known because it is thought to extend beyond the area of study to the northwest. Known length within the area is approximately 70 miles, with the southeastern termination formed by the intersection with Fault "C". Although this fault is generally straight, it exhibits a very gentle arcuate configuration; the concave side faces toward the basin, or to the northeast.

Seismic cross sections suggest that fault movement was very active during Oligocene to Early Miocene, with deposition of more than 8000 feet of sediments on the downthrown side of the fault. Fault movement was less active during Medial to Late Miocene, when about 1000 feet of sediments was deposited on the downthrown side (Figs. 13, 14).

Fault "C". Fault "C" may be described as several step faults within a broad, generally east-trending fault zone, which is 3 to 4 miles wide in some places. At the point of intersection and termination with Fault "B", the trend becomes southeasterly, or parallel to the structural trend of Fault "B". The length of the fault is at least 80 miles. The fault pattern within the zone of faults is complex due to both bifurcation and convergence of faults.

Fault "C" is arcuate in part, with the concave, downthrown side facing south. Seismic profiles indicate that fault movement was active during Oligocene to Early Miocene; throw exceeded 12,000 feet. An additional 3000 feet of displacement occurred during Medial to Late Miocene (Figs. 13, 14).

Fault "D". Fault "D" defines the southern edge of the Penyu basin and separates the basin from the Singapore platform. This east-trending fault, which is more than 95 miles long, extends eastward beyond the study area into the Boundary trough.

The fault generally is spoon-shaped in plan view; minor branching faults are present on the downthrown, or north side of the fault. Maximum throw is on the concave side, and seismic profiles indicate that at least 7000 feet of displacement occurred during Oligocene to Early Miocene. The throw involving younger units is minimal, and fault movement ceased during Medial to Late Miocene (Figs. 13, 14).

Other Faults. Some of the numerous unnamed faults are relatively large, and many are growth faults. These faults generally parallel at least one of the major faults. Many have curved or arcuate traces. Throw varies widely, but it does not exceed 7000 feet.

Structural Noses

Structural noses which are interpreted to be significant contemporaneous features include the following informally designated structures: Structures U and V portrayed by Reflector III and Structures U, V, X, and Y defined by Reflector II.

Structures Defined by Reflector III. Structures U and V are bounded structurally by the main faults of the basin (Fig. 15), and they form large-scale and broad anticlinal features which plunge eastward and southeastward, respectively. Trends of these structures parallel the general trends of faults of the basin. The structures are thought to have formed by gentle compressive stresses which were related to, or developed from:

1. Basinal subsidence during which tangential compressive stress was developed within downthrown fault blocks as a result of restriction in space.

2. Residual compressive stress in the continental plate which was operative during Miocene when westward motion of the subducting, northeastern oceanic plate ended.

<u>Structures Defined by Reflector II</u>. The relatively minor structural noses at the position of Reflector II (Fig. 13) are interpreted to be related to, or have formed by, differential basinal subsidence, residual compressive stress, differential compaction, local vertical uplift related to isostatic readjustment (Hsu, 1965), and/or paleotopography.

East-trending Structure U and northwest-trending Structure V are apparently growth features which have their roots in the basement. They form anticlines which plunge to the east and southeast, respectively, and Structure U is somewhat domal in configuration. Because the structural mechanism involved folding of the basement, it is thought that both Structures U and V were formed by gentle compressive stress involving a ductile basement. Contemporaneous topographic "highs" may also have influenced their formation by differential compaction.

Structure X (Fig. 12) is a domal, turtle-back fold which is characterized by three structural noses radiating to the northwest, northeast, and south. The northeast-plunging nose is thought to join the south-plunging Structure V across a minor saddle. Structure X is apparently not related to the basement structure; it is interpreted to be caused by a combination of differential basinal subsidence, lateral compressive stresses, and differential compaction.

Structure Y is an anticlinal feature which plunges to the west-southwest. The structure, which may be related in part to underlying faults, is thought to have formed primarily by differential basinal subsidence and secondarily by differential compaction.

Other Structural Noses. Other structures, such as structural rollovers or reverse-drags and drape folds, are common minor features in the basin. Because these features generally are present near major faults, they are thought to be the result of movements along these faults.

Stable Elements

Singapore Platform

The Singapore platform is an extensively flat, positive feature which covers a large area of the Sunda Shelf. The platform stretches from the Sea of Java to the northern Sunda Shelf and extends into the study area, where it covers the southern one-third of the area (Figs. 13-16). The east-trending Fault "D" demarcates the northward limit of the platform.

The platform forms a tectonically stable region which consists predominantly of igneous intrusives and metasediments (Isaacs, 1963; Haile, 1970).

Tenggol Arch

The southern part of the Tenggol arch lies within the northeastern part of the study area (Figs. 13-16). Seismic profiles within the vicinity of the arch indicate that it is generally a relatively flat-topped, plunging anticlinal feature which is abruptly interrupted on its southwest flank by the northwest-trending Fault "A". Except for a few minor east-trending faults, other structural features are not known.

The Tenggol arch separates the Penyu basin from the Gulf of Thailand basin (Fig. 3). The fact that the Gulf of Thailand basin is an elongated graben (Murphy, 1974) suggests that the Tenggol arch represents a large-scale upthrown fault block.

Pahang Platform

The Pahang platform also is a large-scale stable block, which extends eastward from the mainland in the general shape of a half diamond (Figs. 13-16). Two bounding faults, the northwest-trending Fault "B" and east-trending Fault "C", define the eastern edge of the platform. An arcuate fault, with the downthrown side on convex side of the arc, connects the two bounding faults, and it apparently was active during Medial to Late Miocene when the southern part of Fault "B" became inactive (Figs. 13, 14).

The Pahang platform is essentially flat, with gentle dip to the east and southeast (Figs. 9, 13). Local undulatory features on some seismic profiles across the platform probably represent paleotopographic "highs" and "lows".

CHAPTER V

BASINAL EVOLUTION

The Penyu basin is one of several basins of the northern Sunda Shelf which are thought to have developed during Late Cretaceous to Late Tertiary under similar tectonic conditions. Therefore, is an interpretation of the evolution of the Penyu basin, it is essential to consider not only the tectonic history of the basin but also the general tectonics of the region. The various structural features suggest that both extensive and compressive stresses were important in development of the basin during Late Cretaceous-Early Tertiary to Late Tertiary (Parke *et al.*, 1971; Pupilli, 1973).

Penyu Basin

Pre-Oligocene Events

During Late Cretaceous to Early Tertiary a northeastern oceanic plate was subducted beneath the stable Cretaceous-Early Tertiary landmass (Fig. 22). The effect was uplift of the region as a broad domal feature and development of extensive stress conditions. The four major zones of weakness which formed as a result of the extensive stresses are oriented in easterly and northwesterly directions. Because these fault zones are differently oriented, it is thought that their formation was influenced by older structural elements and/or heterogeneous composition of the basement rock.

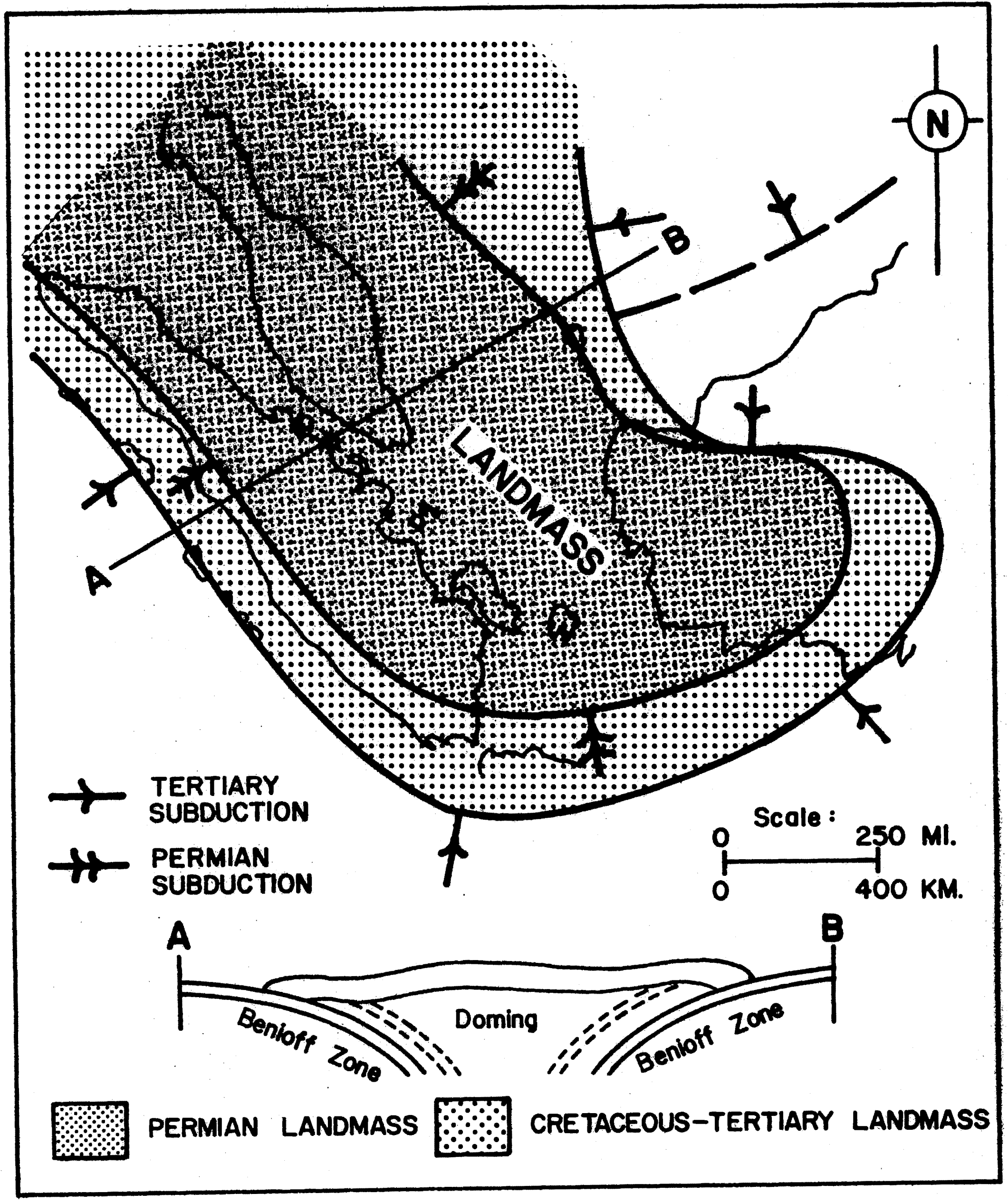


Fig. 22. - Paleotectonic map of Sundaland from Permian to Early Tertiary. Cross section shows opposing subducting oceanic plates. (Modified after Hutchison, 1973).

Oligocene-Miocene Events

Continued uplift until Medial Miocene was accompanied by formation of a westward-bifurcating graben between the major zones of weakness. This graben subsided uninterruptedly during Oligocene to Early Miocene, during which time at least 10,000 feet of sediments was deposited. The rate of subsidence decreased somewhat during Medial Miocene, and by Late Miocene only local areas experienced significant subsidence.

A secondary compressive stress field formed as a result of basinal subsidence by faulting. Additionally, residual compressive stress developed in the continental plate during Miocene when the westward motion of the northeastern oceanic plate ended. The summation of the two stresses caused the relatively ductile basement and sediments to fold, whereas faults formed in the brittle basement. Because basinal subsidence continued to Late Miocene and because no low-angle faults are apparent on the seismic cross sections, the compressive stresses apparently were not intense.

Reverse sense of movement along certain faults, which is thought to have caused reverse-drags and drape folds, apparently occurred during that time.

Pliocene-Recent Events

During Pliocene to Recent, movement of the northeastern oceanic plate ceased. Although basinal subsidence continued at a relatively slow rate over a wide area, that period generally represents a time of tectonic quiescence.

Northern Sunda Shelf

Katili (1971, 1973), Hutchison (1973), Haile (1973), and others have utilized plate tectonics in explaining peculiar parallel occurrences of various igneous rocks. Based on the $(Na_2O+K_2O)/SiO_2$ ratios and radiometric age determinations of igneous rocks, Hutchison (1973) and Katili (1973) have suggested that:

1. The earliest of several episodes of lithospheric descent began during Early Paleozoic.
2. Opposing Benioff zones existed during Permian and Cretaceous to Early Tertiary (Fig. 22).

The latter presents the most significant period of events that initiated development of Tertiary basins of the shelf.

Pre-Oligocene Events

Tectonic events during Late Cretaceous to Early Tertiary were caused by crustal compression which resulted from the interaction between the Late Cretaceous-to-Early Tertiary landmass and the westward subduction of the northeastern oceanic plate (Fig. 22). Because another subducting zone on the west moved to the east and northeast, the interaction of these two opposing motions brought about a general upward arching of the cratonized landmass. Arching, in turn, resulted in extensive stress conditions, which ultimately led to basement faulting and formation of zones of subsidence and sedimentation. The Kuantan and the Segamat basalts and the Midai volcanics may represent the initial stage of fragmentation of the Late Cretaceous-to-Early Tertiary landmass.

Oligocene-Miocene Events

Active basinal subsidence and sedimentation continued during Oligocene to Miocene. However, during Miocene the westward motion of the northeastern oceanic plate apparently ended. Mild lateral compressive stress associated with basinal subsidence and residual compression in the continental plate, coupled with local vertical uplift due to isostatic readjustment, was responsible for formation of some domal features, folds, and faults of the region.

Pliocene-Recent Events

The basins during Pliocene to Recent generally were tectonically inactive. A rather thick development of Pliocene-Recent sediments in some parts of the basins may indicate continuous basinal subsidence, but the rate of subsidence probably was significantly slower than the rate of subsidence of the basins during Oligocene to Miocene.

CHAPTER VI

PETROLEUM GEOLOGY

Reservoir-Rock Potential

Lithologies of sedimentary units penetrated by the Penyu and Pari wells indicate that reservoir rocks of the Penyu basin consist of clastic units. No carbonate rocks are known from examination of well data, and the sedimentologic history does not indicate any significant marine influence, except during Pliocene to Recent. It, therefore, is improbable that carbonate rocks of significant thickness are present in the basin.

The reservoirs consist of poorly to moderately sorted, coarse- to very fine-grained quartz sand and small amount of feldspars and rock fragments. Moderate to abundant clay matrix, carbonaceous material, and occasional calcite cement are other constituents. The beds are commonly friable units, which show a general increase in induration with depth.

Analyses of sidewall cores indicate that porosity of the rocks is generally good (15-20%) to excellent (greater than 25%) and that permeability ranges from fair (1-10 millidarcys) to very good (100-1000 millidarcys) (Levorsen, 1967) (Fig. 23). Both of these reservoir qualities show a general decrease with depth. Because slight decrease in porosity exists, good to fair porosity may be expected for some depth.

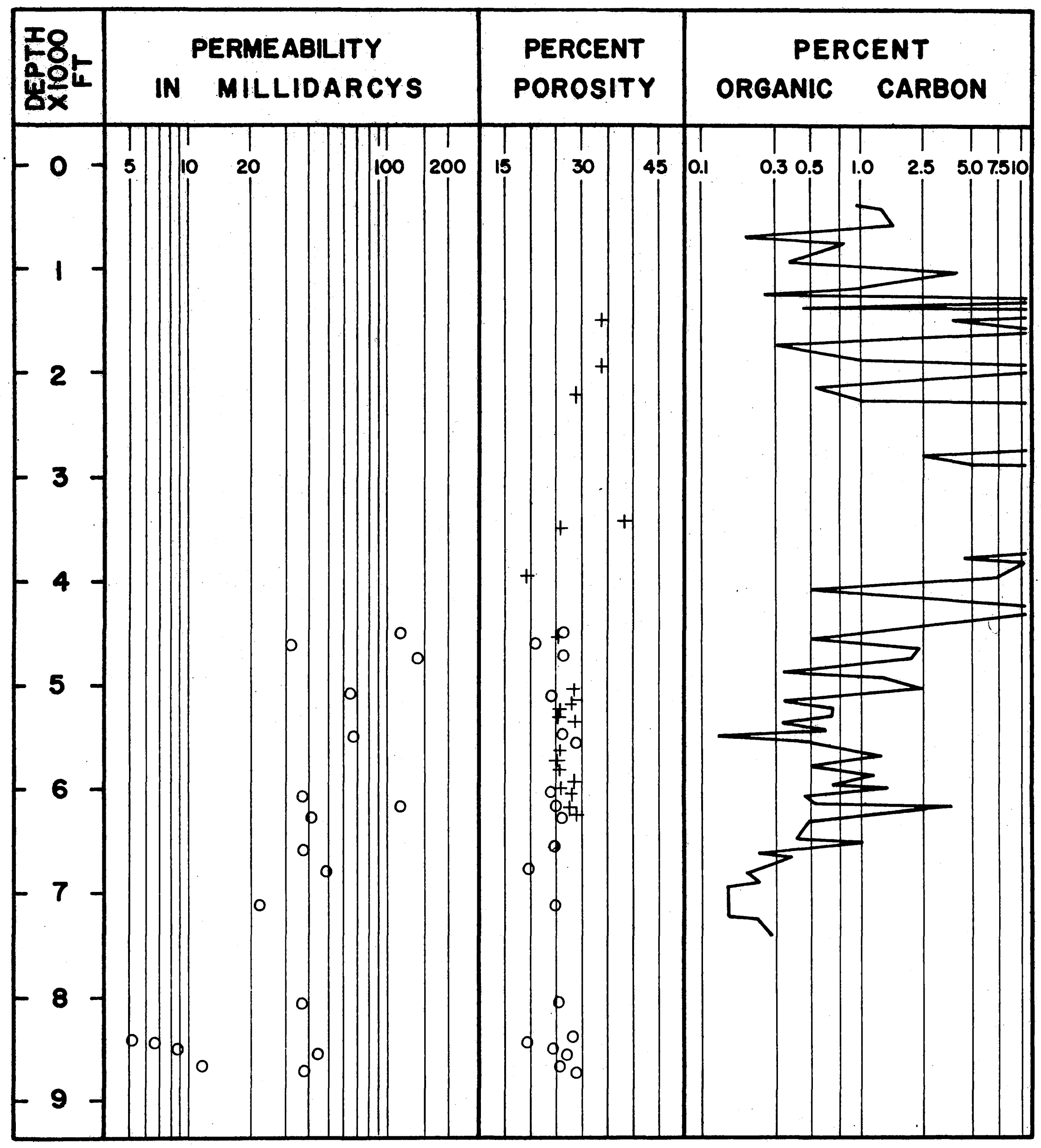


Fig. 23. - Quality of reservoir rocks and organic content of source rocks, Penyu basin, based on analyses of sidewall cores. Circles for Penyu data; crosses for Pari data, organic carbon in Pari cores.

However, reservoir deterioration may be more abrupt where clay matrix is replaced by calcite cement. Good reservoir quality may be retained in any highly geopressured zones. The significant decrease in permeability with depth is thought to be influenced primarily by grain size and degree of lithification.

Source-Rock Potential

Mudstone and siltstone--as coastal, marine, and, to a lesser extent, some continental units--contain abundant organic matter. Analyses of the rocks indicate that organic carbon, exceeding 2 percent in many samples, is present at depths between 1500 to 5000 feet in the Pari well and, based on well correlation, 1500 to 7000 feet in the Penyu well (Fig. 23). The organic carbon in the Pari well is of woody kerogen, which is capable of generating gas and/or gas with some associated liquid hydrocarbons.

Most of the potentially effective source rock is present above approximately 5000 feet in the Pari well and 7000 feet in the Penyu well. The presence of similar units at depth in a thick sedimentary section with a dominance of continental units is speculative. However, because lacustrine beds, such as the Green River Shale, contain substantial organic matter, the possibility of encountering source rock in a section with at least 10,000 feet of sediments is thought to be fairly good.

Evaluation of Hydrocarbon Potential

Average paleotemperatures indicate that the section above approximately 4000 feet in the Pari well probably contains immature source rock (Fig. 24). However, from 4000 feet to the basement at 7100 feet, the interval is within the liquid window (Pusey, 1973). This interval includes about 1000 feet of rocks that contain more than 2 percent organic carbon. In the Penyu well, where the projected basement is 20,000 feet, a thicker section of immature source rock may be anticipated if lower inferred paleotemperatures are approximately correct. The gradient for the Pari well is 2.25°F/100 feet, and a gradient of 1.50°F/100 feet for the Penyu well, representative of the lower values from the Pari well, is thought to give a maximum range in depth for liquid hydrocarbons. With the inferred gradient, immature units lie above 6000 feet, and approximately 10,000 feet of the sedimentary section is within the liquid window. Approximately 3000 feet of the projected 10,000 feet was penetrated by the Penyu well, and 1000 feet contains more than 2 percent organic carbon (Fig. 24).

Philippi (1965) concluded that in the Los Angeles basin, with a geothermal gradient of 2.15°F/100 feet, the bulk of hydrocarbon generation occurred below a depth of 8000 feet. In the Ventura basin, with a geothermal gradient of 1.45°F/100 feet, the bulk of hydrocarbon generation, according to Philippi, occurred below 12,000 feet. If the areas around the Pari and Penyu wells are compared, respectively, to Philippi's interpretations of the Los Angeles and the Ventura basins, no significant hydrocarbon would have been generated in the Pari well area, but significant hydrocarbons may have been generated below 12,000 feet in the Penyu well area.

Traps

Several different types of traps may be recognized from

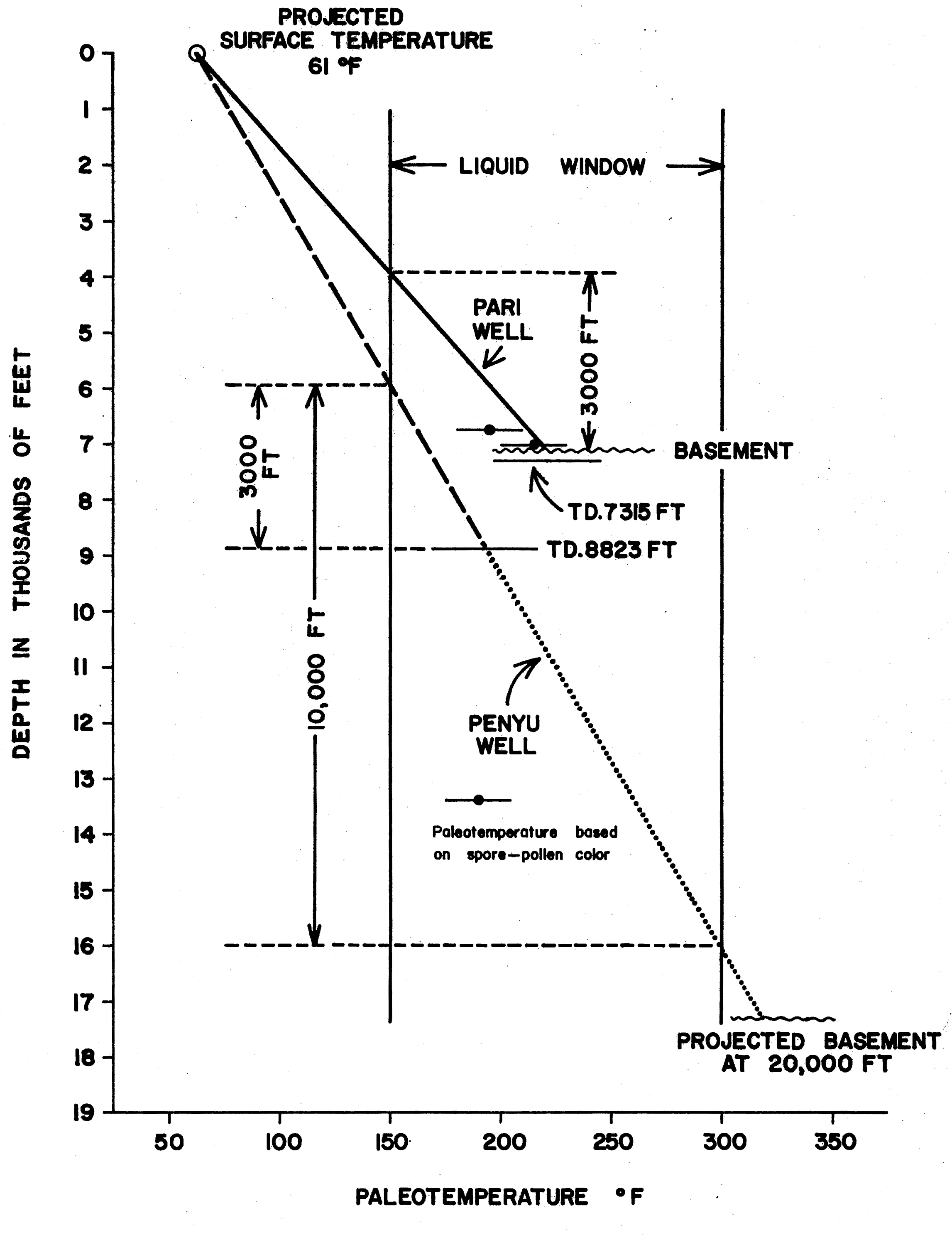


Fig. 24. - Average paleotemperature gradients for CONOCO Pari No. 1 and CONOCO Penyu No. 1. Gradient for Penyu well represents minimal paleotemperature values in Pari well. Thickness values refer to estimated thickness of sediments within liquid window (Pusey, 1973).

examination of structural and isopach maps and seismic cross sections. These traps are structural, stratigraphic, and structural-stratigraphic combination (Fig. 25).

Most structural traps are anticlinal or domal, and they are generally of large-scale, broad features with gently dipping flanks (Fig. 25A). Smaller anticlinal features, such as drape folds, normally are associated with major faults (Fig. 25B).

Traps with a dominant stratigraphic element are probably as numerous as structural traps. They are expressed as pinch-outs, possibly associated with depositional slopes and flanks of anticlines (Fig. 25C, D), and updip terminations of beds against unconformities (Fig. 25E).

Combination traps in the basin include stratal convergence associated with various structural features. This convergence is present along anticlines, drape folds, and areas of differential subsidence.

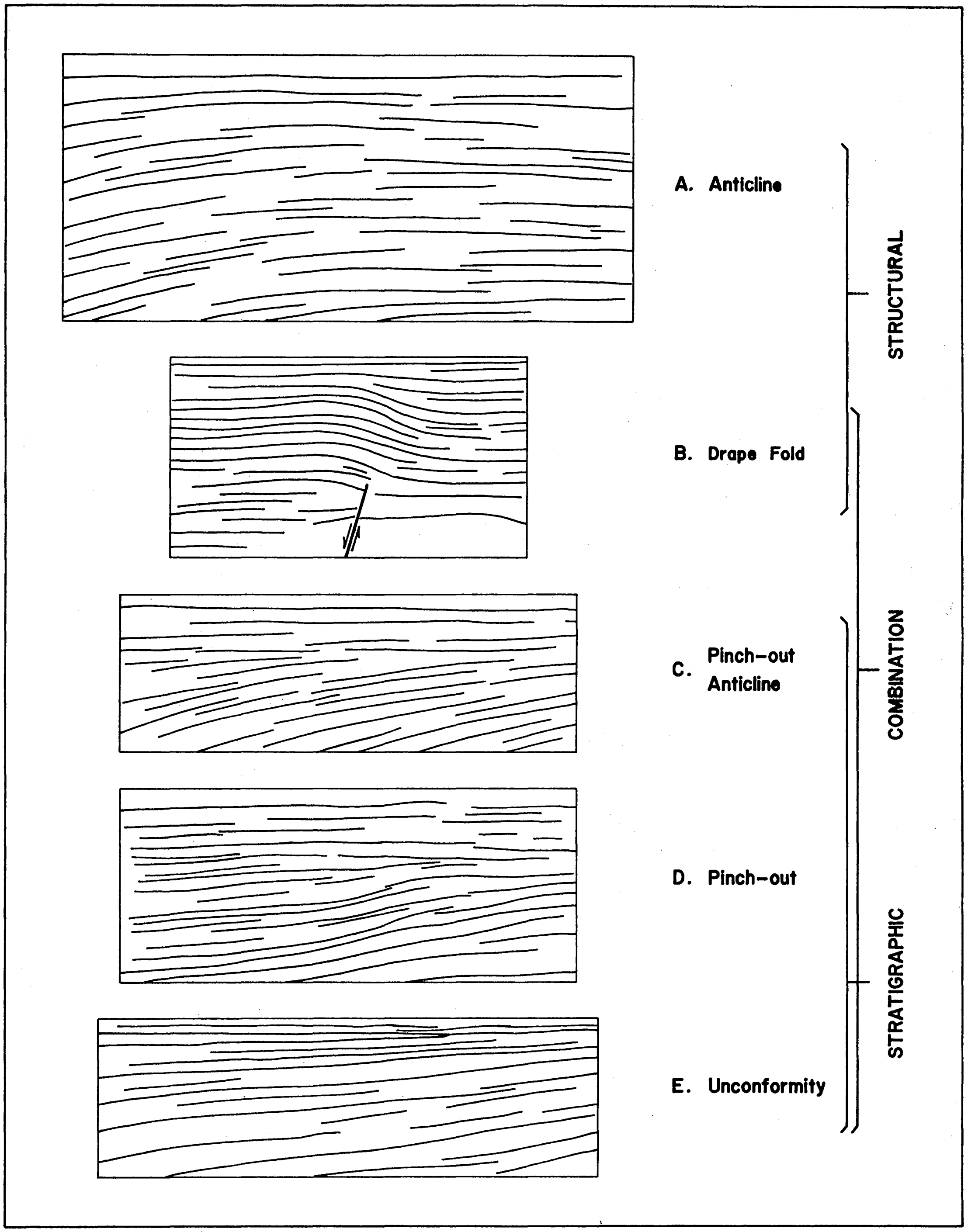


Fig. 25. - Typical traps traced from seismic profiles, Penyu basin.

CHAPTER VII

CONCLUSIONS

The principal conclusions of this study are as follows:

1. The Penyu basin is a complex, bifurcating graben. The present shape is controlled by basement faulting. Trends of faults may have been influenced by older structural elements and composition of the pre-Tertiary basement.

2. Faulting was initiated during Late Cretaceous to Early Tertiary when the Cretaceous-Early Tertiary landmass was arched as a result of subduction of two opposing subducting oceanic plates. Rapid basinal subsidence and accumulation of sediments did not begin until Oligocene. The Tertiary volcanics of Kuantan, Segamat, and Midai probably mark the stage of fragmentation of the landmass.

3. Several anticlinal features which are significant traps resulted from one or more of the following:

   a. Differential basinal subsidence
   b. Mild, residual, lateral compressive stress
   c. Differential compaction
   d. Reverse sense of fault movement as an expression of isostatic readjustment
   e. Paleotopography

Whereas differential basinal subsidence, differential compaction, and paleotopography may have been significant during Oligocene-to-Miocene deposition, some compressive folds and reverse fault movement occurred during Miocene.

4. Thick accumulation of sediments, exceeding 20,000 feet in thickness, represents the summation of active basinal subsidence during Oligocene to Recent. These sediments are of continental, coastal, and marine origins.

5. The continental and coastal units may constitute approximately 90 percent of the total thickness of the sediments. Lithologies of these units within the intervals penetrated by the Penyu and Pari wells are sand, silt, mudstone, lignite, and lignitic beds. It is interpreted from seismic signatures that silts and mudstones are the predominant lithologies in the interval from a depth of 8823 feet at the Penyu well to the acoustic basement.

6. The initial deposits of the basin are continental units.

7. General depositional trends of the continental and coastal units are easterly and southeasterly, paralleling major structural elements of the basin. This relationship implies that the general thickness and distribution of these units are tectonically controlled.

8. Basement rocks include both ductile and brittle materials. Data from the Pari well and the surrounding regions suggest that these materials are metasediments and granitic rocks of Mesozoic/Paleozoic age.

9. Where basinal fill is thick, some 10,000 feet of sediments may be within the liquid window. It is possible that lacustrine units are present in the untested, deeper parts of the basin and that they represent source rock. Significant accumulations of hydrocarbons may occur at depths greater than 12,000 feet.

10. Numerous structural, stratigraphic, and structural-stratigraphic combination traps are present in the basin.

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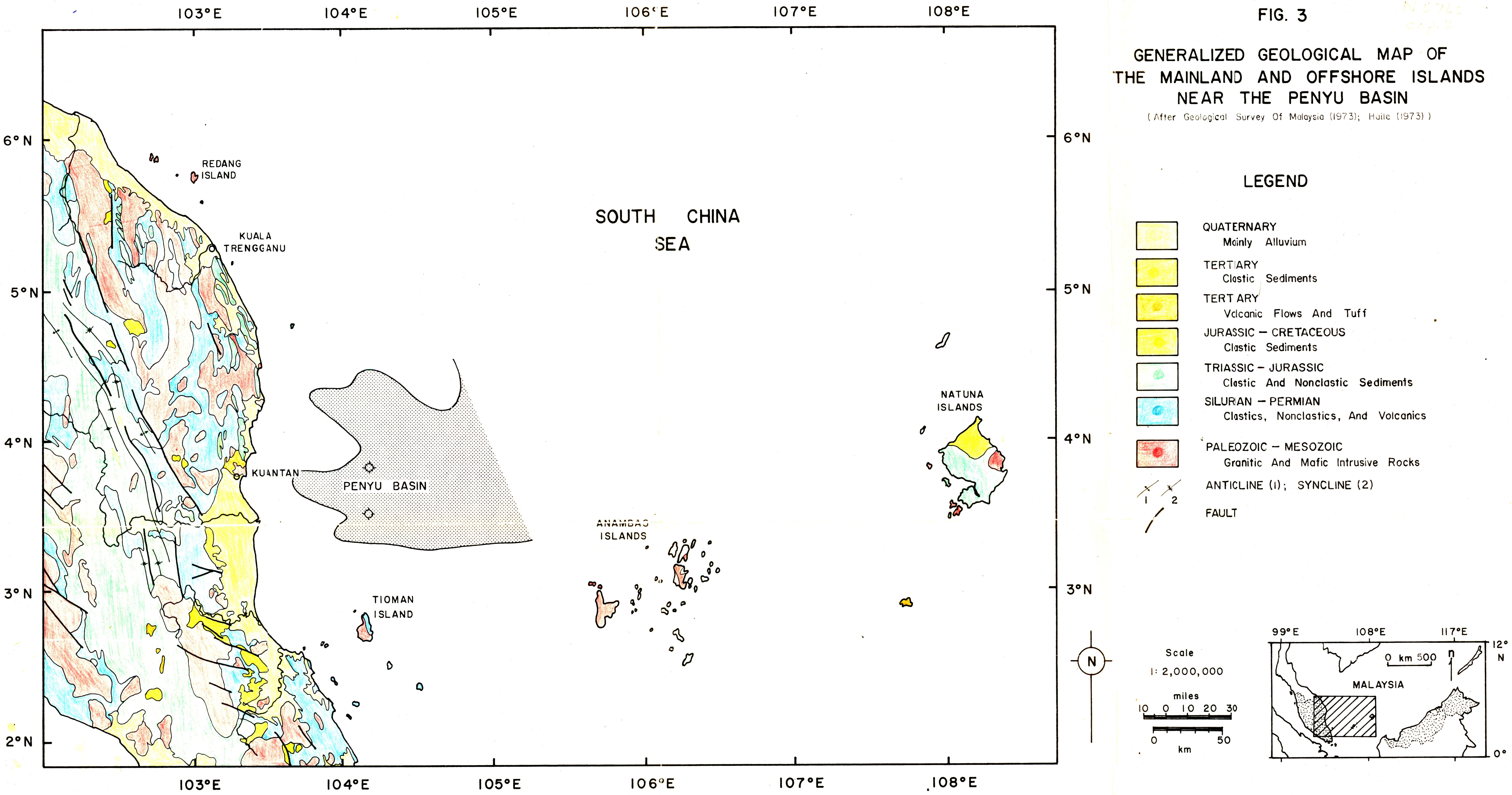
FIG. 3

GENERALIZED GEOLOGICAL MAP OF THE MAINLAND AND OFFSHORE ISLANDS NEAR THE PENYU BASIN

(After Geological Survey Of Malaysia (1973); Haile (1973))



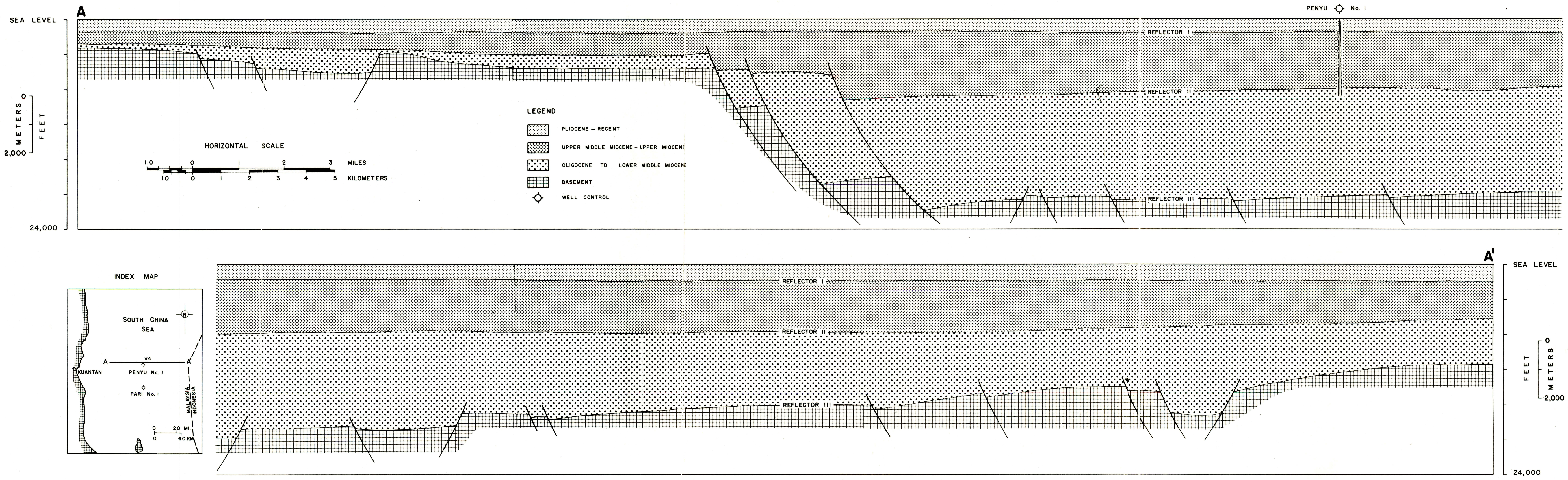


FIG.9–STRUCTURAL CROSS SECTION A-A', PENYU BASIN.

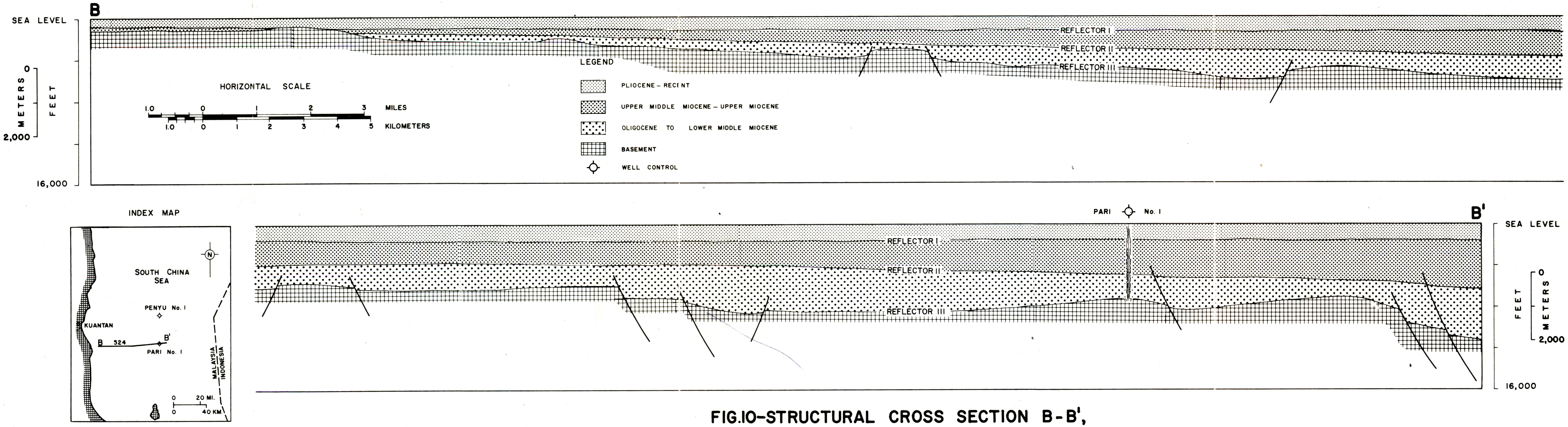


FIG.10–STRUCTURAL CROSS SECTION B-B', PENYU BASIN.

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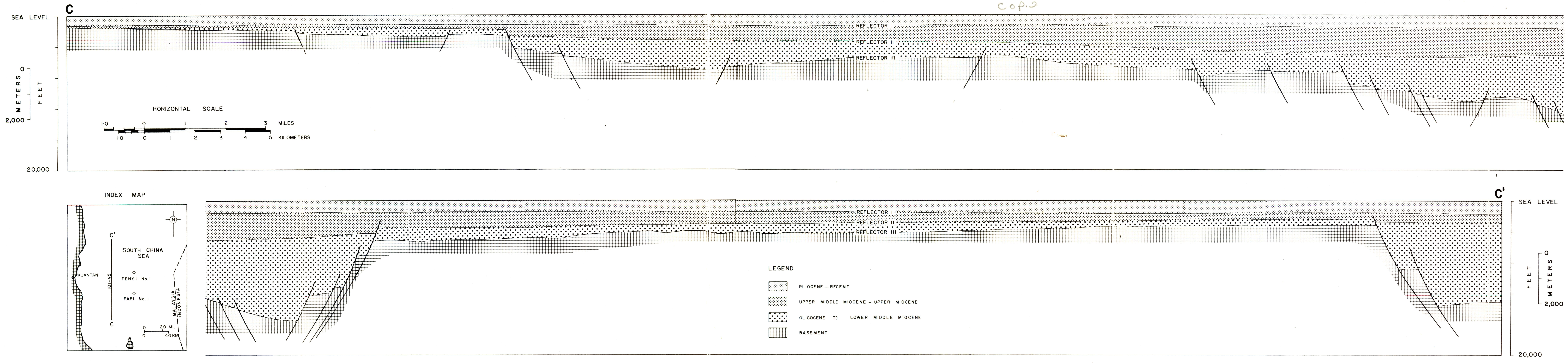


FIG.11–STRUCTURAL CROSS SECTION C-C', PENYU BASIN.

FIG.12–STRUCTURAL CROSS SECTION D-D',
PENYU BASIN.

FIG. 13

STRUCTURAL CONTOUR MAP ON REGIONAL SEISMIC REFLECTOR II, PENYU BASIN.

CONTOUR INTERVAL – 200 FT.

FIG. 14

ISOPACH MAP OF INTERVAL BETWEEN
REGIONAL SEISMIC REFLECTORS I
AND II, PENYU BASIN.

CONTOUR INTERVAL - 200 FT.

▨ LESS THAN 2,000 FT. THICK

▨ 2,000-4,000 " "

▨ 4,000-6,000 " "

▨ GREATER THAN 6,000 FT. THICK

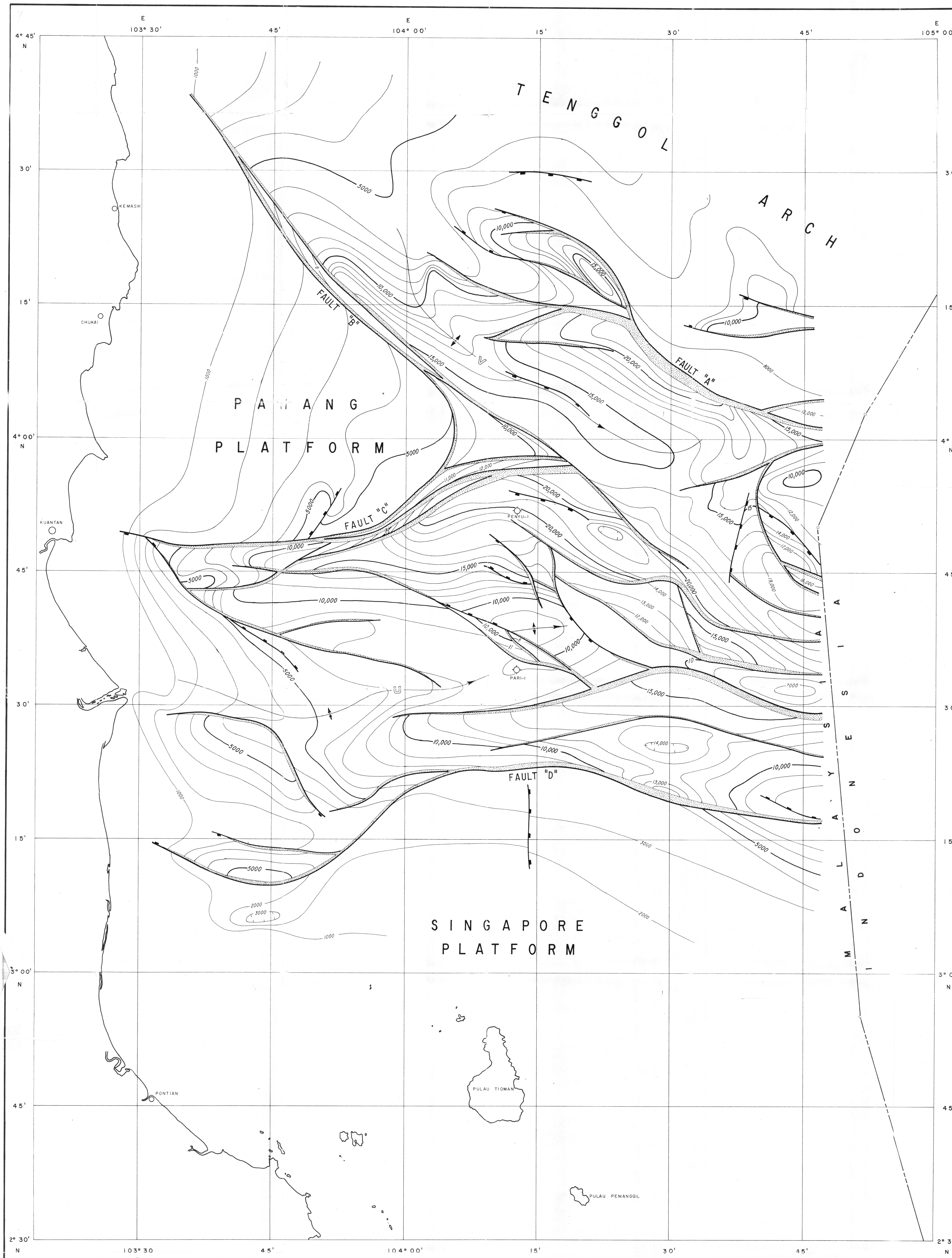


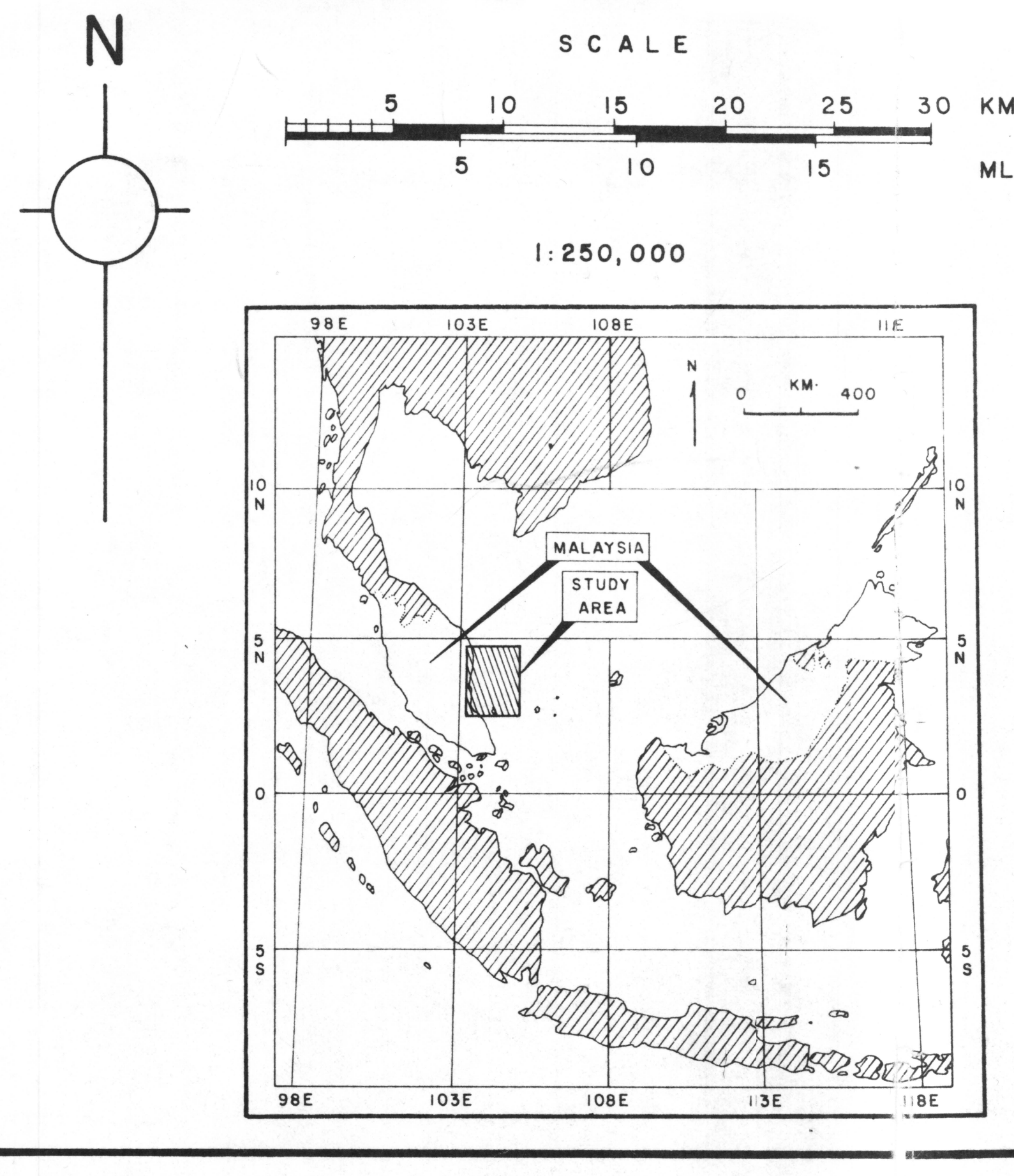
FIG. 15

STRUCTURAL CONTOUR MAP ON REGIONAL
SEISMIC REFLECTOR III,
PENYU BASIN.

CONTOUR INTERVAL – 1,000 FT.

ZONE OF THROW

PLUNGING STRUCTURAL NOSE



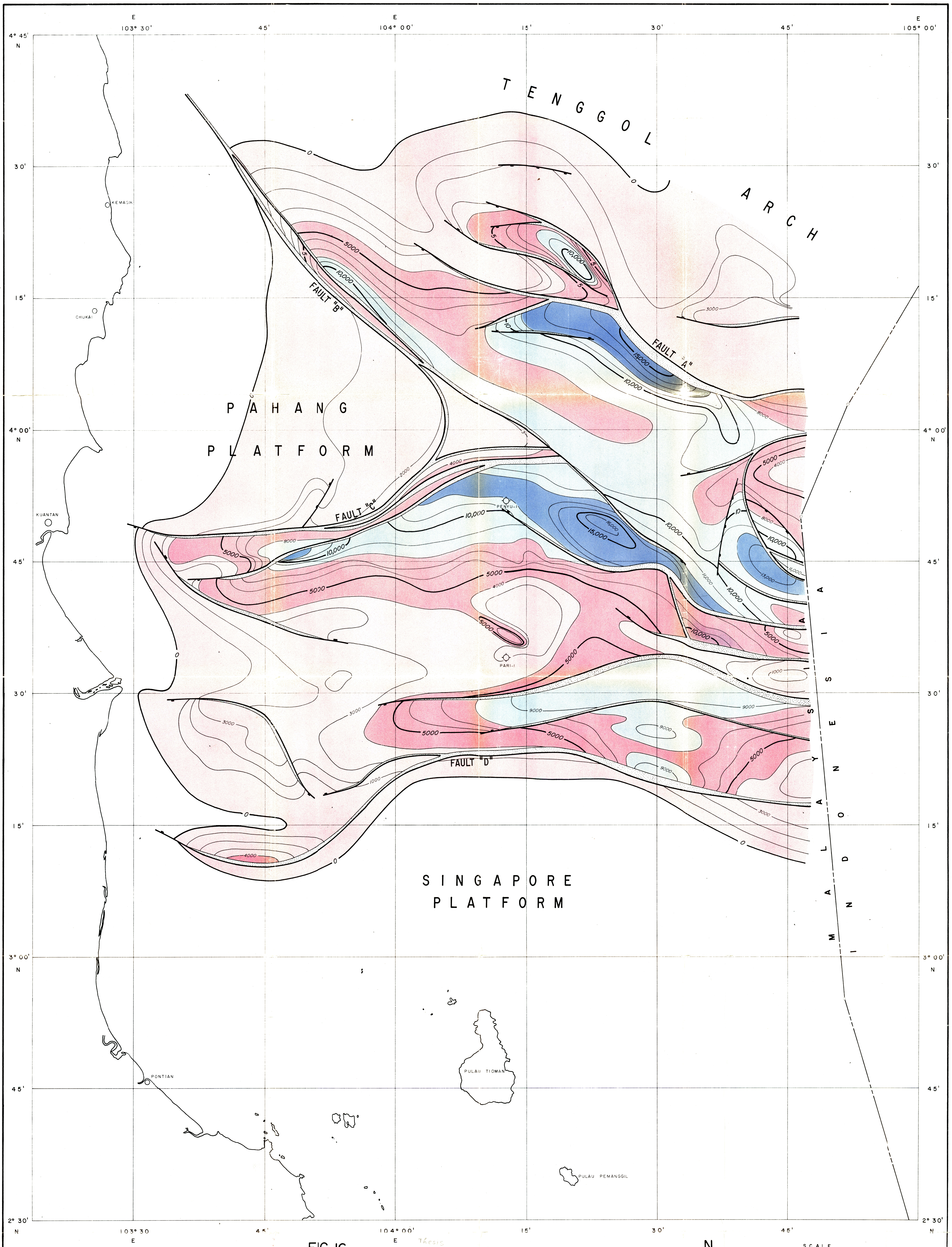


FIG. 16

ISOPACH MAP OF INTERVAL BETWEEN
REGIONAL SEISMIC REFLECTORS II
AND III, PENYU BASIN.

CONTOUR INTERVAL - 1,000 FT.

▨	LESS THAN 4,000 FT. THICK
🟥	4,000 - 8,000 " "
▨	8,000 - 12,000 " "
🟦	GREATER THAN 12,000 FT. THICK

U
D
ZONE OF THROW

N

SCALE

5 10 15 20 25 30 KM

5 10 15 ML

1:250,000