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The North Palawan Block, Philippines: its relation to the Asian Mainland and its role in the evolution of the South China Sea

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Abstract: The island of Mindoro, the northern part of Palawan island and the Reed Bank area (southwestern Philippines) together constitute a continental fragment, the North Palawan block, lying within an island arc-oceanic setting. The Permian to Palaeogene rocks of the block indicate a geological origin and history contrasting with that of the remainder of the Philippine Archipelago, and suggest that the North Palawan block, once occupied a pre-drift position contiguous with the South China mainland.

Four prominent pre-Neogene regional unconformities are recognised both on and offshore the China mainland, in Taiwan and in the Palawan block. The synchrony of these unconformities and the facies relationships of the unconformity-bounded sedimentary units strongly suggest a common pre-Neogene history for all these areas. By contrast, throughout the Palawan area, an important regional unconformity occurs at the top of the Middle Miocene which is absent from the Asian mainland.

Extension in the South China Sea Basin since the Mesozoic, which has separated the North Palawan block from the Asian mainland, has been approximately uniform from west to east. However, there is strong evidence to suggest that this extension has been achieved by temporally separated phases of continental crustal attenuation and more recent sea-floor spreading.

From the above observations and using the most recent magnetic spreading anomaly data for the South China Sea, a suite of palinspastic reconstructions has been compiled. This shows the evolution of the South China Sea area from the Late Triassic to the Pliocene. The reconstructions illustrate amongst other things: (1), the convergent continental margin setting of the North Palawan block during much of the Jurassic and Cretaceous; (2), the Late Cretaceous inception of the Philippine island arc system; (3), the subsequent anticlockwise rotation of the arc system from the Late Eocene onwards; (4) the Palaeocene to Mid-Miocene opening of the South China Sea, and (5) the Early to Mid-Miocene collision between the North Palawan block and the Palawan subduction system.

INTRODUCTION

The Reed Bank, the northern part of Palawan Island and the island of Mindoro, hereinafter referred to collectively as the North Palawan block, are all part of the present day Philippine Archipelago (Fig. 1). However, there is much stratigraphic and tectonic evidence to suggest that this association is a relatively recent phenomenon and that the North Palawan block and the remainder of the Philippine island arc system have distinctly separate origins and geological histories.

Fundamental to this argument is the presence of a Late Palaeozoic to Mid-Mesozoic basement complex throughout the North Palawan block (Hashimoto & Sato, 1968; Hashimoto & Sato, 1973; Balce *et al.*, 1979; Hamilton, 1979) whereas the

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remainder of the Philippine Archipelago comprises a highly complex series of sutured and convoluted island arc systems which formed and accreted fairly continuously from the Late Mesozoic to the present (Balce *et al.*, 1979; Hamilton, 1973, 1979).

The North Palawan block is considered to form the northeastern portion of a much larger area of block faulted and foundered pre-Tertiary continental material which extends throughout the southern part of the South China Sea Basin and includes the Spratley Islands and the Dangerous Grounds area off Borneo (Fig. 1) (Hamilton, 1979). The evidence for the continental composition of the crust of this area is substantial and has been reviewed by Hamilton (1979) and Taylor & Hayes (1980) among others.

Many authors have also suggested that the crustal material comprising the North Palawan block once formed part of the mainland of Asia, attached to southern China (Murphy, 1976; Hamilton, 1979; Balce *et al.*, 1979; Taylor & Hayes, 1980). This paper provides, through examination of the stratigraphy of both the North Palawan block and that of the onshore and offshore areas of mainland China and Taiwan, further support for this hypothesis.

In order to visualise the pre-drift fit of the rifted crustal blocks to the southern flank of the South China margin, the magnetic anomaly data recently acquired and

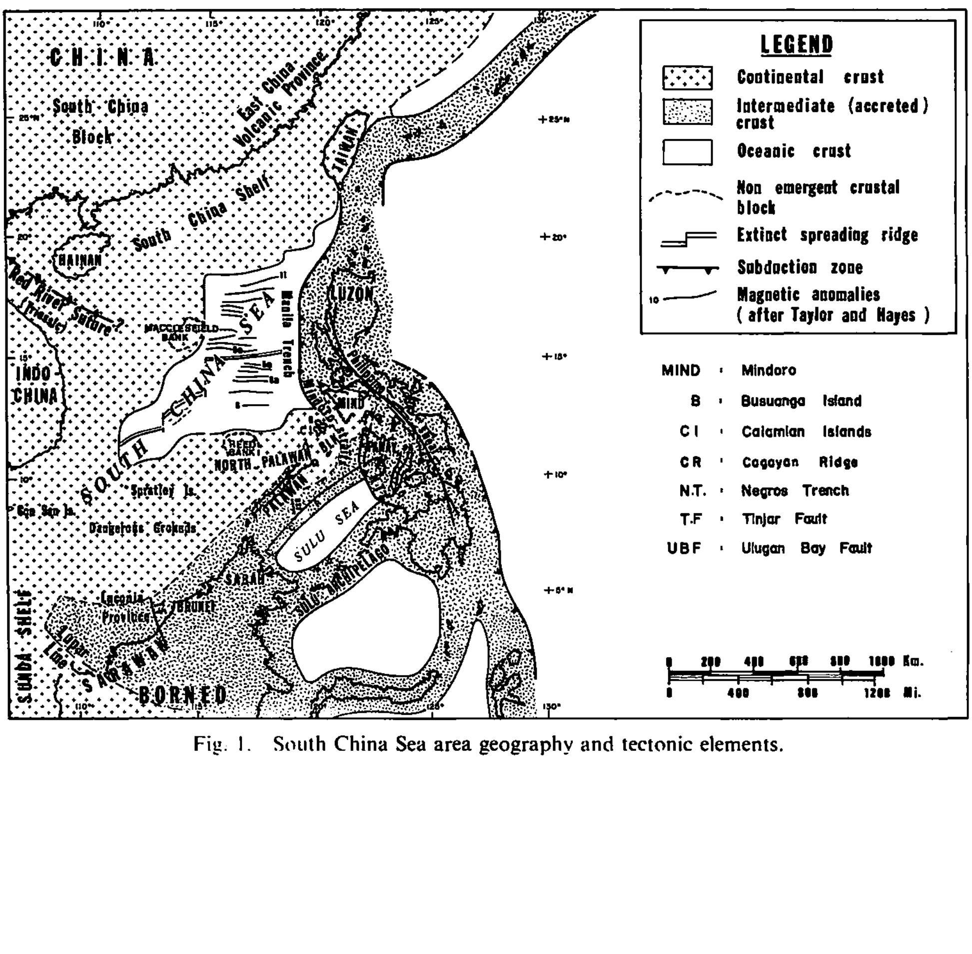

Fig. 1. South China Sea area geography and tectonic elements.

interpreted by Taylor and Hayes (Fig. 1) of the Lamont Doherty Geological Observatory have been used as the basis for a pre-drift reconstruction. From this reconstruction and other tectonic data from surrounding areas, it has been possible to generate a series of palinspastic maps (Figs. 6-16) to illustrate the evolution of the South China Sea Basin from the Late Triassic to the Pliocene.

REVIEW OF TAYLOR AND HAYES DATA AND MODEL

Taylor and Hayes (1980) have made the most recent compilation and interpretation of magnetic anomaly data in the South China Sea Basin. Their data base is more complete than that for any previous interpretation (eg. Ben Avraham and Uyeda, 1973 and Bowin *et al.*, 1978). Unlike previous workers, Taylor & Hayes have, with varying degrees of confidence, been able to correlate their mapped anomalies with the worldwide magnetic reversal time scale and so have been able to ascribe specific ages to these anomalies. The oldest anomaly identified is Anomaly 11 with an age of 32 Ma or Mid-Oligocene. The most recent is Anomaly 5D with an age of 17 Ma or latest Early Miocene. These dates therefore approximate to the inception and termination of sea-floor spreading in the South China Sea and consequently indicate the age of its oceanic crust. This Mid-Cenozoic age is broadly in agreement with that determined from heat flow measurements (Watanabe *et al.*, 1977). The traces of the magnetic anomalies are shown on Figure 2 and are seen to trend approximately east-west. They are also symmetrically distributed on either side of an east-west chain of seamounts which is interpreted to be the extinct spreading ridge of the system. This symmetrical distribution is in keeping with the generally accepted geometry of sea-floor spreading.

An earlier spreading model proposed by Bowin *et al.* (1978) (Fig. 3) is based on interpreted magnetic anomalies which they measured to be orientated N 70° E. However, their model results in asymmetrical spreading geometry about their inferred spreading ridge. Also, the inferred ridge lacks any significant present day bathymetric expression. Furthermore, Bowin *et al.* were unable to date any of the anomalies they mapped. These factors, in addition to the difference in the amount of data available to the two sets of authors, give considerably greater credence to the model suggested by Taylor & Hayes.

However, a geometrical problem must be accounted for in the Taylor & Hayes model. The sub-parallel nature of the anomalies implies a fairly distant pole of rotation for the spreading event in at least the eastern part of the South China Sea Basin. A difficulty therefore arises in explaining the offsetting and westward narrowing of the area occupied by oceanic crust. Two explanations are possible for these phenomena. First, they might result from an earlier phase of spreading with a different pole of rotation and with an orientation as suggested by Bowin *et al.* However, this scheme would make it harder to explain some observed aspects of the geology on and offshore west Sarawak. It would also necessitate severe dislocation within the North Palawan block itself of a type incompatible with that expressed by the Ulugan Bay Fault (Fig. 1 and later discussion). Furthermore, no evidence is seen for such dislocation elsewhere in the block on the large volume of multichannel seismic data available.

The second possible explanation is that the spreading was synchronous throughout but that the large masses of cratonised continental crust on the western

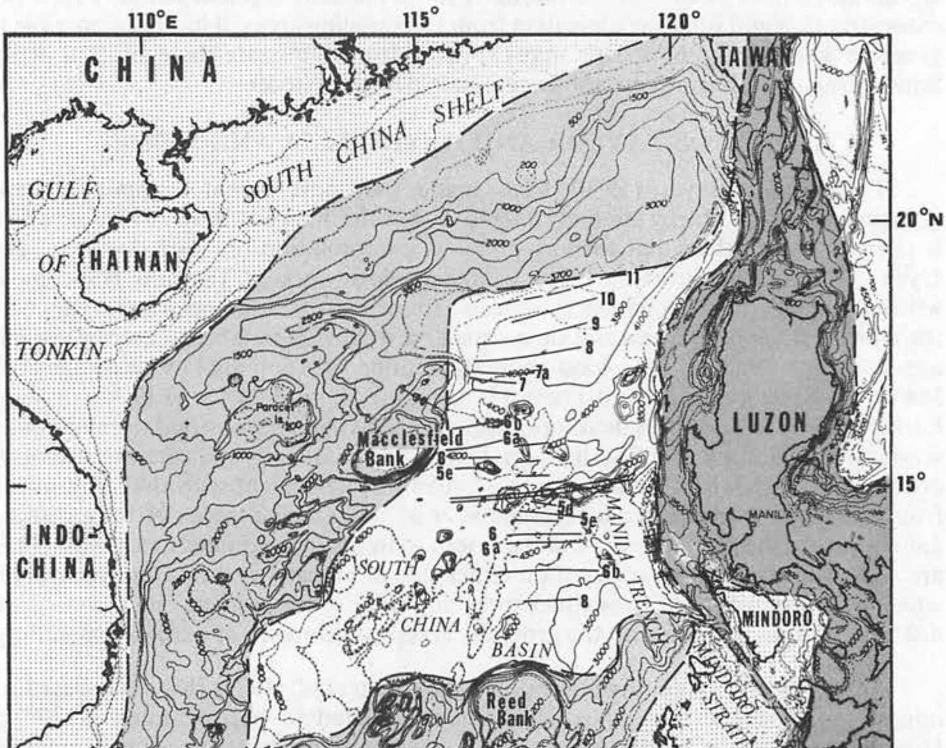

Fig. 2. South China Sea bathymetry. (after Mammerickx *et al.*, 1976) magnetic anomalies and crustal distribution.

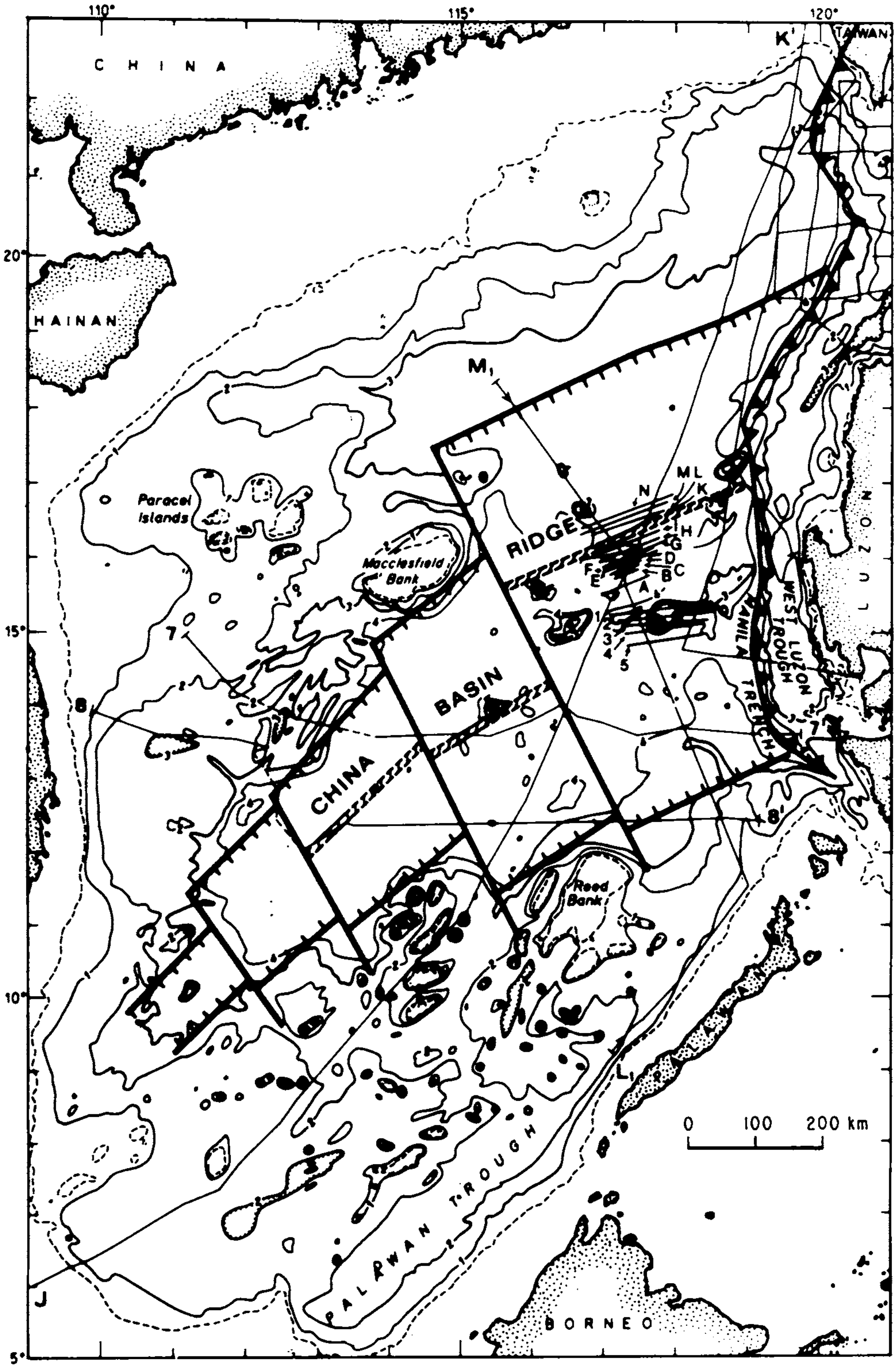

Fig. 3. Magnetic anomalies and sea-floor spreading model for the South China Sea Basin as interpreted by Bowin *et al.* (1978).

margin of the system progressively influenced and distorted the spreading process towards the west. This explanation is the one favoured by the author and is used as a working hypothesis in the evolutionary scheme discussed later.

Taylor and Hayes attempted to relate the South China Sea Basin spreading history to basin margin geology; particularly with reference to the Reed Bank well Sampaguita-1 and the wells drilled by Conoco south-west of Taiwan. Taylor & Hayes recognised two important unconformities within the Sampaguita well section which are dated as Mid-Eocene and Middle to Upper Oligocene. Taylor & Hayes interpreted these unconformities as the "rift-onset" and "breakup" unconformities (Falvey, 1974) respectively of the South China Sea Basin spreading episode.

It will be shown later in this discussion, by reference to substantial additional well and seismic data unavailable to Taylor & Hayes, that the "rift-onset" unconformity should be placed at the Cretaceous-Palaeocene boundary rather than at Mid-Eocene level. In other respects, Taylor & Hayes' interpretation is broadly corroborated.

STRATIGRAPHIC REVIEW

The oldest known sediments of the North Palawan block are Permian. Rocks older than Permian occur in onshore areas of China but are not considered relevant in this discussion and are therefore omitted from the following review.

Mindoro

Much confusion and contradiction exists in the literature concerning the stratigraphic column in Mindoro especially with regard to the upper Palaeogene and Neogene sections. The dating of the various associated extrusive and intrusive rocks is also unclear.

The oldest rocks of Mindoro constitute the Mindoro metamorphic basement complex and consist of undifferentiated amphibolite, quartz feldspathic and mica schist and phyllitic slates frequently associated with marble and quartzite. In some areas greenschist, talc schist, gneissose rocks and serpentinite have also been recorded (Hashimoto and Sato, 1968; Philippines Bureau of Mines, 1974). The whole sequence is locally intruded by hornblende quartz diorite. The age of intrusion is unknown but, owing to the presence of igneous clasts at the base of the locally overlying Jurassic sequence (Hamilton, 1979), it is speculated here that the event could be Triassic or Early Jurassic. The basement complex is dated tentatively as Permian and older on regional correlation with North Palawan, where Permian fusulinids have been found, and a Permo-Carboniferous limestone outcrop on Carabao Island off the northwestern tip of Panay Island (Fig. 1) (Hamilton, 1979). The Mindoro basement complex is also overlain unconformably by Jurassic strata (Hashimoto and Sato, 1968).

The Jurassic of Mindoro consists of an ammonite bearing clastic sequence comprising arkose, subgreywacke and mudstone with associated chert. The sequence locally ovelies a basal conglomerate. These rocks have been dated as Callovian to Oxfordian (Hashimoto and Sato, 1968).

No Cretaceous or Palaeocene sediments are recorded onshore Mindoro though the Cretaceous has apparently been penetrated by offshore drilling in the Mindoro Straits (Fig. 1). A Lower Eocene section has been described by petroleum geologists as mostly quartz-rich arkosic sands with thin interbedded carbonate and shale beds deposited in a shallow marine environment. The Middle and Upper Eocene consist mainly of oncolitic and orbitoidal limestones with minor interbedded shale.

The presence of Oligocene rocks on Mindoro is disputed amongst various authors. The Philippine Bureau of Mines (1974) records an Oligocene to Miocene sequence of conglomeratic wackes, shales and reef limestones associated with basic to intermediate lava flows and pyroclastics. Balce *et al.* (1979), however, dates this volcanic assemblage as Pliocene to Recent.

The Upper Miocene to Recent sequence consists chiefly of marine clastics and reefal carbonates overlain by mainly alluvial deposits.

North Palawan

The stratigraphy of northern Palawan island is less complex than that of Mindoro but is likewise documented only from a number of reconnaissance surveys. The following account is based on Hashimoto and Sato (1973) and from field work by Phillips geologists.

The oldest rocks of northern Palawan are dated as Middle Permian on the basis of fusulinids and conodonts. They consist of brecciated and contorted sandstone, altered tuffs and slate. Overlying this sequence is a massive Middle to Upper Permian fusulinid bearing limestone. The Permian section of northern Palawan is believed to be the unmetamorphosed equivalent of the Mindoro metamorphics.

The Middle Triassic is represented on North Palawan by conodont-bearing cherts which unconformably overlie the Permian sequence. They in turn are overlain by an undated sequence of slightly metamorphosed arkosic sandstones. These are also tentatively assigned to the Mid-Triassic in this paper.

Although not seen on northern Palawan itself, limestones with a Rhaetian (Jurassic/Triassic boundary) fauna have recently been documented (Fontaine, 1979) on the Calamian islands to the north (Fig. 1). In this setting, Fontaine described the Rhaetian limestones as unconformably overlying a deep marine formation consisting largely of radiolarite which he dated as Mid-Triassic. These radiolarites presumably correlate with the conodont bearing cherts of nothern Palawan.

The Jurassic and Cretaceous systems are apparently unrepresented onshore northern Palawan. Tertiary rocks are only very locally distributed and consist entirely of carbonate. Most notable of these carbonate occurrences is the St. Paul's limestone. This massive sequence of coralgal and foraminiferal limestones has been studied by

Phillips geologists and samples collected by them demonstrate an age span from Eocene to Middle-Miocene (Park & Peterson, 1979). The difficult terrain of the area precluded an even distribution of sampling throughout the St. Paul's limestone section but it is suspected, on regional grounds, that a hiatus is present at Middle to Upper Oligocene level.

Upper Miocene to Recent carbonates, developed peripherally to the main St. Paul's limestone buildup, point to a phase of late Mid-Miocene uplift and non-deposition corresponding to that found in offshore areas (see below).

Igneous rocks in northern Palawan are chiefly represented by two quartz monzonite plutons which cut the older sediments and metasediments. No radiometric dates are available for these plutons and various ages have been assigned to them. However, it is speculated here that these, like the intrusives within the Mindoro metamorphics, are of Late Triassic to Early Jurassic age.

Offshore Northeast Palawan (Sulu Sea)

Mesozoic sediments have been found in the subsurface off the Sulu Sea coast of northern Palawan. The sediments are typically poorly sorted argillaceous and locally conglomeratic quartzose sandstones interbedded with clays and silts. This sequence has been tentatively assigned an Upper Cretaceous age on palynological grounds. Ultrabasic rocks were encountered beneath the Cretaceous section but it is not known whether the relationship between the two is stratigraphic or tectonic.

Also present in the subsurface section is a significant angular unconformity whose age is established as late Middle Miocene. This is inferred from the occurrence of uppermost Mid-Miocene silty sands and clays immediately above the unconformity, and Mid-Miocene clays below the unconformity. The post unconformity sediments grade from calcareous clays and sands of late Middle and Late Miocene age into platform and reefal limestones dated as Pliocene to Recent.

Offshore West and Northwest Palawan

Pre-Tertiary sediments have been penetrated by at least three wells on the west and northwest Palawan shelf. The oldest sediments are Permian limestones which were found in the northwestern part of the shelf and are presumably correlatives of the Permian carbonates which crop out onshore. Upper Jurassic to Lower Cretaceous shales and carbonates have been encountered in the same area while Lower Cretaceous neritic carbonates, sands, silts and shales are present further to the southwest.

Lower Palaeogene sediments are generally absent in the Palawan shelf subsurface, but in one well a thin Lower Eocene dolomite sequence overlying a basal conglomerate was penetrated. The Late Palaeogene in much of the northwest Palawan shelf is represented by an Upper Eocene transgressive sand overlain by an Upper Eocene to Lower Oligocene carbonate platform (Beddoes, 1980; Hatley, 1980). The middle and upper part of the Oligocene appears to be missing throughout the west and northwest Palawan shelf area.

The Lower Miocene is commonly represented by carbonates, however, rhyolitic volcanics dated radiometrically as 22 Ma were found in one well. In contrast, the Middle Miocene is dominated by neritic clastics. The end of the Middle Miocene is marked by a pronounced regional unconformity which is believed to correlate with that found in the Sulu Sea subsurface and onshore.

The Upper Miocene section chiefly consists of a prograding sequence of mixed neritic clastic sediments which give way in the Pliocene and Pleistocene to shelf and reefal carbonates.

Reed Bank

Published information (Taylor & Hayes, 1980) on the stratigraphy of the Reed Bank area is derived from the Sampaguita-1 well. The oldest sediments penetrated comprise a paralic to neritic sequence of mixed clastics and carbonates tentatively dated as Lower Cretaceous. A major hiatus exists between these sediments and the overlying Palaeocene/Eocene section. The base of this sequence is marked by a thin limestone overlain by neritic shales followed by massive, neritic, quartzose sands. These sands are clearly the erosional product of nearby continental granitic basement and constitute one of the main pieces of evidence that the Reed Bank area comprises continental crust.

The Lower Eocene sands underlie bathyal shales which persist upwards to an important stratigraphic break at the end of the Middle Eocene. The Upper Eocene to Lower Oligocene section consists of paralic coarse sands and interbedded silts and shales. This sequence is separated from the overlying Upper Oligocene to Recent massive shelf and reefal carbonates by another important regional hiatus of Middle to Late Oligocene age.

China Shelf (Pearl River Mouth Basin)

The stratigraphy described below for the China shelf area is mostly inferred from onshore geology and extensive recently completed seismic surveys. Little well control is available in the area and much of the older part of the section has never been penetrated.

Acoustic basement underlying much of the South China shelf probably consists of Early to Late Palaeozoic meta-sediments. Triassic sediments are thought to be mostly absent and the system is probably represented by a period of intense magmatism. The Mesozoic section spans from the Lower Jurassic to the lowermost Upper Cretaceous. However, the high intensity of Late Jurassic magmatic activity recorded in the Upper Jurassic onshore mainland China (Jahn *et al.*, 1976) suggests that a corresponding Upper Jurassic hiatus is likely to be present offshore. The Jurassic and Cretaceous sediments are expected to consist of a largely non-marine to paralic sequence of feldspathic sandstones and conglomerates with shales, siltstones and coals.

A major angular unconformity separates the Mesozoic sequence from the overlying Palaeogene sediments. The missing section comprises almost the whole of the Upper Cretaceous. The earlier part of this stratigraphic gap corresponds with a second peak of magmatic activity, as recorded in onshore areas (Jahn *et al.*, 1976). The Palaeogene section is believed to consist largely of lacustrine, argillaceous sediments with minor amounts of silt and sand.

The Neogene overlies the Palaeogene unconformably with the Middle and Upper Oligocene missing. The basal part of the Neogene interval is thought to consist of fluvio-lacustrine sands and shales grading up into marginal marine clastics and, locally, carbonates. The middle and upper parts of the Neogene comprise marine, mainly argillaceous rocks. An unconformity is present at base Pliocene level.

Offshore Taiwan

Stratigraphic information for the wells drilled by Conoco offshore southwest Taiwan has been published by Taylor & Hayes (1980). Information is also available from the Tungliang well located on the Penghu islands in the Formosa Strait.

The oldest rocks penetrated are indurated sands, silts and shales of Lower Cretaceous age. These are overlain unconformably in the more basinal Conoco wells by a very thin Lower Oligocene sand/shale sequence. Elsewhere the Cretaceous is directly overlain by the Neogene. In the Tungliang well, the basal part of the Neogene section comprises a thin carbonate horizon of Lower Miocene age which underlies a predominantly arenaceous, marine, Middle and Upper Miocene sequence. The equivalent section in the Conoco wells comprises shale and silt. An unconformity occurs at the base of the Pliocene in both areas and is overlain by marine clays.

Onshore Taiwan

Penghu-Peikang High. Three stratigraphic tests have been drilled on the Penghu-Peikang High which is an east-west basement axis underlying part of the western coastal plain of Taiwan. These wells penetrated a Mesozoic section unconformably underlying a Neogene cover of paralic to marine mixed clastics. The Mesozoic sediments are of brackish to marine origin and consist of conglomerates, quartzites, grey-wackes and shale with some minor carbonate intercalations. The sequence is intruded by quartz porphyry, quartz basalt and diabase (Chou, 1970, 1972).

The dating of the Mesozoic sediments has been subject to controversy. The sequence is apparently subdivided into three parts by two angular unconformities. Dips in the lowest part are up to 40° whereas in the middle part they moderate to between 4° and 12°. Dips in the upper part are generally less than 4° (Stach, 1958).

Stach (*op. cit.*) dated the middle part of the sequence as Jurassic on the basis of a crushed ammonite specimen. He therefore designated the lower part as pre-Jurassic and the upper part Cretaceous. Matsumoto *et al.* (1965) examined a larger volume of material and identified three species of ammonites and fourteen species of other molluscs from the middle part of the sequence which indicate an Early Cretaceous age. The dating by Matsumoto *et al.* would therefore appear to be more reliable than that of Stach. The dating of the lower and upper parts is still open to debate. The lower division is here tentatively assigned to the lower part of the Jurassic on the grounds of its greater deformation and induration; a possible result of the Late Jurassic phase of magmatism and deformation recorded in mainland China (Jahn *et al.*, 1976). It is also suggested here that the upper part could be Upper Cretaceous or possibly Lower Palaeogene.

Central Range. The oldest rocks exposed on Taiwan are found within the Central Range metamorphic sequence. These comprise schist, gneiss and marbles (Ho, 1967; Biq, 1974) intruded by amphibolites, metadiabase and serpentinites; the metamorphic equivalents of various basic and ultrabasic effusive rocks (Ho, 1967). Traces of Permian fusulinids have been identified from the marbles.

Unconformably overlying the Late Palaeozoic sequence is a Cretaceous to Oligocene succession of slates, phyllites and subordinate quartzites (Biq, 1974). The environment of depostion appears to grade upwards from bathyal to paralic. The sequence is apparently divided by an unconformity which separates the Cretaceous from the overlying Palaeogene (Biq, *op. cit.*; Ho, *op. cit.*). It is also intruded by quartz diorites which show dates of 86 Ma and 33 Ma (Ho, *op. cit.*). Some authors (Ho, *op. cit.*) document an unconformity between the Palaeogene section and the overlying Neogene sequence, i.e. corresponding to the Late Oligocene. The Neogene comprises a shallow marine to paralic mixed clastic facies with local coal development.

Onshore China

The following summaries of onshore China stratigraphy are drawn from a compilation by Robertson Research (1978) and from "A Regional Stratigraphic Table of China" compiled by the Geological Research Institute of the Academia Sinica (1958). Both sources are based on numerous original references.

Eastern Fukien. The Permian is represented mostly by red shales grading up into brown sandstones and grey-black shales deposited under mainly shallow marine to paralic conditions. The Triassic is absent but the Lower Jurassic comprises a paralic sequence of quartzites and vari-coloured shale. The Lower Jurassic is overlain unconformably by a thick volcanic suite consisting of rhyolite, andesite, andesite tuff and volcanic breccia. This assemblage has been dated as Cretaceous. The volcanics are locally covered by an Upper Miocene to Recent sequence of conglomerates, sands and shales. No Palaeogene or lower Neogene sediments are present.

Hong Kong. In the Hong Kong area, the Permian comprises marine shales and silts locally showing evidence of low grade metamorphism. The Triassic is absent and the Permian is overlain by a Lower and Middle Jurassic sequence of deltaic to marine sands, silts and shales topped by acid lavas and ignimbrites. No Upper Jurassic sediments occur but the interval is represented by a number of granitic intrusives. The Lower Cretaceous comprises fluvial sands and conglomerates while the Upper Cretaceous to Eocene section consists of fluvial or lacustrine shales and silts. Middle Eocene to Pliocene sediments are absent but Pleistocene breccias occur locally.

Eastern Guangdong. The Permian of eastern Guangdong consists of fossiliferous carbonates underlying a continental mixed clastic sequence with local coal development. The Permian is unconformably overlain by a thin paralic Lower Triassic sand/shale sequence. The Middle and Upper Triassic are absent. The Lower Jurassic comprises a mainly arenaceous continental sequence with coaly horizons. No sediments of Middle or Upper Jurassic age occur but the Late Jurassic is represented by granitic intrusions.

A more or less full Cretaceous section occurs in eastern Guangdong and is developed in two facies; a volcanic assembage of rhyolite with associated quartz porphyry and a paralic to shallow marine sand/shale sequence. An unconformity separates the Mesozoic and Cenozoic sections. The Cenozoic is represented by a continental facies of conglomerates, sands and shales. No distinct hiati have been documented in the Cenozoic sequence but the sediments are thin and diagnostic fossils are rare. Several periods of non-deposition may therefore be represented.

INTERPRETATION FROM STRATIGRAPHIC CORRELATION

Figure 4 is a stratigraphic correlation chart of all the areas reviewed above. Immediately apparent is the regional persistence of the major gaps in pre-Neogene sedimentation throughout the areas examined. Four prominent regional unconformities have therefore been recognised all of which can be correlated with important tectonic events documented on, or immediately offshore, the southern China mainland.

The oldest of these unconformities occupies most of the Triassic in the majority of areas but is present without exception in the Upper Triassic. This break is therefore coincident with the Indosinian Orogeny which is recorded throughout Indochina and the southern borders of China. The orogeny reached its climax in the Upper Triassic with the suturing of the Indochina and South China Blocks along the Red River line (Fig. 1) (Hutchison, 1975; Fontaine & Workman, 1978).

Intrusives of this age occur in the vicinity of the Red River line and have also been found in the subsurface of the South China shelf. The quartz monzonite and quartz diorite intrusions within the North Palawan basement and the Mindoro metamorphics are also very tentatively correlated with Indosinian orogenic activity. Fontaine (1979) also attributes the unconformity between the Mid-Triassic radiolarites and the Rhaetian limestones on the Calamian Islands to the Indosinian event.

The second regional unconformity is dated as Upper Jurassic and may therefore be related to one of the earlier phases of the Yenshanian orogeny of mainland China. This phase of the Yenshanian was accompanied by extensive magmatic activity (Jahn, *et al.*, 1976) as represented on Figure 4 by the granites of eastern Guangdong and Hong Kong.

The Cretaceous-Palaeocene boundary is indicated as being the age of the third regional event. The only area where this break is not obviously expressed is in the vicinity of Hong Kong. However, the sediments present are part of a thin, poorly dated continental sequence. The apparent lack of expression of the unconformity in the Hong Kong area is therefore not considered significant.

This third event corresponds with the latest phase of the Yenshanian Orogeny as recorded onshore China. It also corresponds, according to petroleum industry seismic

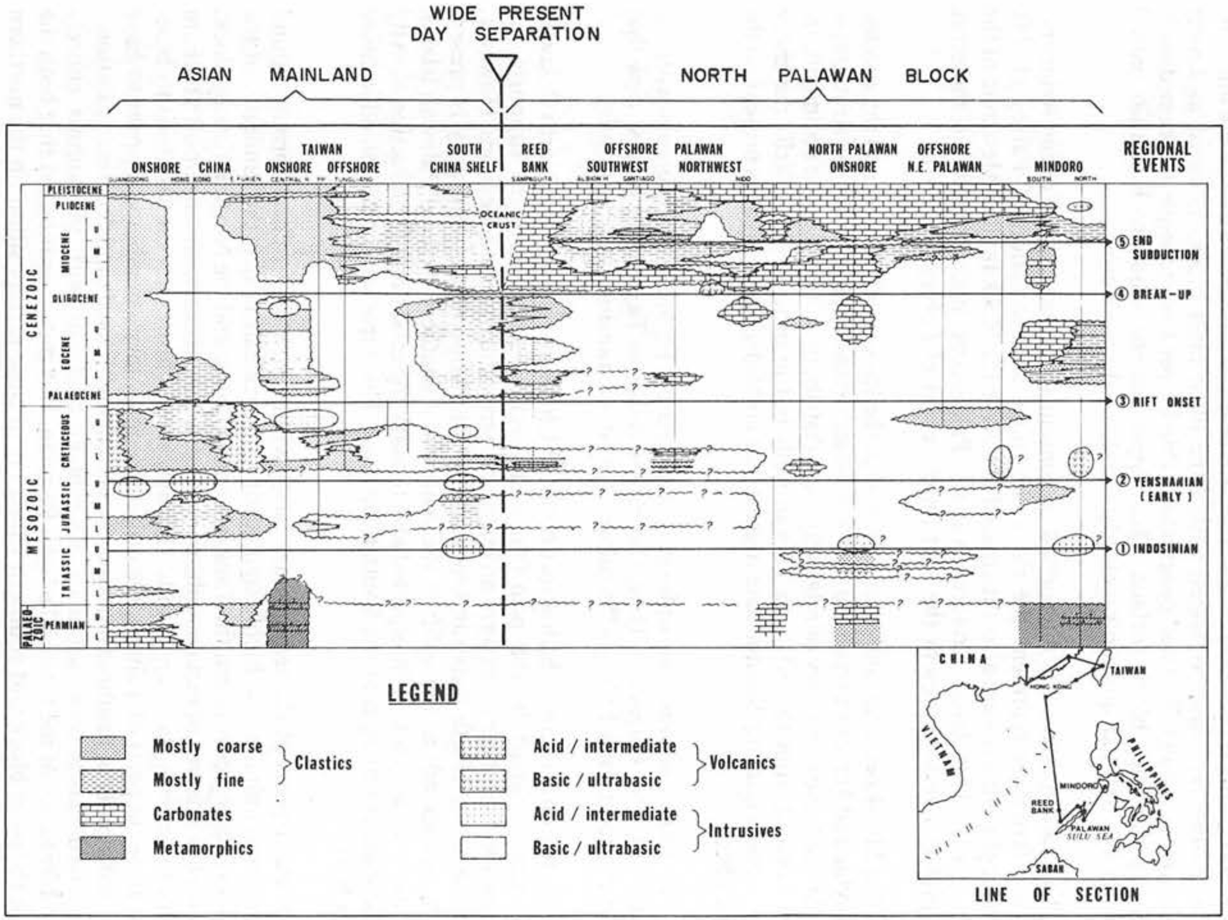

Fig. 4. Lithostratigraphy of the northern and southeastern margins of the South China Sea Basin.

data, with the inception of tensional block faulting on the South China margin and in the North Palawan block. Figure 17 is a northwest-southeast orientated seismic profile from Phillip's Northwest Palawan contract area. Control for the dating of the various sedimentary units is provided by a well drilled at the southwestern end of the line. The oldest sedimentary unit contained within the tilted fault blocks is dated as Lower Cretaceous and older. The well penetrated a thin Upper Eocene sequence immediately overlying the fault block surface. This Upper Eocene sequence is a thin partial equivalent of the half-graben fill clearly visible to the northwest.

The half graben fill is interpreted to contain Palaeocene and Eocene sediments and is inferred to represent the rift valley stage sedimentation of Falvey (1974). Palaeocene sediments are also anticipated to overlie the block faulted Mesozoic of the China shelf. This latest Cretaceous/Early Palaeocene unconformity is therefore interpreted here to represent the "rift-onset" event of Falvey (*op. cit.*).

The Mid-Eocene unconformity present in the Reed Bank section and interpreted by Taylor and Hayes to represent the "rift-onset" event appears from the stratigrapic correlation table to be only of relatively local distribution. Mid-Eocene sediments are indeed absent from the offshore Taiwan wells but in most of these wells the entire Palaeogene is missing. Seismic date suggest that no Mid-Eocene break is present on the China shelf.

The fourth regional unconformity depicted on Figure 4 corresponds with the Middle to Upper Oligocene. Here, the author endorses Taylor and Hayes' view that this event represents Falvey's "breakup" (rift-drift transition) unconformity.

No regional events which affect both the China margin and the North Palawan block are apparent in the post-Oligocene section which strongly supports the supposition that these areas were no longer conterminous in Neogene times. However, confined to the North Palawan block, a late Mid-Miocene unconformity is present which corresponds to the uplift of the central and southern parts of Palawan island. The unconformity is here interpreted also to mark the cessation of subduction activity on the southern margin of the South China Sea. This topic will be examined in more detail later.

Some aspects of the sedimentary facies within each major unconformity bound depositional unit are also highly significant. Of particular note is the similarity of the Permian lithologies between the Taiwan Central Range and the North Palawan block. Although the degree of metamorphism of these sediments varies from almost absent in much of northern Palawan islands, through greenschist facies on Mindoro to blueschist facies in parts of Taiwan, the original sedimentary assemblages appear to have consisted mainly of fusulinid limestones and shales with local sandstone intercalations. This mixed clastic and carbonate assemblage contrasts with the almost entirely carbonate facies of the typical Tethyan Permian. It is therefore inferred that both the North Palawan block and southern China lay in close juxtaposition on the northern margin of the Tethys seaway.

The original metamorphism of the Permian and older sediments was probably due to Indosinian orogenic activity. However, in Taiwan, this has become partially overprinted as a result of Pliocene island arc collision (Bowin *et al.*, 1978).

Facies comparison of the Jurassic unit (deposited between the Indosinian and Early Yenshanian events) is difficult owing to the very poor representation of this sequence on the North Palawan block. However, the Cretaceous unit shows a progressive facies change from northwest to southeast from fluvio-lacustrine with abundant associated volcanics in onshore China via fluvio-deltaic and shallow neritic on the China Shelf, Taiwan and the Reed Bank to fully marine in the northwest Palawan subsurface. The only exception to this progression is the occurrence of paralic Upper Cretaceous sediments in the Sulu Sea subsurface offshore Northeast Palawan. It will be shown later that these sediments were probably deposited in an outer-arc environment while the more marine assemblage to the north can tentatively be assigned to a forearc basic setting. A similar north to south progression from fluvio-lacustrine to marine facies is seen within the overlying Palaeogene section.

In the Neogene section, a sharp conrast is observable between clastic dominated facies on the China margin and carbonate dominated facies on the North Palawan block. This contrast indicates a lack of continuity between the two areas and is inferred to have resulted from their increasing separation by oceanic crust generation.

In conclusion, both the tectonic and stratigraphic inferences made from the correlation of late Palaeozoic to Recent stratigraphy of the South China Sea margins strongly support the supposition that the North Palawan block was an integral part of the southern China continental massif until the Mid-Oligocene.

SPREADING BY CONTINENTAL CRUST ATTENUATION

Before attempting to reconstruct the pre-rift and drift positions of the geological elements under discussion, a closer look must be taken at the areas of continental crust which flank the wedge of true oceanic crust in the South China Sea Basin. Examination of Figure 2 demonstrates the extremely irregular bathymetry of these areas and indicates the very broken nature of the crustal material. Furthermore, the bathymetry data show that there is a substantial westward increase in the breadth of broken continental crust towards the Indochina Block and the Sunda Shelf. A corresponding westward decrease in the width of true oceanic crust is also evident. These observations and the almost regular rhomboidal form of the South China Sea margins suggest that the total extension in the the South China Sea Basin has been essentially uniform from east to west. However, it appears that in the west, most of this extension has been achieved by stretching of the continental crust whereas in the east a greater part has occurred as a result of true sea-floor spreading. It is suggested here that this phenomenon was in some way controlled by the presence of the cratonised mass of the Indochina Block and Sundaland on the immediate western margin of the spreading system.

A consequence of this interpretation is that all the extension by continental crust attenuation in the South China Sea Basin must have taken place between the "rift-onset" and "breakup" events, i.e. between the latest Cretaceous/earliest Palaeocene and the Mid-Oligocene. As it is likely that no true oceanic crust is present in the basin west of $111\frac{1}{2}$°E, spreading in this area must theoretically have been completed by Mid-Oligocene times. However, tectonic events in western Sarawak (Liechti *et al.*, 1960; Haile, 1974) suggest that, in this western zone, spreading ceased in Late Eocene times owing to marginal constraint on the spreading system.

As will be shown later during discussion of the evolutionary model, the southern margin of the China shelf continental material must have migrated southwards towards Borneo by nearly 700 kms between the beginning of the Palaeocene and the Late Eocene: a period of about 25 Ma. This represents a southward movement slightly in excess of 3 cms per year (comparable with sea-floor spreading rates) and an overall continental crustal stretching of about 85%.

Stretching and stretching rates of this magnitude have recently been documented to have occurred in various sedimentary basins around the world. In the North Sea Basin, a stretching of between 50% and 100% took place between the Middle Jurassic and the end of the Early Cretaceous (Sclater and Christie, 1980). A stretching of 100% is apparent in the Basin and Range region of the western U.S. (Profett, 1977), and 200% in the Pannonian Basin of Hungary (Sclater *et al.*, 1980).

Sclater and Christie (1980) and Jarvis and McKenzie (1980) have described a mechanism by which stretching of continental crust of these proportions may take place and have demonstrated such a mechanism to have been operative in both the North Sea and Pannonian Basins. Essentially the phenomenon is initiated by a strong thermal event which causes a thermal relaxation of the crustal material. Stretching and attenuation of the crust and the deeper lithosphere then take place by listric normal faulting, magmatic intrusion and possibly physical stretching of the crustal material itself. In the South China Sea Basin, listric normal faulting is probably the principle stretchng mechanism and this faulting is clearly demonstrated on seismic profiles. Figure 5 shows a good example off the coast of Vietnam.

The model suggests that stretching is at a maximum near the axis of attenuating crust and decreases towards the edges. This is almost certainly the case in South China Sea Basin as oceanic crust eventually broke through along the axial zone.

The attenuation phenomenon in the South China Sea Basin is believed to have been fairly uniform from west to east (despite variations arising from local differences in lithological composition and competence). However, the absolute velocity of southward movement would have been proportional to the width of crust being attenuated. As this width is far greater in the west than in the east, the speed of southward movement would have correspondingly decreased from west to east. This decrease may have been absorbed evenly across the stretching crust or it may have been taken up on a series of discrete offsets. If the latter were the case, these offsets might have influenced the development of the observed offsets in the subsequently generated oceanic crustal wedge.

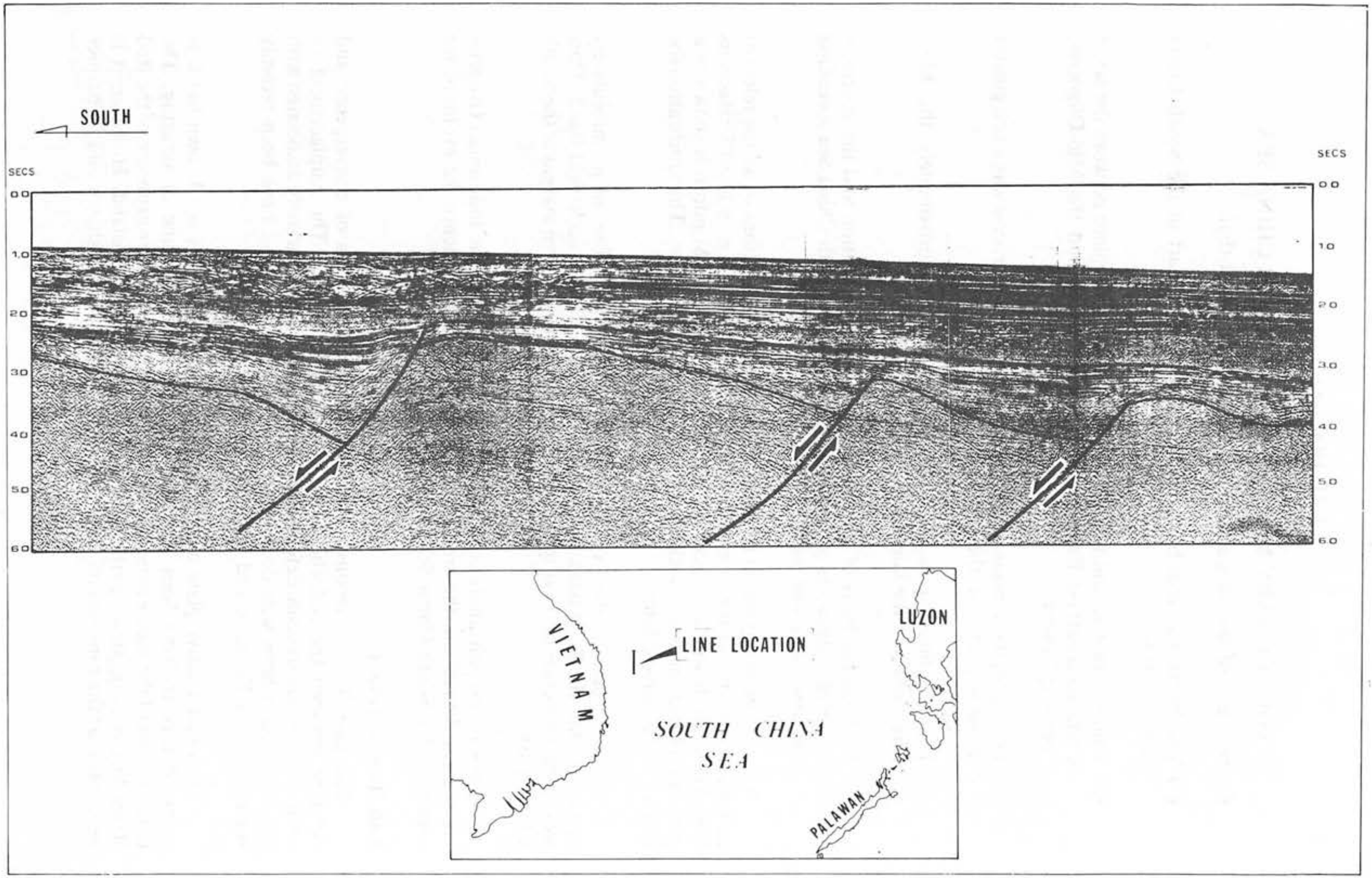

Fig. 5. Unmigrated time seismic section. Block faulting in the South China Sea Basin off Vietnam.

EVOLUTIONARY MODEL FOR THE SOUTH CHINA SEA

On the basis of the foregoing discussion, we can accept that:

(1) The North Palawan block was once an integral part of the South China continental massif.

(2) That substantial continental crust attenuation took place between the latest Cretaceous/earliest Palaeocene "rift-onset" event and the Mid-Oligocene "breakup" event.

(3) The the total extension achieved by this attenuation process was much greater in the west than in the east.

(4) That sea-floor spreading took place between approximately the Mid-Oligocene and the latest Early Miocene.

(5) That, on the basis of the magnetic anomaly orientation and the generally accepted constraints of spreading geometry, the South China Sea spreading was essentially due north-south.

We are now in a position to reconstruct the relative positions of all the relevant geological elements as they were before the onset of rifting (i.e. in latest Cretaceous times) (Fig. 8). It will be noticed on this reconstruction that Mindoro is shown in a position rotated some 80° clockwise from its present orientation. The justification for this will be discussed later.

The close juxtaposition of Mindoro and present day Taiwan is immediately apparent while the Reed Bank is seen to lie northeast of the Macclesfield Bank. Thus we can gain a picture of the original configuration of the southern margin of the South China massif.

The stratigraphic analysis has shown that the effects of the Indosinian Orogeny are present throughout the area so it is appropriate to commence the evolutionary history of the South China Sea in the Late Triassic.

Late Triassic (Fig. 6)

The Late Triassic reconstruction shows the final stages of convergence and suturing between the Indochina and South China blocks. The emplacement of ophiolites, metamorphism, deformation and igneous intrusive activity associated with this event have been well documented by many workers and have been recently summarised by Fontaine and Workman (1978).

The exact relative plate motion leading to the collision is not known but it is assumed here to have been approximately normal to the line of suturing. The continuation of the suture zone southeastwards from the onshore exposure of the Red River line is conjectural, particularly to the east of Hainan island. However, it is probable that the zone was offset to the north as schematically shown on Fig. 6, since

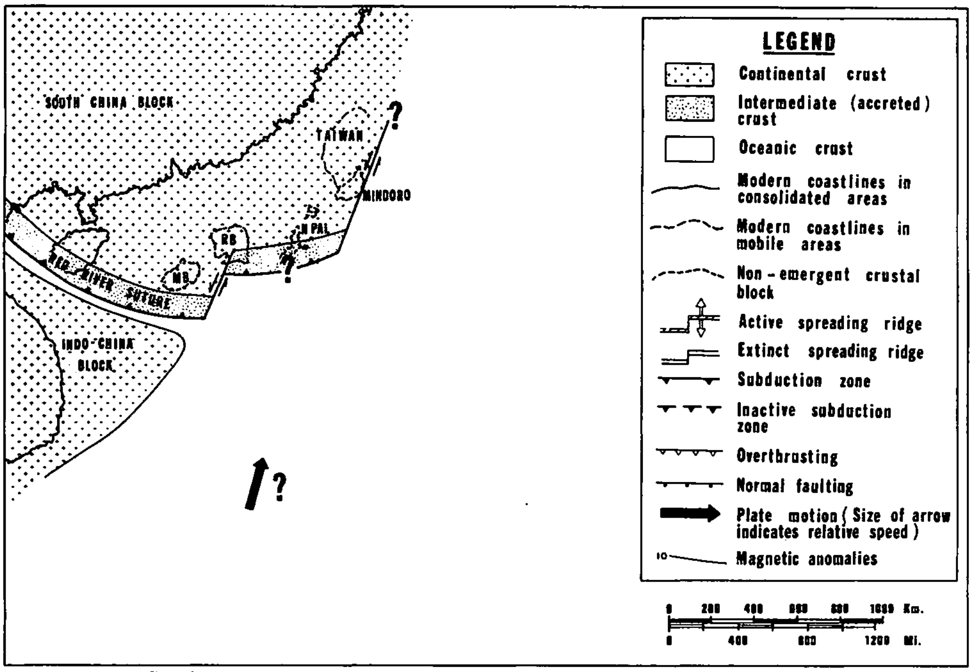

Fig. 6. Late Triassic reconstruction. MB: Macclesfield Bank, RB: Reed Bank, N PAL: North Palawan.

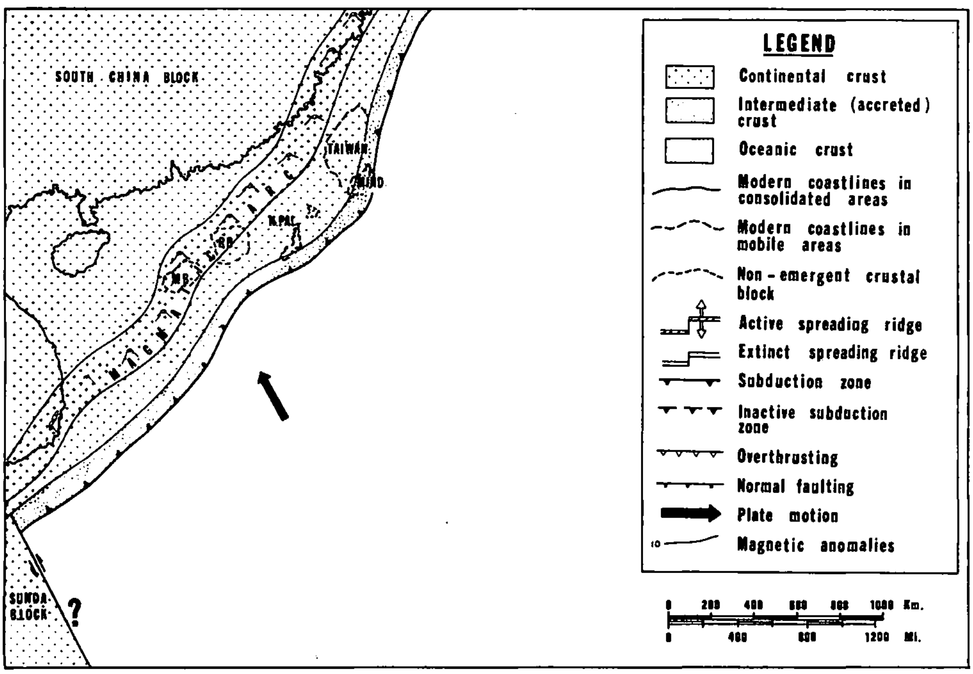

Fig. 7. Mid Jurassic-Mid Cretaceous reconstruction. MB: Macclesfield Bank, RB: Reed Bank, MIND: Mindoro, N PAL: North Palawan.

the metamorphism recorded in the Permian sediments in these more eastern areas is thought to be related to the Indosinian rather than a later event.

Mid-Jurassic to Mid-Cretaceous (Fig. 7)

A major realignment of plate motions followed the Indosinian event. Of particular significance is the commencement of a spreading episode between Australia and a continent (or continental fragments) to the northwest in the Mid to Late Jurassic. This event is documented by the east-northeast orientated Oxfordian and Kimmeridgian spreading anomalies recorded in the Wharton Basin (Hamilton, 1979) off the northwest coast of Australia.

The net result of this spreading episode was to produce north-northwest directed plate motion which converged with a northwest dipping subduction zone on the southeastern margins of the Indochina and South China blocks (Fig. 7). This subduction is recorded by the Mid-Jurassic to Mid-Cretaceous calcalkaline extrusive and intermediate to acid intrusives of southeastern Vietnam and eastern China (Hamilton, 1979). The Late Jurassic phase of the Yenshanian Orogeny with its attendant magmatism and uplift is therefore related to this subduction.

The position of the subduction zone shown on Fig. 7 is inferred from an acceptable magmatic arc-trench gap with respect to the Vietnam and east China magmatics. The zone should also have lain just southeast of the reconstructed position of the North Palawan block. The position of the magmatic arc between the southeast Vietnam and east China points of control has therefore in turn been inferred from the position of the subduction zone to maintain an arc-trench gap of no more than 300–400 kms. It will be noticed that the magmatic arc is shown trending southwestwards offshore from the Fukien coast of China and to the west of Taiwan. Some evidence for the probable existence of this offshore continuation of the magmatic arc has recently emerged. Extensive multi-channel seismic data, recently acquired across the breadth of the China shelf south of the port of Shantou, shows a broad southwest trending basement high. This high displays a magnetic signature characteristic of igneous rocks.

The inferred position of the Jurassic-Cretaceous subduction trench to the southeast of Vietnam also establishes the pre-drift southern limit of continental crust in the western part of the South China Sea Basin. The distance between this limit and the northern limit of extensional faulting, which lies just south of the island of Hainan, permits an estimate of the original width of continental crust before attenuation. This in turn allows the computation of the 85 % degree of attenuation referred to previously.

The position of the subduction zone also shows the relationships of the North Palawan block to the probable positions of the trench, outer arc and forearc zones of the system.

Owing to the presence of Sundaland to the southwest of the Indochina block, the South China margin subduction trench could not have continued southwestwards much beyond the southeastern flank of present day Vietnam. The termination could have been in the vicinity of the Con Son Islands (Fig. 1) where Jurassic to Cretaceous granites are documented (Hamilton, 1978). It is suggested here that the subduction system was offset over 1000 kms to the south-southeast by a transcurrent fault which must have followed the northeastern margin of the west Borneo sector of the Sundaland block. This arrangement presupposes that the west Borneo area has undergone approximately 45° of anticlockwise rotation since the Cretaceous. Such a rotation has been suggested by the palaeomagnetic evidence of Haile *et al*, (1977). The transcurrent fault would then have linked with another convergent margin on the southern flank of Sundaland from southeast Borneo across to Java and Sumatra.

Late Cretaceous (Fig. 8)

Overall vectors of plate motions established in the Jurassic continued into the Late Cretaceous. However, subduction had ceased on the South China margin. This is inferred from the cessation of calcakaline volcanic activity on the China margin at this time. It is suggested here that the zone of convergence jumped south-southeastwards to eliminate the transcurrent offset along the northeast margin of Sundaland. Thus an almost uninterrupted northward dipping subduction trench was created which ran from Sumatra through Java and southeast Borneo and on to the east-northeast. The cause of this jump may have been connected with the collision of a microcontinental fragment with southeastern Borneo in the early Late Cretaceous. The dating of the collision and the involvement of a microcontinental block are inferred from the Late Cretaceous emplacement age of the Meratus Mt. ophiolites and melange of southeast Borneo (Hamilton, 1979), and the documentation of continental basement from well data in the northern part of the East Java Sea between southeast Borneo and southwest Sulawesi.

The extension of the subduction system to the east-northeast beyond the eastern extremity of Sundaland probably represents the inception of the proto-Philippine island arc system. The earliest island arc assemblages of the Philippines date from this time (Hamilton, 1979; Balce, 1979) and are found on several islands. The origin of the Philippines in approximately this position is supported by the palaeomagnetic date of Hsu and Sharon (1970, as quoted in CCOP/IOC, 1980), which suggest that Luzon island has suffered 70° of anticlockwise rotation and substantial northward movement since the Cretaceous. Dunn *et al.* (1979, as quoted in CCOP/IOC, 1980), in a more recent study, have shown that no significant movement has taken place since the Miocene. It will be seen in later stages of this model that the northward and anticlockwise rotational movements of Luzon were essentially completely by the Miocene.

It should be emphasised here that no attempt is made in this paper to present a detailed model for the evolution of the Philippine Archipelago. The representation of plate tectonic features in the Philippine area (except Palawan) is greatly simplified and entirely schematic. The model only purports to show the general area where the complex events of Philippine island arc development are taking place in relation to the other South China Sea margins. The modern coastline of the Philippine archipelago is shown on pre-Miocene reconstructions with the effect of the Miocene and post-Miocene Philippine shear zone removed.

The Late Cretaceous is the inception age of southward subduction activity along the Lupar line of western Sarawak (Haile, 1974; Hutchison, 1979). This predates

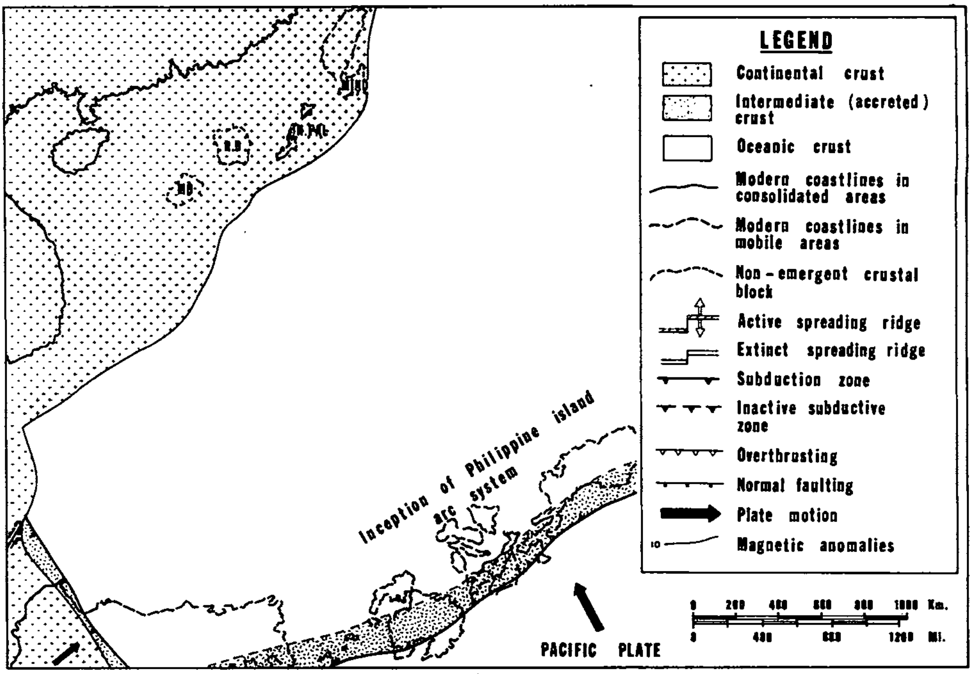

Fig. 8. Late Cretaceous reconstruction. MB: Macclesfield Bank, RB: Reed Bank. N PAL: North Palawan, MIND: Mindoro. Note that representations of plate tectonic features in the main part of the Philippine Archipelago on this and subsequent reconstructions are highly simplified and schematic.

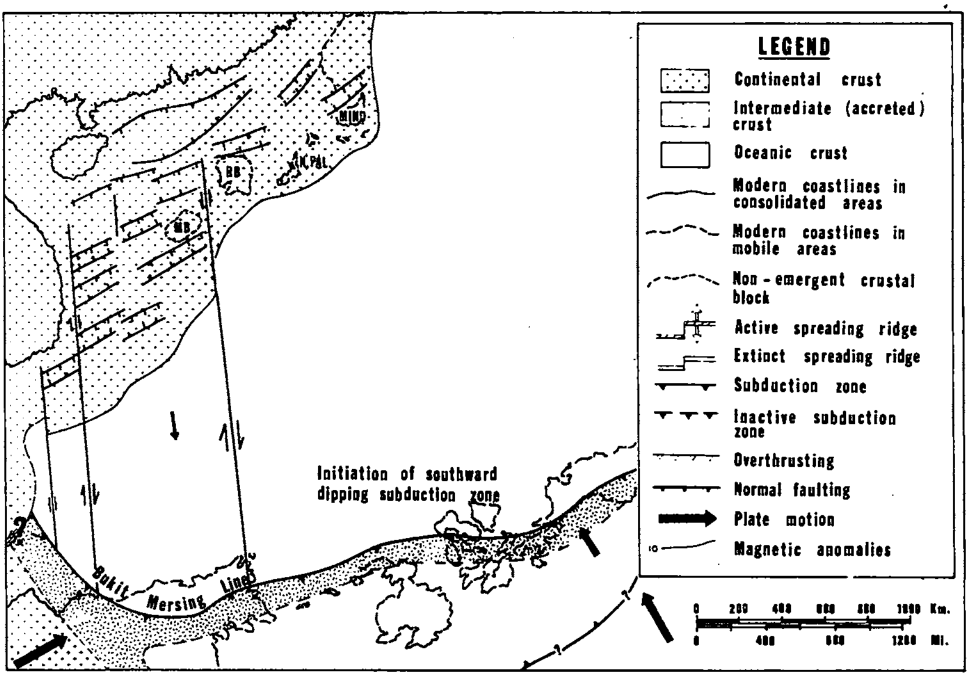

Fig. 9. Palaeocene reconstruction. MB: Macclesfield Bank, RB: Reed Bank, N PAL: North Palawan, MIND: Mindoro.

the initiation of southward crustal movement in the South China Sea Basin and must therefore be attributed to anticlockwise rotation of the west Borneo basement.

Palaeocene (Fig. 9)

By Palaeocene times, continental crust attenuation had commenced on the South China margin with concomitant southward movement of oceanic crust. Faulting on the China margin was initiated on a predominantly southwest-northeast trend approximately along the structural grain established during the Mid-Jurassic to Mid-Cretaceous subduction phase. Greatest crustal thinning is believed to have taken place along the trace of the palaeomagmatic arc. On the model of Sclater and Christie and Jarvis and McKenzie, this would be a logical location for the greatest intensity of thermal activity. The arc would also provide a natural zone of weakness along which the greatest crustal stretching could occur.

Convergence continued in western Sarawak both as a result of Borneo rotation and the southward movement of oceanic crust ahead of the advancing South China continental margin. During the Palaeocene, the accretionary wedge of the Sarawak subduction system built out to the north. Consequently, the position of the subduction trench also migrated northward. At some stage in the Palaeocene, the subduction trench is thought to have lain along the Bukit Mersing line of central Sarawak where ophiolites of Palaeocene emplacement age have been documented (Hutchison, 1975). This accretion, the continued rotation of Borneo and a complex interaction of plate boundaries in central Borneo apparently caused the southward dipping Sarawak subduction system to extend northeastwards into the proto-Philippine arc complex. Thus the complete Northwest Borneo/Palawan subduction system was established at this stage.

Meanwhile, to the south of the Philippine complex, northward convergence was still taking place as a result of Pacific Plate movement (Hilde *et al.*, 1976). This subduction zone probably represents a continuation of the southern Sundaland margin convergent system, by this time running through Java and Sulawesi (Hamilton, 1979).

Late Eocene (Fig. 10)

A major change in the direction of Pacific Plate movement occurred in the Late Eocene (44 Ma) as recorded by the change of alignment in the Emperor and other seamount chains in the Pacific (Clague and Jarrard, 1973). The new direction of movement near the Asian margin became west-northwest. It is suggested that it was this event which caused the evolving Philippine island are complex to commence its anticlockwise rotation towards its present position.

Meanwhile, continental crust attenuation of the China Margin continued uninterrupted in a north-south orientation. Slippage of the southward migrating continental blocks against the Indochina and Sunda cratonic areas was presumably taken up by right lateral shear. The approximate position of this shear is manifested in present day bathymetry off Vietnam where a strongly linear and steep submarine escarpment is present (Fig. 2). Evidence of shearing is also apparent in deepwater multichannel-seismic profiles available in the area.

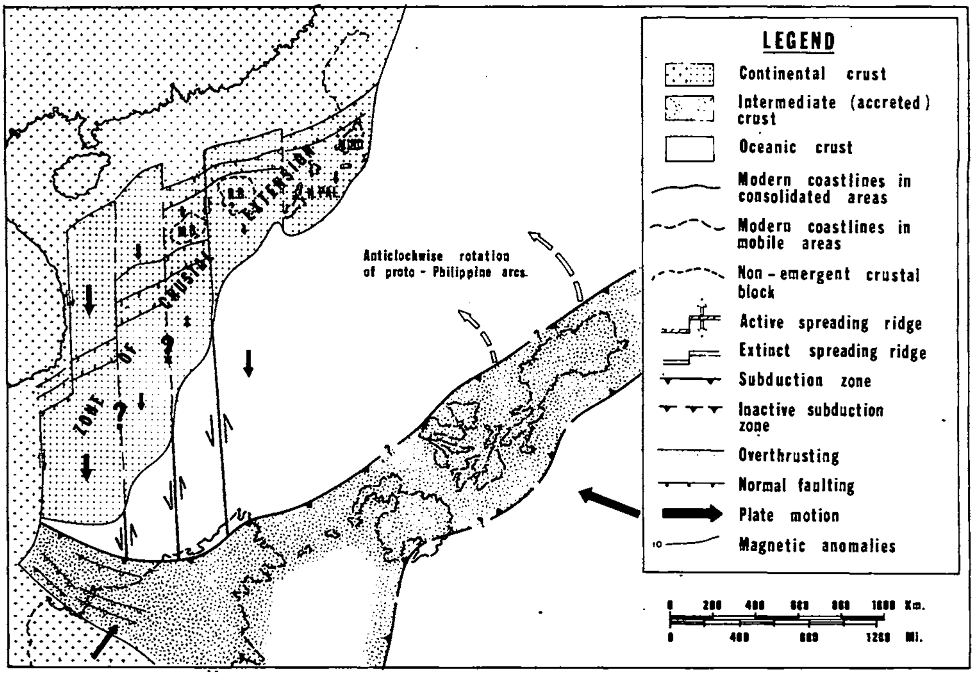

Fig. 10. Late Eocene reconstruction. MB: Macclesfield Bank, RB: Reed Bank, N PAL: North Palawan, MIND: Mindoro.

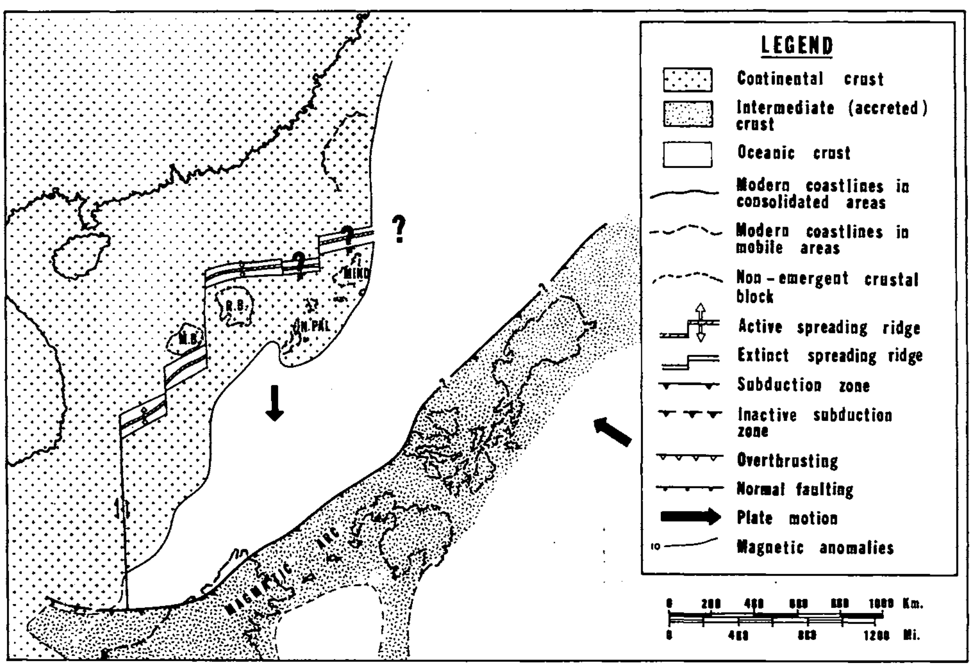

Fig. 11. Mid Oligocene reconstruction. MB: Macclesfield Bank, RB: Reed Bank, N PAL: North Palawan, MIND: Mindoro.

As mentioned earlier, the speed of southward movement of the attenuating continental material decreased from west to east owing to the decreasing width in this direction of crust under attenuation. It was also suggested earlier that this difference in speed may have been taken up on a series of discrete north-south orientated offsets. These are shown schematically on Fig. 10. Their positions are inferred from the offsets now visible in the more recently formed wedge of oceanic crust. One possible onshore expression of one of these postulated offsets may be the northwest trending Tinjar Fault and hingeline (Fig. 1) of onshore and offshore northeastern Sarawak. This feature forms an important geological boundary in terms of structural style, sedimentary history, geothermal gradient and hydrocarbon occurrence between the Balingian and Baram Provinces. If this interpretation is correct, the original position and orientation of the feature must have been somewhat modified by later tectonic activity.

The Late Eocene was a period of major tectonism in western and central Sarawak which resulted in the uplift, imbrication and low grade regional metamorphism of the Belaga Fm (Liechti *et al.*, 1960; Haile, 1974). The Belaga Fm has been interpreted by Hamilton (1979) and others as the accretionary wedge of the Sarawak sector of the northwest Borneo subdution system. The Late Eocene tectonic event is interpreted here to have resulted from the impact of the western end of the southward migrating continental material against this subduction system. The position of the trench is thought to have been well to the north of the pesent coastline by Late Eocene time as Belaga type sediments constitute economic basement for hydrocarbon exploration in the southern part of the Sarawak Luconia offshore province. The ultimate effect of the collision was a locking up and cessation of the subduction process in the western sector of the northwest Borneo subduction system.

Mid Oligocene (Fig. 11)

Mid-Oligocene is the age of the oldest magnetic anomaly(Anomaly 11) recorded by Taylor and Hayes in the eastern part of the South China Sea Basin. The Mid-Oligocene is therefore regarded as the time of cessation of continental crust attenuation and the commencement of sea-floor spreading. This event is recorded in the strongly expressed "breakup" unconformity in the stratigraphy of the surrounding areas.

The position of the spreading axis in the western part of the basin is interpreted to have been controlled by the trend of the Jurassic-Cretaceous palaeomagmatic arc. The position of this arc had by this time been distorted and offset by the continental crust attenuation process. The offsetting and apparent skewness of the two western sectors of the spreading axis are also interpreted have been controlled by the prior crustal attenuation.

To the east, the Philippine island arc system is interpreted to have continued its anticlockwise rotation. Despite complications resulting from the development of the Philippine Plate, it is considered that the overall net movement of oceanic crust on the eastern side of the Philippine Archipelago was still towards the west-northwest. Most of the convergence as a result of this movement is believed to have been taken up on the western side of the archipelago as recorded in the Oligocene trench complex of the

Zambales Range in western Luzon (Balce *et al.*, 1979). Meanwhile, subduction continued in the Palawan area with its corresponding magmatic arc developing in the position of the present day Cagayan Ridge (Fig. 1).

Late Oligocene (Fig. 12)

By Late Oligocene times, Borneo is believed to have completed its anticlockwise rotation and continental material is thought to have impinged against the Brunei sector of the northwest Borneo subduction system with resulting cessation of activity. Onshore geology indicates that no major orogeny took place at this stage and therefore the impingement must have been relatively gentle. Indeed the extinct trench and its associated outer-arc basin must have remained in existence as the depocentres for the enormous thickness of Oligocene to Early Miocene bathyal marine shales recorded onshore (Brondijk, 1962; Hamilton, 1979). Activity on the westernmost sector of the spreading ridge is inferred to have stopped as a result of subduction cessation in the Brunei sector.

The Late Oligocene reconstruction shows active back-arc sea-floor spreading to be occurring in the Sulu Sea Basin. The exact age of inception of this spreading is uncertain and details of the evolution of the Sulu Sea Basin are beyond the scope of this discussion. However, onshore geology in eastern Sabah suggests that spreading could have commenced as early as Eocene owing to the presence of thick and widespread flysch sequences whose deposition started at that time (Leong, 1976).

The Philippine island arc system continued its anticlockwise rotation.

Early Miocene (Fig. 13)

An Early Miocene age is assigned to the major period of tectonism, imbrication and uplift of the flysch terrain of Sabah (Liechti *et al.*, 1960; Hamilton, 1979). This event is interpreted here as resulting from further collision of continental material with the Northwest Borneo subduction system and the cessation of spreading activity on a second sector of the South China Sea spreading ridge. This Early Miocene tectonism in Sabah is believed to be the most recent event attributable in the area to the spreading and subduction activity of the South China Sea system. However, several locally intense episodes of deformation have affected western parts of Sabah since the Early Miocene (Bol and Van Hoorn, 1980). Probably these deformational phases are related in some way to ongoing subduction activity on the southwestern and southeastern margins of the Sulu Sea; activity which continued into the Pleistocene (Hamilton, 1979).

Concomitantly with Early Miocene collision in northwestern Sabah, the southward protruding part of the North Palawan block began to impinge against the northern sector of the Palawan subduction system. This impingement is believed to have resulted in offset of the subduction trench to the south towards the Cagayan Ridge. The zone of offset between the two sectors of the Palawan subduction zone became a right lateral transcurrent fault along the line of the Ulugan Bay Fault. The collision was not complete until the Middle Miocene and will be referred to again in the next section.

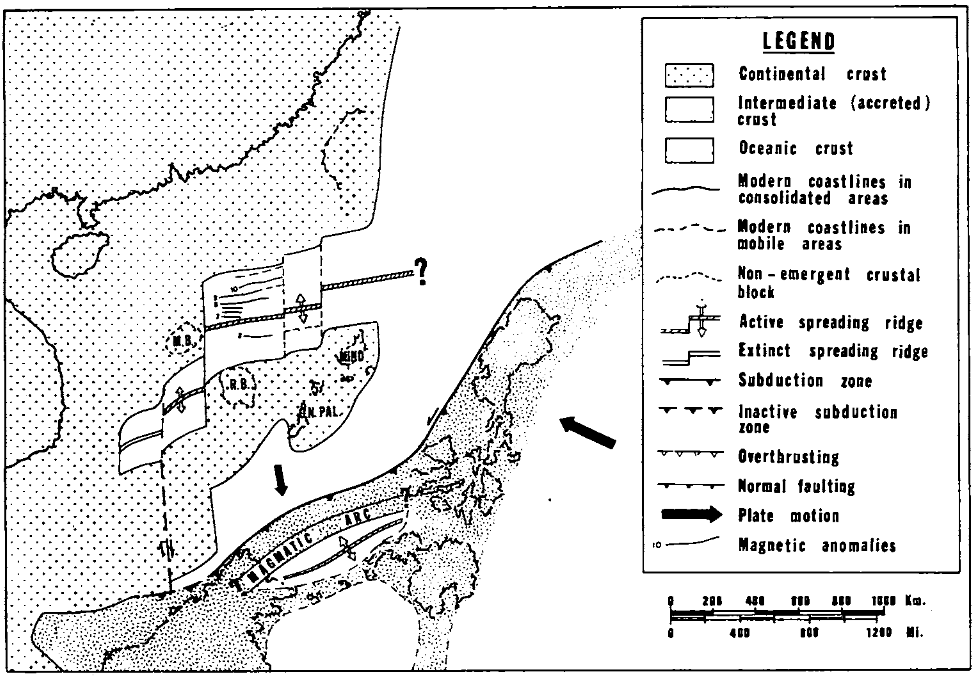

Fig. 12. Late Oligocene reconstruction. MB: Macclesfield Bank, RB: Reed Bank, N PAL: North Palawan, MIND: Mindoro.

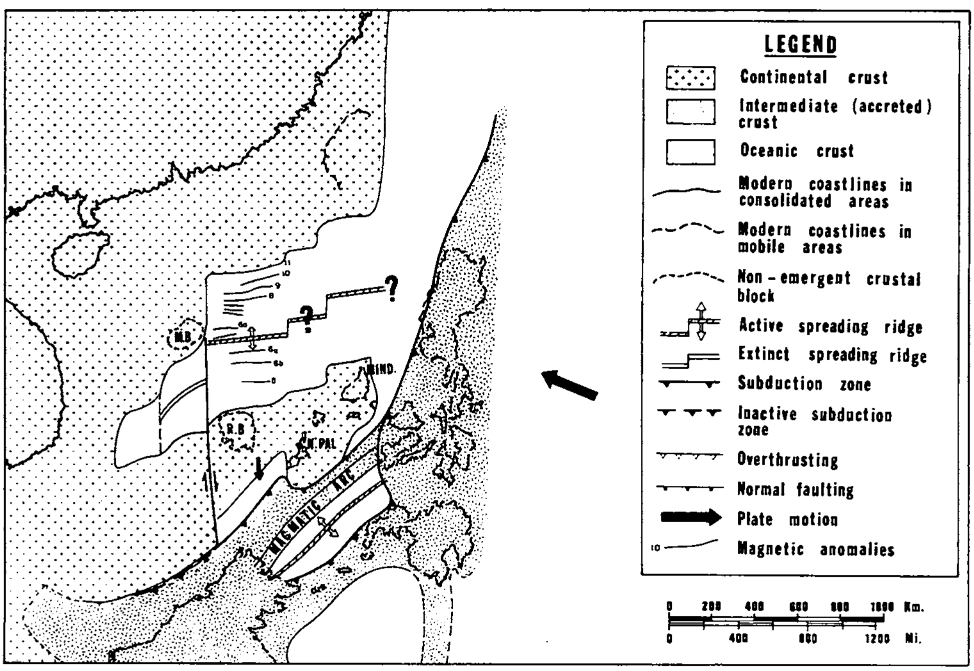

Fig. 13. Early Miocene reconstruction. MB: Macclesfield Bank, RB: Reed Bank, N PAL: North Palawan, MIND: Mindoro.

The only sector of the original Northwest Borneo/Palawan subduction system to remain active throughout the Early Miocene was that part off central and southern Palawan. The detailed features of this sector are elegantly documented by seismic and well data in the area. Figure 18 is a seismic profile across the Palawan shelf clearly showing the downgoing plate, the thrust faults of the imbricate subduction melange and the post-subduction drape of sediments beneath the sea bed.

Both the imbricate thrusting and the Mid-Miocene age of the subduction cessation unconformity below the post-subduction sediment apron are confirmed by the Phillips Albion Head-1 well. Figure 19 shows a stratigraphic column for this well. It can be seen that section containing both Middle and Lower Miocene sediments is twice repeated as a result of thrust faulting. Fig. 21 is a seismic profile slightly further to the northeast (Glenn, 1979) which also shows the downgoing plate, the imbricate wedge and an apparent reefal development on the downgoing plate. A second Phillips well, Santiago-1, has penetrated this feature and has proved its reefal nature (Fig. 20). The subsidence of the reef complex as it approached the subduction zone is clearly demonstrated. A third well in this vicinity reached a neritic Lower Cretaceous sedimentary section within the downgoing plate; further confirmation of the continental nature of the underlying crust.

Mid-Miocene (Fig. 14)

Although the magnetic anomalies mapped by Taylor and Hayes suggest that sea-floor spreading in the South China Sea Basin ceased at the end of the Early Miocene, the pronounced uplift in southern and central Palawan and the corresponding strongly expressed unconformity in the offshore area (Figs. 17 & 18) are firmly dated as late Middle Miocene. This suggests that subduction and therefore probably spreading did not fully terminate until this time. Indeed it is probable that the collision of the Reed Bank sector of the North Palawan block with the southern sector of the Palawan subduction system was the cause of spreading extinction.

In the northern sector of the Palawan system, collision between the protruding northern Palawan island sector of the block and the subduction system was completed. This resulted in the deformation of the thick Upper Cretaceous to Lower Miocene passive margin apron of sediments which had accumulated on the southeastern margin of the North Palawan block. The strongly compressional style of deformation is well illustrated on the seismic profile Fig. 22.

The model described above necessitates that the original southward dipping subduction zones must have become sutured against the Cagayan Ridge. A possible section of this subduction zone which is still active as part of the Negros Trench system (Hamilton, 1979), may be seen on the seismic profile Fig. 23. Direct evidence for the presence of a sutured subduction zone just to the north of the Cagayan Ridge is lacking. However, it is notable that the bathymetric expression of the ridge (Fig. 2) is much stronger in the northeastern sector than further to the southwest towards Sabah.

It may be imagined that the greatest resistance to the further southward movement of the North Palawan block was concentrated in the northern sector of the collision zone described above. It is therefore suggested that some of the stress was

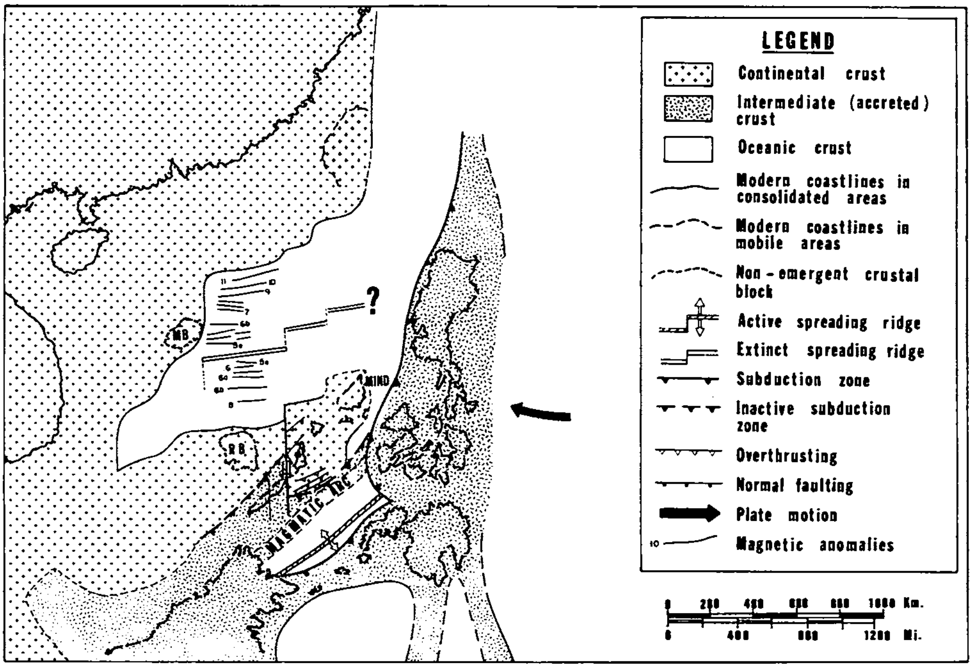

Fig. 14. Mid Miocene reconstruction. MB: Macclesfield Bank, RB: Reed Bank, N PAL: North Palawan, MIND: Mindoro.

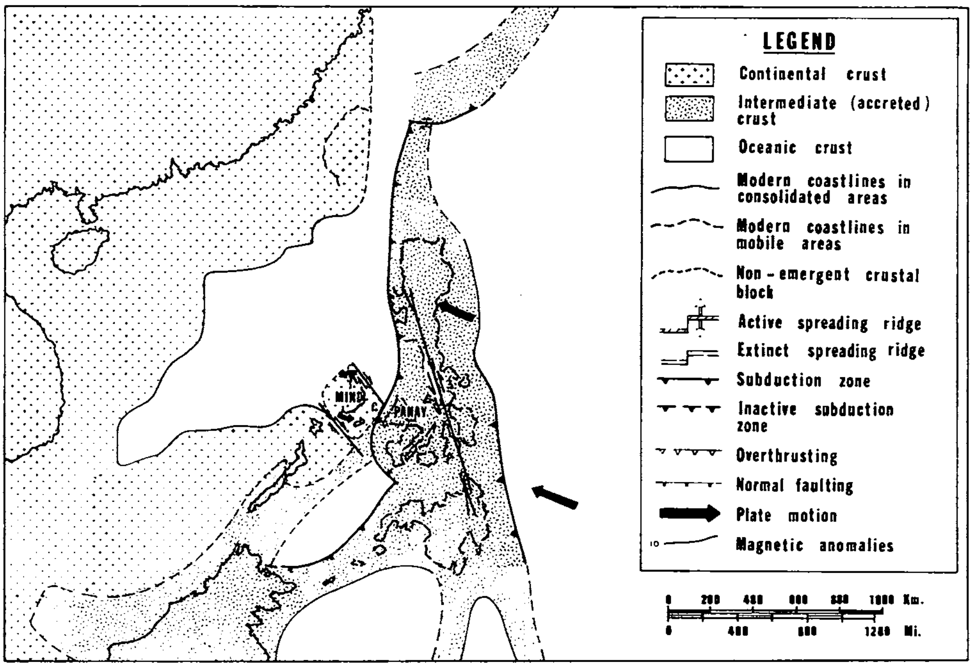

Fig. 15. Late Miocene reconstruction. MIND: Mindoro.

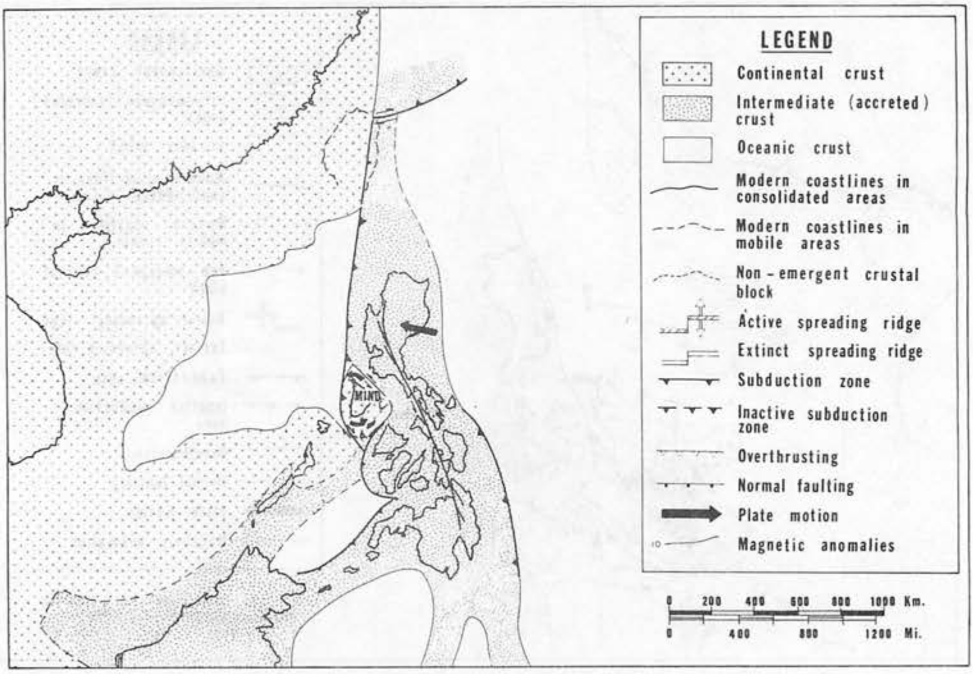

Fig. 16. Mid Pliocene reconstruction. MIND: Mindoro.

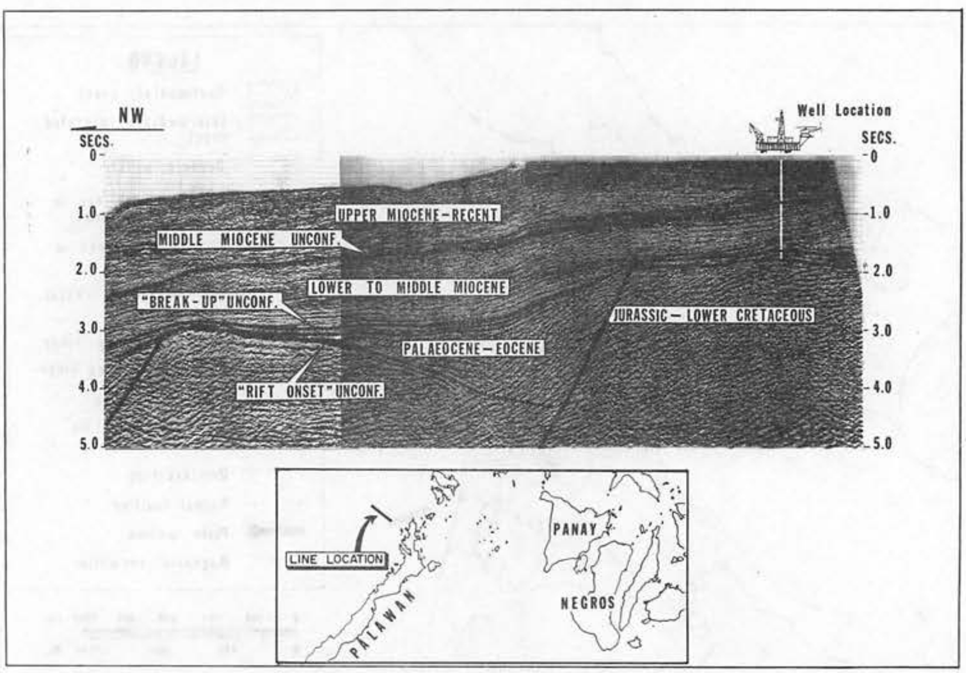

Fig. 17. Migrated time seismic section showing block faulting and age of major unconformities and sedimentary units off northwest Palawan.

relieved by slight northward movement of the eastern sector of the North Palawan block. The consequent displacement is postulated to have taken place by sinistral strike-slip along the Ulugan Bay Fault. This would satisfy the observation from bathymetric and other data that the most recent phase of movement on this fault was left lateral.

The final resulting relationship between continental and accreted/oceanic crustal elements in the Palawan area is demonstrated by the aeromagnetic map, of Bosum *et al.*, 1972 (Fig. 24). This shows the high amplitude and irregularity of the magnetic anomalies off parts of central and southern Palawan in contrast to the relatively smooth and low amplitude anomalies off northern Palawan.

Late Miocene (Fig. 15)

By Late Miocene time all active spreading had ceased in the South China Sea as had subduction along the entire length of the northwest Borneo/Palawan subduction system. Only on the western advancing margin of the rotating Philippine Archipelago was subduction still active. The continued rotation eventually resulted in impact between the archipelago and the eastern end of the North Palawan block. This impact took place in the vicinity of Mindoro island. The Late Miocene age of the impact is documented by contemporaneous intense compressional folding in parts of southern

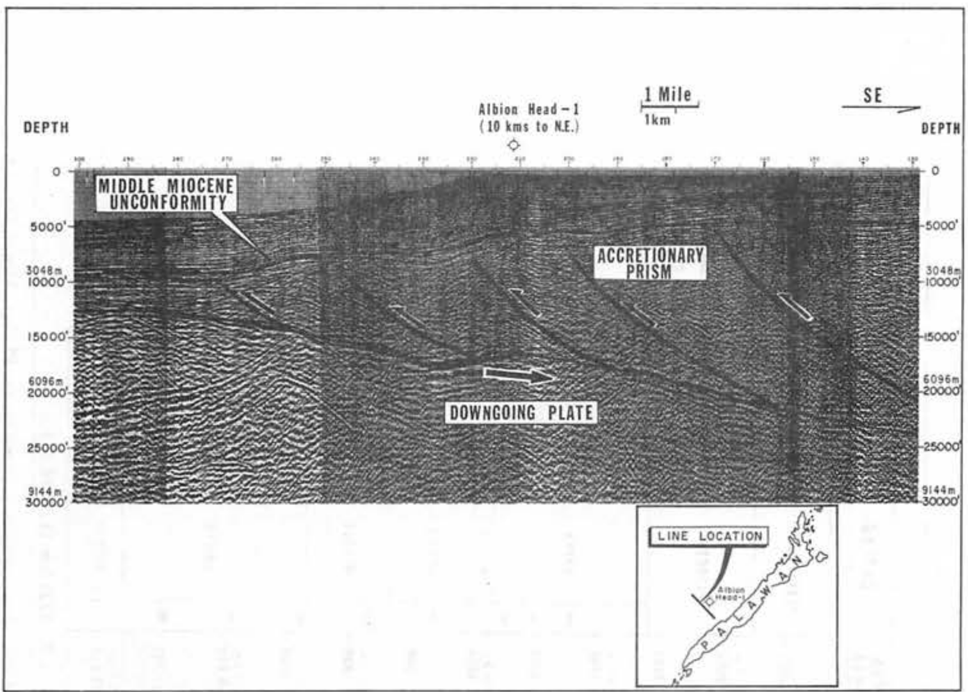

Fig. 18. Migrated depth section. Elements of the Palawan subduction system showing the relative position of the Albion Head-1 exploration well to the accretionary prism.

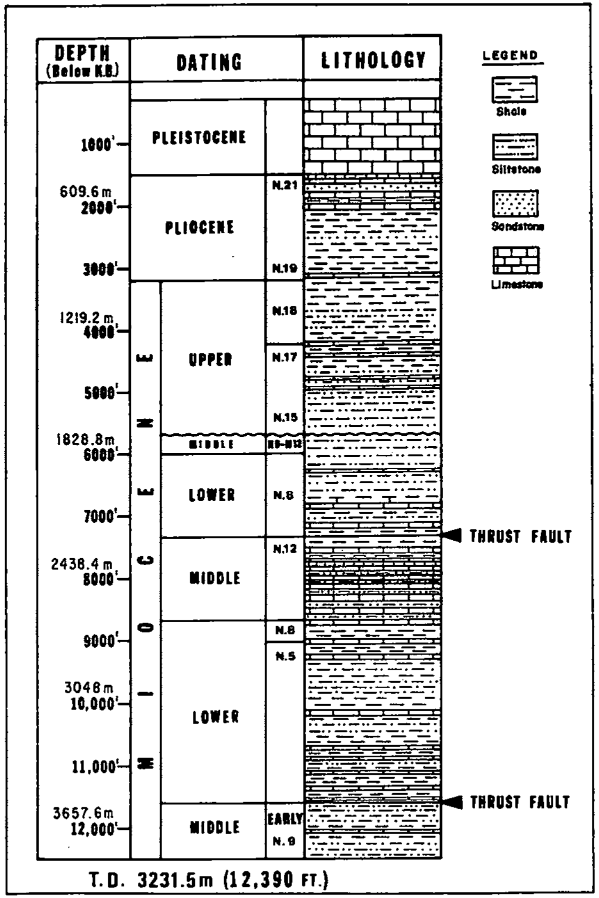

Fig. 19. Stratigraphic column for the Phillips Albion Head-1 exploration well offshore west Palawan.

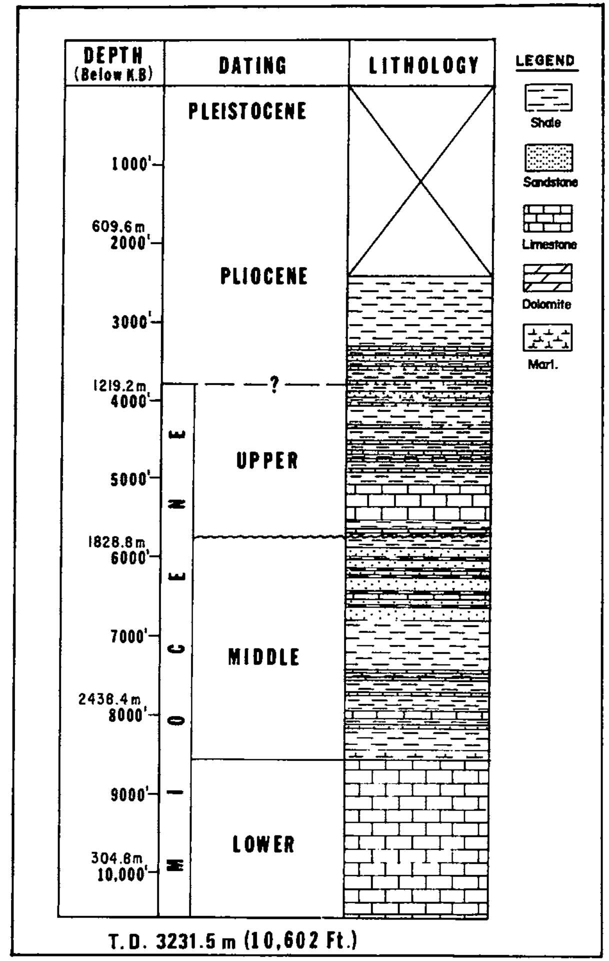

Fig. 20. Stratigraphic column for the Phillips Santiago-1 exploration well offshore west Palawan.

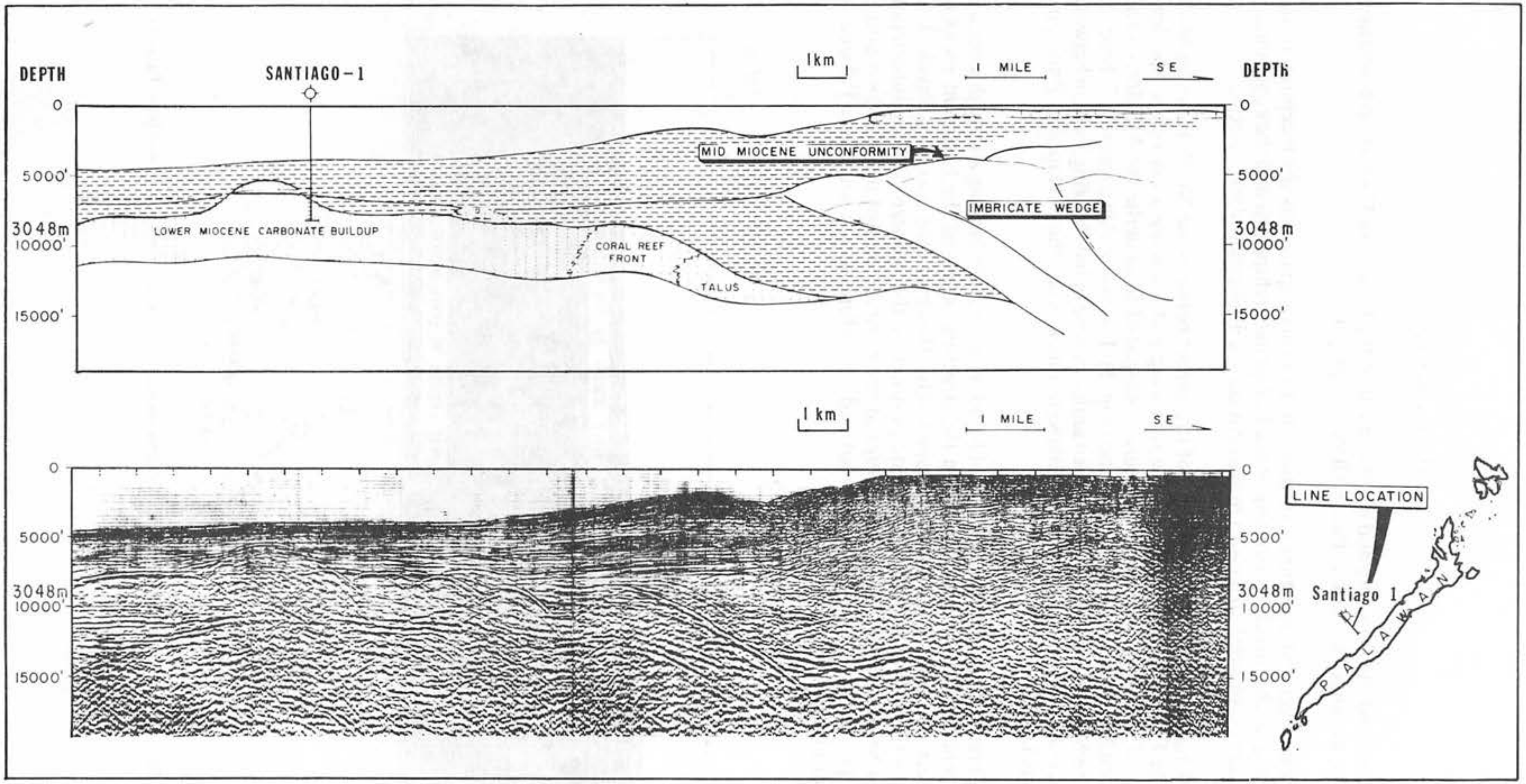

Fig. 21. Unmigrated depth seismic section and geological interpretation (After J.M. Glenn, 1979). Elements of the Palawan subduction system reefal and carbonate platform development on the downgoing plate and the approximate position of the Santiago-1 exploration well.

Mindoro and the thrusting and emplacement of the Paniciuan Formation blueschist-bearing melange in western Panay (Balce, in prep.).

It is suggested here that a further effect of this impact was the inception of the observed double oroclinal bending of the Philippine archipelago and the concomitant initiation of sinistral strike-slip movement on the Philippine shear system.

A further inferred consequence of the impact between the North Palawan block and the Philippine Archipelago is the rupturing and breaking away of the Mindoro sector of the block. The line of rupture is suggested to underlie the Mindoro Strait between Mindoro and Busuanga island (Fig. 1). Following this rupture it is believed that the Mindoro sub-block was rotated anticlockwise in ball-bearing fashion between the remainder of the Northern Palawan block and the advancing Philippine Archipelago.

Direct evidence for the rotation of Mindoro is virtually lacking although a certain divergence may be observed between the structural grain of the basement rocks in northern Palawan and Mindoro respectively. However, the model is invoked to explain the later, very anomalos, interposition of the modern Manila subduction trench between Mindoro and Busuanga at the northern end of the Mindoro Straits (Fig. 1); i.e. between two parts of what had heretofore been a single late Palaeozoic crustal block.

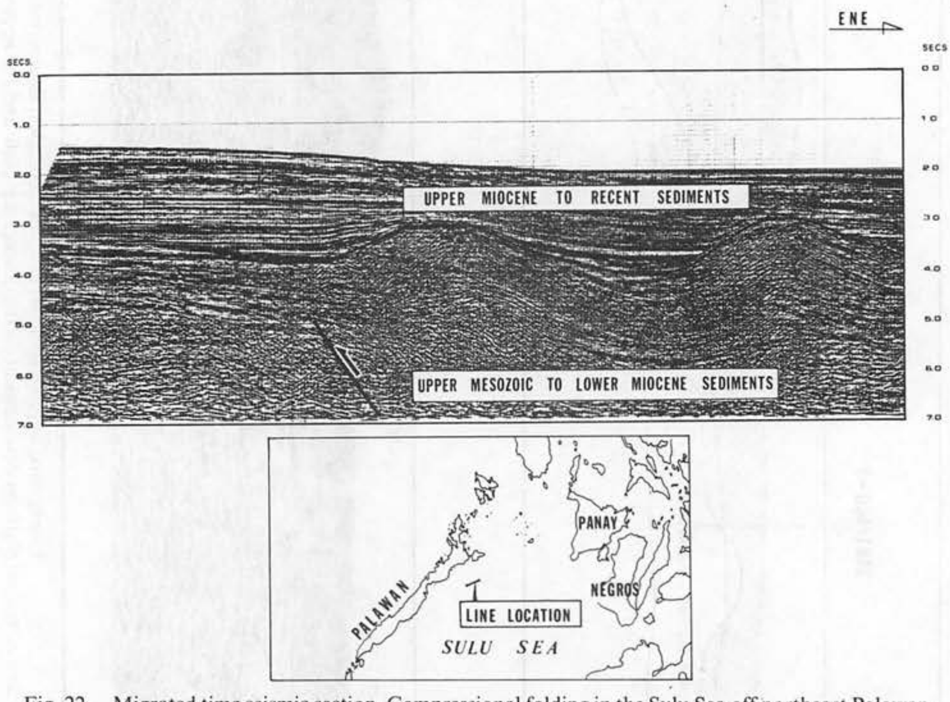

Fig. 22. Migrated time seismic section. Compressional folding in the Sulu Sea off northeast Palawan.

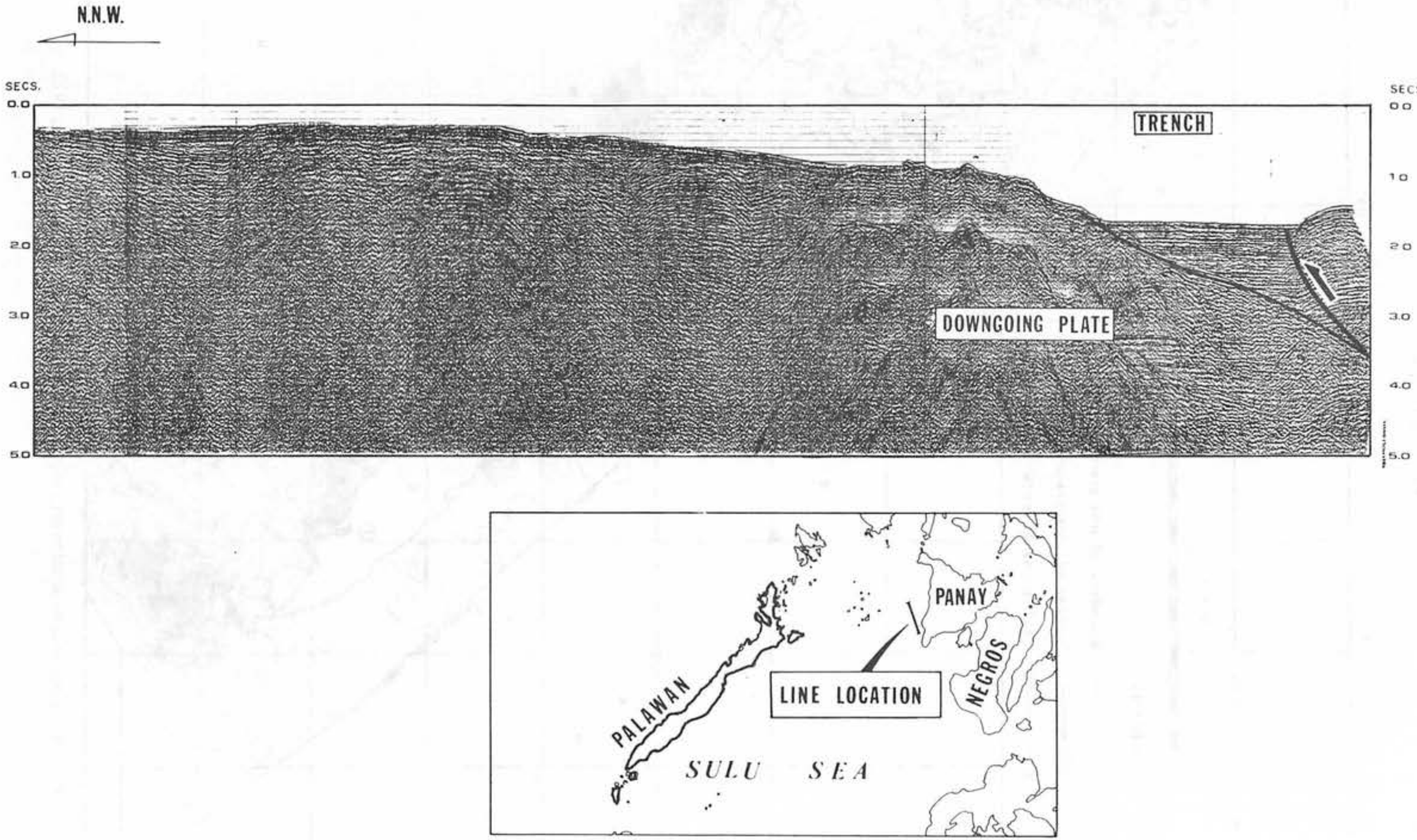

Fig. 23. Migrated time seismic section. Profile across the Negros Trench off Panay Island.

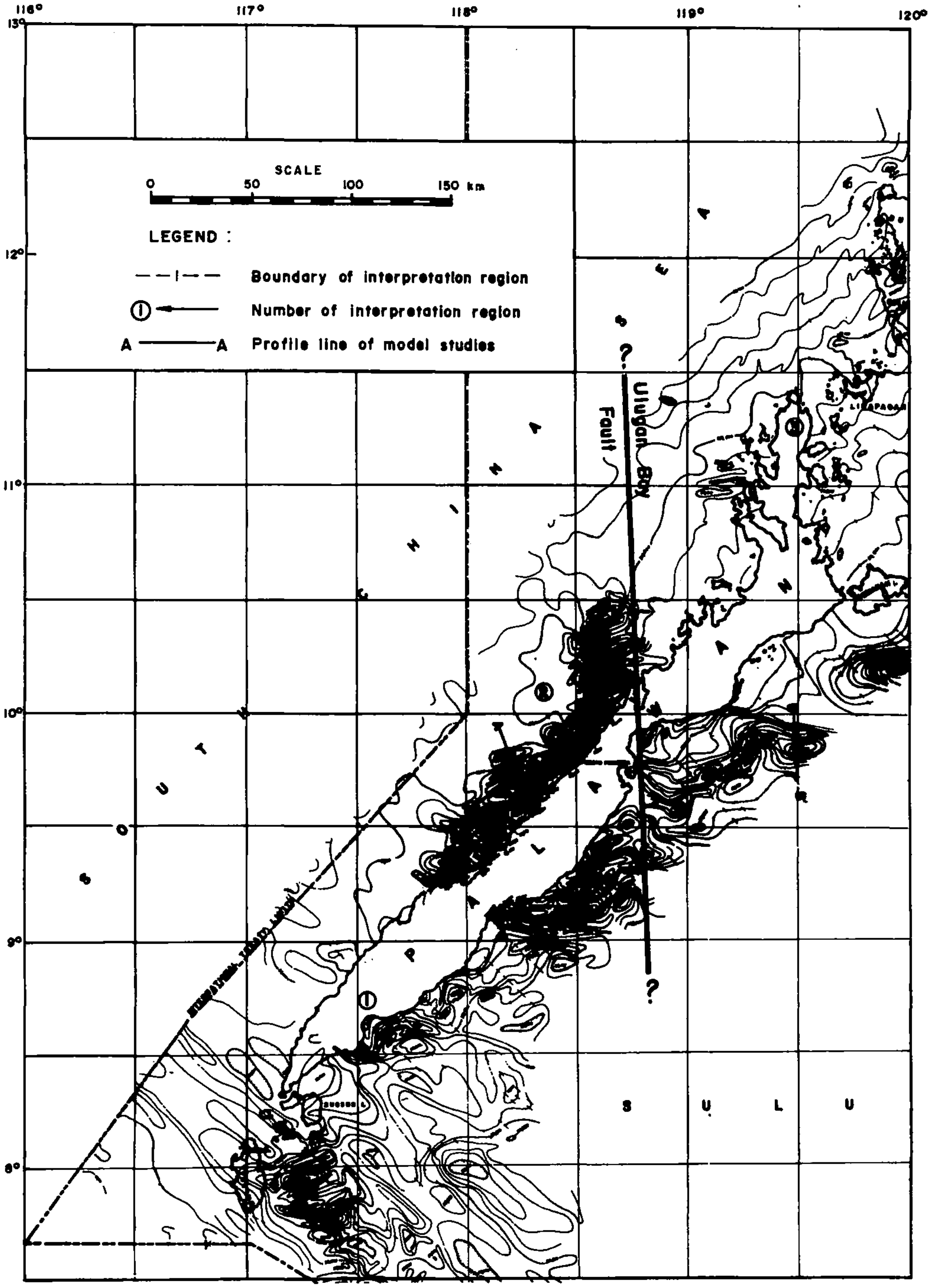

Fig. 24. Total magnetic intensity map of Palawan Island. After Bosum *et al.*, 1972.

Pliocene (Fig. 16)

Subduction in the Manila Trench continued into the Pliocene as Luzon advanced further westward. The Mindoro sub-block continued its rotation as the southwestern flank of Luzon closed against it. This closing caused the southern end of the subduction system to jump from between Mindoro and Luzon to the western side of Mindoro. Balce (in prep) has dated the basaltic and andesitic lavas and pyroclastics of Mindoro as Pliocene to Recent. Thus it may be inferred that these effusives record the establishment of the southern end of the Manila Trench to the west of Mindoro.

The western flanks of Mindoro and Luzon now migrated westward together with concomitant South China Sea oceanic crust consumption. As the subduction zone curved into the Mindoro Straits it became a right lateral transcurrent fault accomodating the slip between the southwestern flank of the rotating Mindoro sub-block and the remainder of the North Palawan block. This pattern continues to the present day.

CONCLUSIONS

In the foregoing discussion, an attempt has been made to collate date from the greatest possible variety of sources from within and around the South China Sea Basin in order to investigate both the relationship of the North Palawan block to the Asian mainland, and to develop a Triassic to Present evolutionary model for the South China Sea area.

The closely related pre-Neogene stratigraphy of the North Palawan block to on- and offshore areas of China coupled with the synchrony of pre-Neogene tectonic events throughout, strongly suggests that the two elements were contiguous in pre-Neogene times. The Cretaceous rocks in particular can be related to the inferred positions of the various elements of a typical subduction system, such a system being postulated to have existed on the South China margin from Mid-Jurassic to Mid-Cretaceous times.

Substantial spreading took place in the South China Sea Basin by a process of continental crust attenuation. This attenuation may be dated as having occurred between the "rift-onset" event, here established to be of latest Cretaceous/earliest Palaeocene age, and the "breakup" event, dated as Mid-Oligocene. It is also apparent that the effects of this attenuation were far greater in the western part of the South China Sea Basin than the eastern part owing to the much greater breadth of crust undergoing attenuation. The crust is believed to have stretched by about 85% which represents a maximum southward migration of the southern boundary of the continental crustal area of nearly 700 kms. The migration occurred over a 25 Ma period with the result that oceanic crust ahead of the attenuating continental material moved southwards at a maximum rate in excess of 3 cms per year.

True sea-floor spreading and generation of oceanic crust followed the "breakup" event in the Mid-Oligocene. Termination of spreading is believed to have been coincident with cessation of subduction in the Palawan Trench. The latter event has been dated as late Middle Miocene on the basis of strong uplift in onshore areas of

Palawan and a marked unconformity offshore. This dating is slightly at variance with the latest Early Miocene age assigned to the youngest magnetic anomaly.

The magnetic anomaly orientation in the South China Sea indicates an essentially due north-south spreading direction. The spreading was much more extensive in the eastern part of the basin than in the west possibly owing to the interference effect of large masses of cratonised continental crust (Indochina and Sundaland) on the western margin of the system. As a result, spreading in the western part of the basin was almost completed (by crustal attenuation) before any significant spreading had taken place in the east. Hence, the highly diachronous nature of the compressional tectonic events from Late Eocene in western Sarawak to Mid-Miocene in southern and central Palawan is explicable in terms of the diachronous impingement of continental crust against the southward dipping Northwest Borneo-Palawan subduction system.

The detailed anatomy of part of the extinct Palawan system is excellently documented by both seismic and well data off western Palawan. The repetition of stratigraphic section within the imbricate accretionary wedge is especially well demonstrated. The presence of continental crust within the downgoing plate, which was responsible for locking the system, is evident from the Lower Miocene platform carbonates and Mesozoic neritic sediments associated with the downgoing slab penetrated by some of the wells in the vicinity.

The Philippine archipelagic complex is believed to have been initiated on an east-northeast trend to the east of Borneo following a Late Cretaceous readjustment of plate boundaries. The rotation of the complex towards its present orientation is concluded to have started with the Late Eocene change in Pacific Plate motion doumented by the angularity of the Emperor and other seamount chains. The final phases of rotation and impact with the North Palawan block in the late Miocene are interpreted to have broken off and rotated that part of the block containing the island of Mindoro, and to have initiated sinistral movement on the Philippine shear system.

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