Journal of Asian Earth Sciences 39 (2010) 371–385

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

What are the Spratly Islands?

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ARTICLE INFO

Article history:
Received 16 July 2009
Received in revised form 17 April 2010
Accepted 20 April 2010

Keywords:
Dangerous Ground
Marginal basin rifting
Coral–algal reefs
Spratly Islands
South China Sea
Mid-Miocene Unconformity

ABSTRACT

Seismic records, combined with dredged samples and a core, indicate that the Spratly Islands of the Dangerous Ground Province are constructed of presently active carbonate build-ups, known to extend back continuously at least to the Pleistocene and presumed to have initiated in the Miocene, most likely upon the crests of sea-floor cuestas that trend north-east–south-west parallel to the sea-floor spreading magnetic anomalies of the contiguous abyssal plain of the southern part of the South China Sea. The cuestas range from spectacular to subdued, constructed of Triassic and Cretaceous strata and no older rocks have been identified from dredges.

The cuesta axes plunge towards the south-west away from the islands, suggesting that the reefs began colonising their more elevated parts, but the timing is uncertain. The highest seismically recorded cuesta crest is in 440 m of water and the islands and reefs are generally closely surrounded by water deeper than 1500 m. Since the so-called Mid-Miocene Unconformity (MMU), the region has been undergoing post-rift thermal subsidence. However, the nearby seismic lines show no evidence of drowned carbonate reefs. It is suggested that the coral-algal reefs colonised the crests of the most elevated cuestas that have maintained stability as shown by the 165 m core of one reef indicating periodic exposure with caliche horizons. Deepening water has protected the build-ups from extinction by post-rift draping strata in contrast to the Central Luconia Province, and the build-ups have been able to keep up with regional thermal subsidence.

The dredged Mesozoic strata indicate that the Dangerous Ground is not exotic and should be interpreted as an integral part of the pre-rift Sundaland continent that included South China, Vietnam, Peninsular Malaysia, western Sarawak and possibly part of Sabah. Igneous and metamorphic samples have been dredged. Although individual spot K/Ar dates cannot be accepted at face value, such rocks can also be interpreted as an integral part of Sundaland. Post-MMU dredged samples are predominantly deep-water calcareous mudstones typified by the draping strata of the Ocean Drilling Program (ODP) Site 1143 cored from Recent to Late Miocene.

1. Introduction

The purpose of this paper is to attempt an understanding of the geology of the islands and the Dangerous Ground, supported by nearby seismic lines and dredge sample descriptions. The Spratly Islands, mostly reefs, are well known more as a region of different territorial claims. A substantial number of papers have been published on the Dangerous Ground (e.g. Clift et al., 2002, 2008; Hutchison, 2004) but there is a lack of studies on the actual geology of the Spratly Islands themselves, except for Gong et al. (2005). Taylor and Hayes (1980, 1983) wrote about the Reed Bank that is close to but not actually one of the Spratly Islands.

There are more than 600 reefs and islets in the southern South China Sea. Most lie between 7–12°N and 112–116°E. (Fig. 1). They were named after Captain Richard Spratly, master of the British whaler 'Cyrus South Seaman', who in 1843 sighted the Spratly Island, also known as Ladd Reef. China refers to them as the Nansha Islands. Admiralty charts have the warning "Dangerous Ground" printed over this region, to warn sailors of the reefs, many of which were uncharted. The region has come to be referred to as 'Dangerous Ground' in the absence of any formal name. As far as can be determined, all of the Spratly Islands are capped by active coral reef and there are no other rock outcrops. Most of the 'islands' are under water at high tide, but some maintain a partial low elevation of a rim surrounding a lagoon, in which case they are sparsely vegetated and inhabited by sea birds. There are no indigenous human inhabitants, but tourists visit for diving and fishing and the military occupy many for territorial claims.

This paper is mainly confined to seismic data acquired within Malaysian Exclusive Economic Zone (EEZ). There are numerous islands and reefs within the maritime boundary of Malaysia's EEZ. The main reefs and islands are shown in Fig. 2. The names in the

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doi:10.1016/j.jseaes.2010.04.013

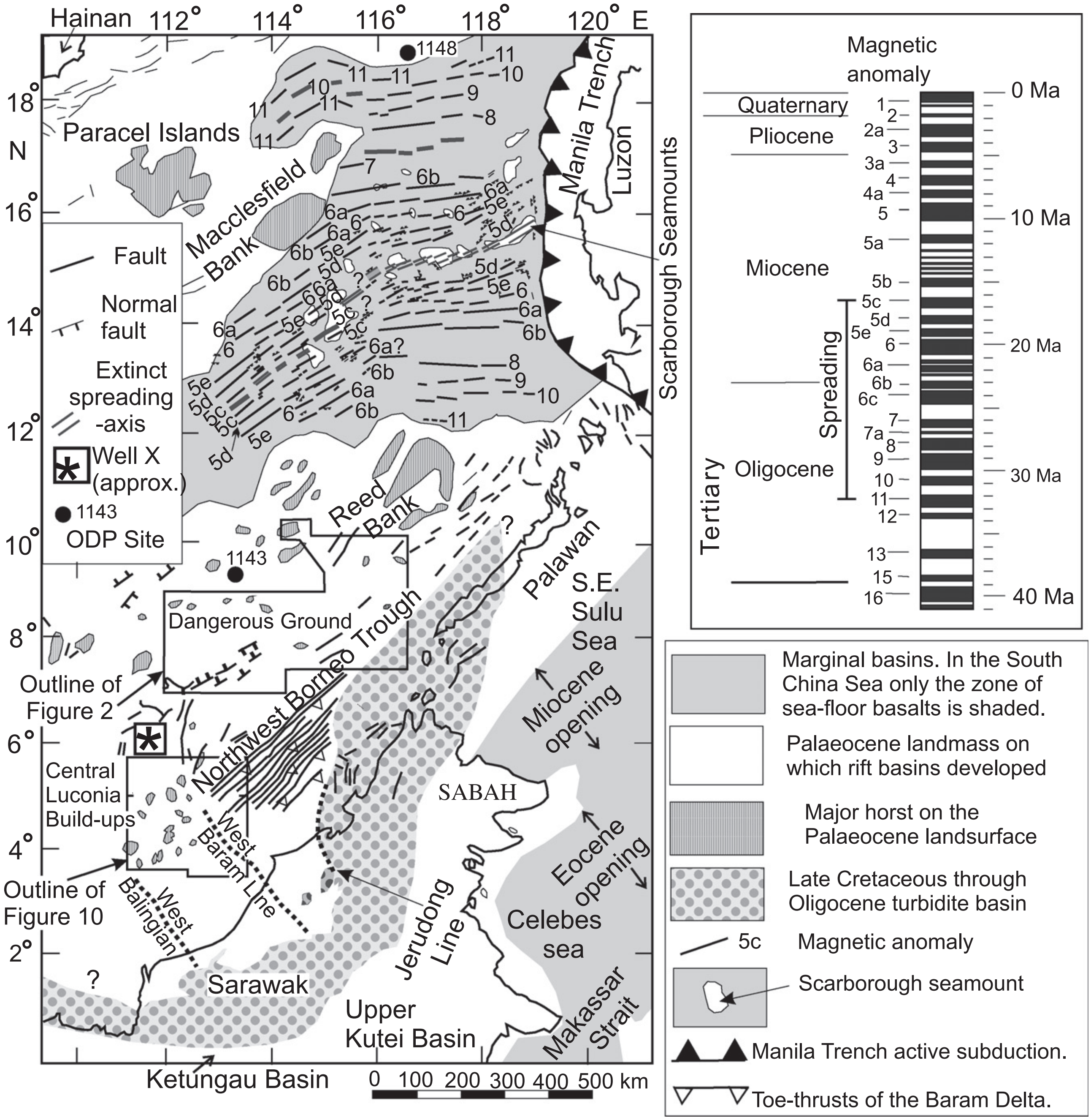

Fig. 1. The major geological features of the southern South China Sea, showing the approximate extent of the Spratly Islands, Central Luconia and Dangerous Ground. Magnetic anomalies are from Briais et al. (1993). Revised anomalies by Barckhausen and Roeser (2004) interpret the end of sea-floor spreading earlier, at anomaly 6A (20.5 Ma). The rifted terrain enveloping the zone of sea-floor spreading, on the west and south, was developed initially on the Palaeocene Sundaland landmass (Hutchison, 1992).

admiralty charts differ from those given by claimant countries. However, a considerable amount of confusion exists regarding their naming and which countries claim and occupy them. Comprehensive non-geological details are given by Hancox and Prescott (1995) and Dzurek (1996). This paper does not deal with the legal and occupational claims by contiguous coastal countries.

The Spratly Islands are mostly reefs. Pulau[1] Layang-Layang has been identified as an atoll with a box-like shape suggesting fault control. The old theory of Darwin (1842), that atolls are carbonate build-ups upon the calderas of extinct volcanoes, is no longer valid and Purdy and Winterer (2001) have shown that a carbonate rim enclosing a lagoon is a result of fresh water karstic weathering at sea level. A rim and lagoon are not, however, universal. The atoll morphology in no way suggests control from the underlying basement morphology.

There is a reconnaissance network of 2D seismic lines over most of the area (Fig. 2), except in the vicinity of the Barque Canada Reef (Terumbu[1] Perahu), Commodore Reef (Terumbu Laksamana) and Amboyna Cay (Pulau Kecil Amboyna).

In 2007 several deep-penetration 2D seismic lines were acquired in this area, as part of the Malaysian Continental Shelf Project. However, they are not included in the present paper.

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[1] In Malay language, pulau means island, terumbu means reef.

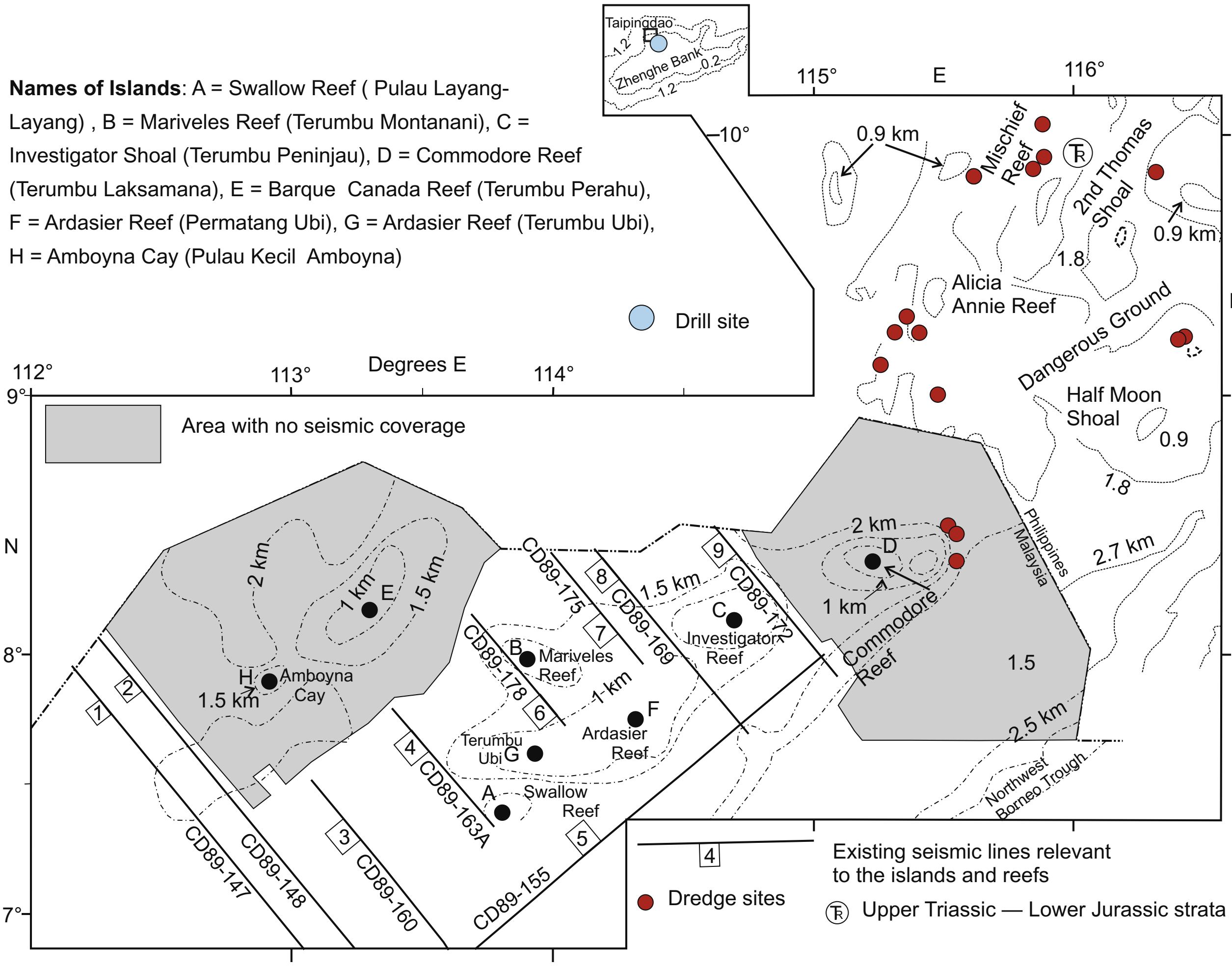


Fig. 2. Map showing positions of the individual Spratly Islands within the Malaysian marine EEZ (exclusive economic zone). The bathymetric contours are only approximate. The selected seismic lines are shown. The areas of no seismic coverage are where the islands/reefs are said to be occupied by Vietnam or the Philippines. Figure location shown on Fig. 1.The dredge sites are from Kudrass et al. (1986).

2. Data sources

The data banks of the Malaysian National Oil Corporation PETRONAS were searched and the nine seismic lines closest to the Spratly Islands were selected for interpretation. The only available shallow drilling on a carbonate reef was analysed by Gong et al. (2005). The available dredging was by Yan et al. (2009) and Kudrass et al. (1986).

3. Bathymetry

Bathymetry maps of this region that have been derived from sea level altimetry generally have poor resolution. Fig. 3A is a map from a ship-borne survey. It shows a very distinct N70°E-trending fabric demonstrated by some of the larger islands and shoals, suggesting they result from carbonate build-ups on the ridges of bedrock cuestas. This is more clearly demonstrated by the oblique view from the south-west (Fig. 3B). However, there are individual islands (e.g. Pulau Layang-Layang) that appear to stand alone as atolls and the box-like shape suggests an origin involving fault control.

The islands and shoals rise abruptly to around sea level from water depths of 1.7–2.0 km, even as deep as 2.5 km near Viper Shoal (Fig. 3A). The only cored reef is on Taipingdao (Fig. 2). Reef facies coral-algal limestone was cored to a depth of 165 m, but the complete thickness of limestone and the nature of the underlying bedrock are unknown (Gong et al., 2005). The oldest date obtained by Gong et al. (2005) is Pleistocene. Off-reef the water plunges abruptly (Fig. 3A).

The Dangerous Ground is the continental slope whose crust has been rifting to form cuestas which then underwent post-rift thermal subsidence. An important question remains – have the carbonate build-ups been continuous upon the cuesta crests since the Mid-Miocene Unconformity (MMU)? Unfortunately Taipingdao has not been drilled to the base of the build-up. There is also no seismic to show the stratigraphy of or beneath the build-ups of the Spratly Islands. However, within the Central Luconia Province (Fig. 1), seismic data show poor resolution beneath the buried carbonate build-ups (Epting, 1980), but horsts or platforms were interpreted (Vahrenkamp, 1998).

4. Mid-Miocene Unconformity

What has come to be called the Mid-Miocene Unconformity (MMU) has turned out to be a complex of Miocene events and different authors have inadvertently emphasised different individual sub-events resulting in the present confusion. Mat Zin and Tucker (1999) have shown that there are both Early and Middle Miocene events. The confusion has also resulted from the misguided belief that any unconformity is geographically universal. A prominent unconformity seen in shallow nearshore waters should be expected to change with regional variations and become a perfect conformity in deeper waters farther offshore.

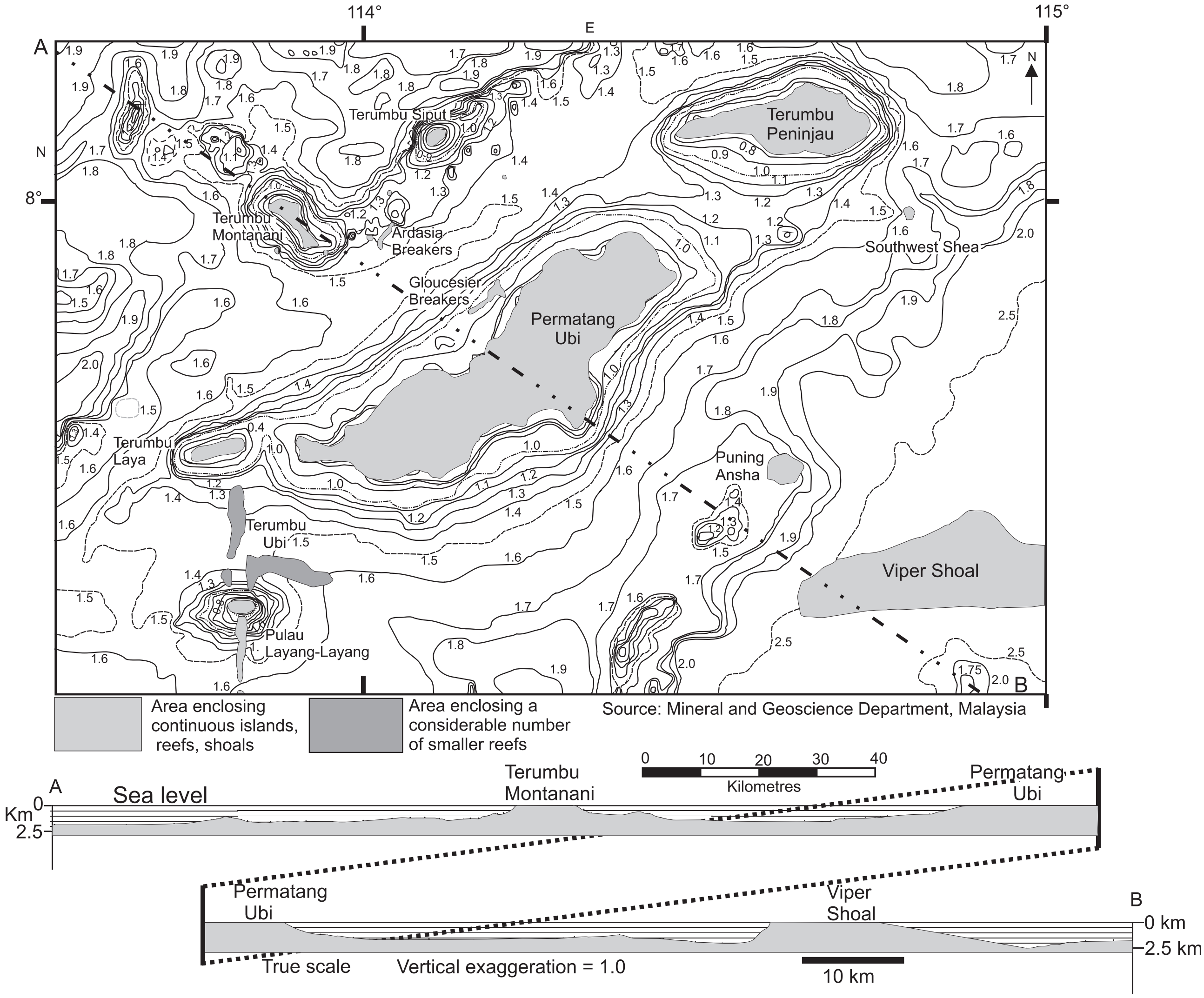
The Mid-Miocene Unconformity (MMU) has been marked on the following seismic lines as the distinct boundary between underlying rifted terrane and overlying post-rift draping strata. This is the only horizon that can widely be identified on seismic records. However, there is inconsistency regarding the interpretation, timing and nature of this boundary.

Hutchison (2004) and Mazlan (1999) gave this boundary a Middle Miocene age. Krebs and Van Vliet (2009) and Van Vliet (personal communication) stated that seismic and well biostratigraphic data concurrently reveal that the MMU is in most places neither of Middle Miocene age nor an unconformity in the traditional sense of a true break in the stratigraphic record. They concluded that the crests of fault-blocks (or anticlines) experienced minor (probably entirely submarine) erosion and the resulting sediments were deposited in adjacent lows. Hemipelagic sediments draped this irregular, essentially structural, topography and thinned atop highs to form condensed sections above local unconformities. There was, however, near continuous deposition at this time in the lows. Bako-1 and Mulu-1wells, drilled on non-carbonate paleo-highs, reveal that the MMU is late early Miocene and is covered by a condensed section that comprises about 10 m.y.

Robinson et al. (2009), based on data from a non-carbonate well 'X' (Fig. 1), confirm an Early Miocene dating but with different views. The MMU, recognized as a pronounced angular unconformity throughout the deepwater Sarawak area, is in fact Early Miocene with a strontium isotope age of 18.5–19.0 Ma, with a 2.0–2.5 m.y. hiatus at the unconformity. The sediments below the unconformity show consistent Early Miocene dating in all the deepwater offshore wells of Sarawak.

However, we shall for convenience continue to call it the MMU. Very importantly, the unconformities described by Robinson et al. (2009) and Krebs and Van Vliet (2009) are not actually the prominent boundary between overlying post-rift draping strata and the underlying rifted terrane. Especially Robinson et al. (2009) illustrate their Lower Miocene dated unconformity as considerably underlying the end of the rifting/beginning of draping horizon. Thus, it is clear that the confusion arises because the multiple Lower/Middle Miocene events have all been amalgamated into the 'Mid-Miocene Unconformity'.

The observations of Krebs and Van Vliet (2009) and Robinson et al. (2009) are applicable only to the deep water areas north of



Source: Mineral and Geoscience Department, Malaysia

Fig. 3A. Bathymetric map around the Spratly Islands, isobaths in km. The lower cross section was drawn with no vertical exaggeration to show the cuesta nature of the islands and shoals. The N70°E trend of the cuesta strike is obvious. Islands such as Pulau Layang-Layang show no elongation and have an atoll-like appearance.

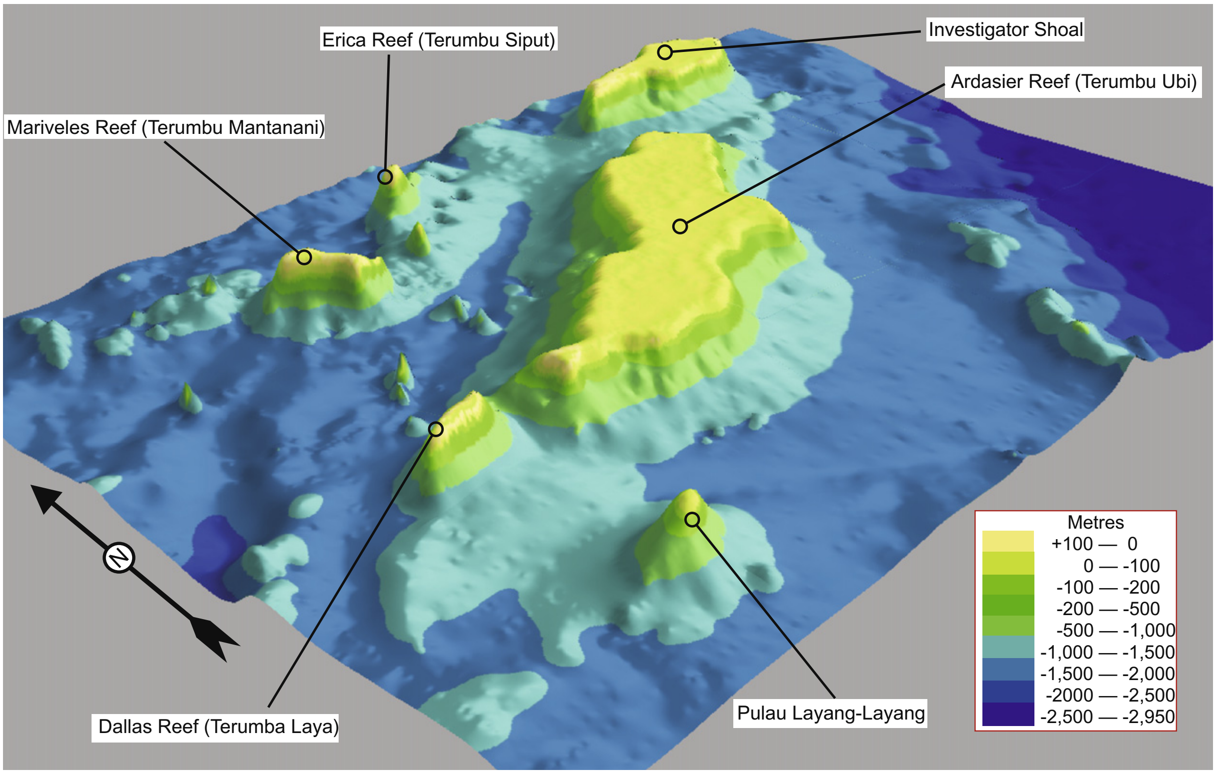


Fig. 3B. Perspective view of the Spratly Islands based on the bathymetry of Fig. 3A, showing the elongated asymmetrical shape of the reefs and a more conical Pulau Layang-Layang.

the Central Luconia Province. However, Mat Zin and Tucker (1999) have shown that there is a real erosional unconformity in the Middle Miocene, with greater erosion upon the compressed and upfaulted anticlines, and lesser erosion in the intervening synclines. The folding of the Oligocene–Lower Miocene strata, both onland and offshore in the Balingian Province must also have been part of the complicated Middle Miocene events, and Hutchison (2005) has shown that a major tectonic event not only folded the strata but also caused uplift of the pre Middle Miocene formations to form a new landmass north of the isoclinally folded Sibu Zone flysch (Fig. 10). At approximately the same time, the pattern of regional rifting of the Dangerous Ground ceased and the rifted terrain was unconformably draped over by unfaulted hemipelagic strata of calcareous mudstone, with no depositional breaks from Middle Miocene to the present day (Li et al., 2005). It appears that the so-called MMU represents a complicated series of tectonic events, some of which may have been Early Miocene, others Middle Miocene. On seismic lines, without chrono-stratigraphic control, we have marked the MMU as the distinct boundary between underlying rifted terrain and overlying draping strata.

5. Structural interpretation of seismic lines

5.1. Lines 1 and 2

These seismic lines show interesting features related to the existence of the Amboya Cay (Pulau Kecil Amboyna), which may be applied elsewhere in the Dangerous Ground. They are the nearest available to that island (H on Fig. 2). Resolution dies out rapidly with depth and the best possible geological interpretation is presented (Fig. 4A).

As with all seismic sections across the Dangerous Ground, the geological subdivisions may be summarised as follows (Fig. 4A):

1. A basement usually without seismic resolution
2. A syn-rift sequence, characterised by strata dipping towards a master fault that was active during deposition.
3. A post-rift sequence that drapes over and generally buries all the older rocks. It is flat-lying, but at this 8× vertical exaggeration the flexures shown by the drape may be mistaken for folding. Its flexures mimic the highs and lows of the underlying cuestas.

The following are the major features:

5.1.1. Sea-floor cuestas

A cuesta is a geomorphological feature formed by strata dip slope (usually gentle) and a normal fault scarp slope (usually steep). The two slopes come together as a prominent linear cuesta ridge, indicated as A on both lines of Figs. 4A and 4B. There is an excellent correlation between Lines 1 and 2 (Fig. 4B) resulting in the following measurements: the trend of the cuesta crest between the two lines is N61°E, consistent with the orientation of the magnetic anomalies (Fig. 1) of the abyssal plain of the South China Sea marginal basin (Briais et al., 1993). Barckhausen and Roeser (2004) have made changes to the anomaly identification, now early Miocene 6a and 6b in the SW prong contiguous with the Dangerous Ground, but not to their south-west–north-east orientation. However it should be remembered that none of the anomaly identifications has been confirmed by drilling and dating. Faults in the Dangerous Ground area (continental slope) are parallel to magnetic anomalies in the contiguous abyssal plain indicating that the rifting was of a single crustal attenuation regime.

The water depth to the cuesta crest is 1336 m (Line 1) and 846 m (Line 2). The axis therefore plunges to the south-west, more elevated towards the islands and reefs (Fig. 4B). Calculated actual scarp slope dips are 12.2° (Line 1) and 25° (Line 2). The gentle dip slope is calculated to be 0.25° (Line 1) and 1.3° (Line 2).

The cuesta ridge becomes higher (overlain by shallower water) towards the north-east (Fig. 4B). Unfortunately there is no seismic coverage in that direction. It is our hypothesis that carbonate build-ups upon the cuesta ridges have been able to keep pace with regional thermal subsidence while the off-ridge deep water accommodated the post-rift muddy sediments thereby maintaining clear water on the crests for continuous reef growth. This is in contrast to burial by a high influx of siliciclastic sediments in the Central Luconia Province (Fig. 9). No extinct carbonate build-ups have been seen in seismic lines. Only where islands occur have there been build-ups, and seismic records have not been acquired close enough to the islands to demonstrate that every build-up has continued active to the present day.

A second parallel, but less spectacular, ridge is seen at B on both seismic lines of Figs. 4A and 4B. Measurements are given as follows: trend of cuesta ridge N54°E. This sharp cuesta also plunges towards the south-west, more elevated towards the north-east where there are several reefs (Fig. 2).

The minor peak at C cannot be traced from Line 1 to Line 2, similar to a peak recorded elsewhere by Yan and Liu (2004). It may be possible to follow their view that it is a Miocene volcanic edifice or possibly a drowned carbonate build-up, rising from the MMU or from beneath it, but this cannot be proven.

5.1.2. Sea-floor ponded strata (turbidite ‘fairways’)

An impressive sea-floor fairway is illustrated in Figs. 4A and 4B. The flat-lying turbidite sequence occupies a bathymetric low immediately on the north-west side of the large cuesta at A. The top of the turbidite pile is impressively flat-lying. Bathymetry measurements have been made as 2037 m and 2050 m along the base of the scarp slope. The far end bathymetry measurements are at 2044 and 2030 m water depth (Fig. 4B). The turbidite fairway trends north-east–south-west, parallel to the bounding scarp face A. The width of the turbidite channel is 19 km (on Line 1) and 27 km (on Line 2).Turbidite thickness is ~0.5 km (Line 1) and ~1.1 km (Line 2).

The amalgamated sea-bed turbidite flows have cut down and partly eroded into the post-rift draping sequence (Fig. 4A). From this, it is clear that the sea-floor channelised turbidites had been flowing from the south-west towards the north-east but meandering over the width of the fairway. The sediment supply was not from Sabah because of the deep intervening North-West Borneo Trough, rather coming from Sundaland, either from Sarawak or the Mekong River across the Sunda Shelf. It is remarkable that this formerly unknown flat-lying young turbidite fairway is 20–30 km wide, comparable to the well known North-West Borneo Trough that is a major sea-floor bathymetric feature. But the fairway cannot be traced farther away from these seismic lines.

5.1.3. Discussion

The major fall in eustatic sea level at the end of the Serravallian (Mid Miocene 10.6 Ma), as documented by Haq et al. (1987), may have accentuated uplift at the Mid-Miocene Unconformity (MMU) but Mat Zin and Tucker (1999) and Hutchison (2005) have shown that this major erosional unconformity may have been the tectonic result of sea-floor spreading in the South China Sea pushing the Dangerous Ground area (including the Spratly Islands) southwards to cause the Lower Miocene and older strata of Borneo to be folded and compressed and uplifted against the Rajang group foldbelt (Fig. 10).

5.2. Lines 3 and 4

Seismic interpretations of parallel Lines 3 and 4 are illustrated in Fig. 5. Line 4 passes very close to Pulau Layang-Layang. It contains no clues to the existence of a nearby reef. The water depths are fairly flat

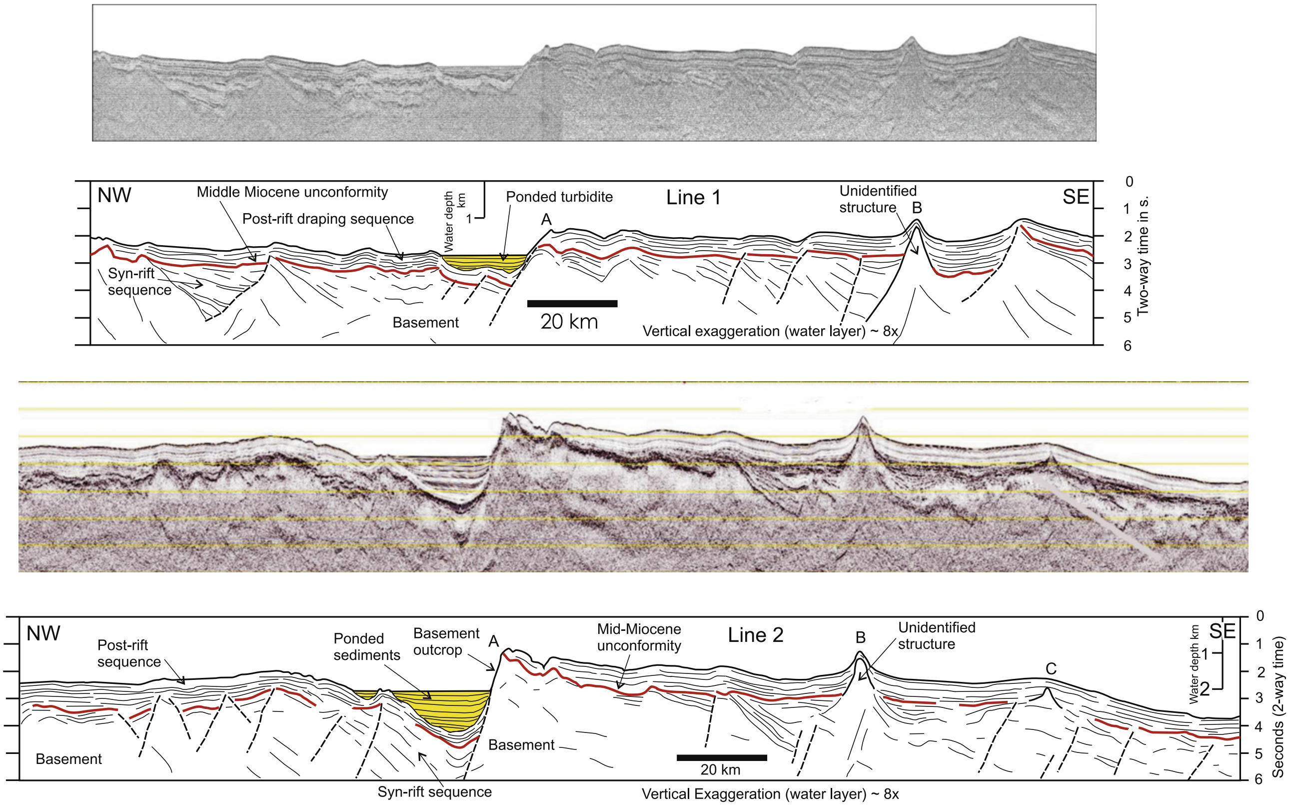


Fig. 4A. Interpretation of the structure and geology of parallel north-west–south-east seismic Lines 1 and 2 (location on Fig. 2). Both lines have a vertical exaggeration of the water layer of ~8×. This means that the steep fault plane at A of about 70° dip is actually only 18° (tangent of the angle ÷ vertical exaggeration). The prominent scarp at A bounds, along its north-west side, a young turbidite fairway, of 19–27 km width. The uninterpreted seismic lines are also shown.

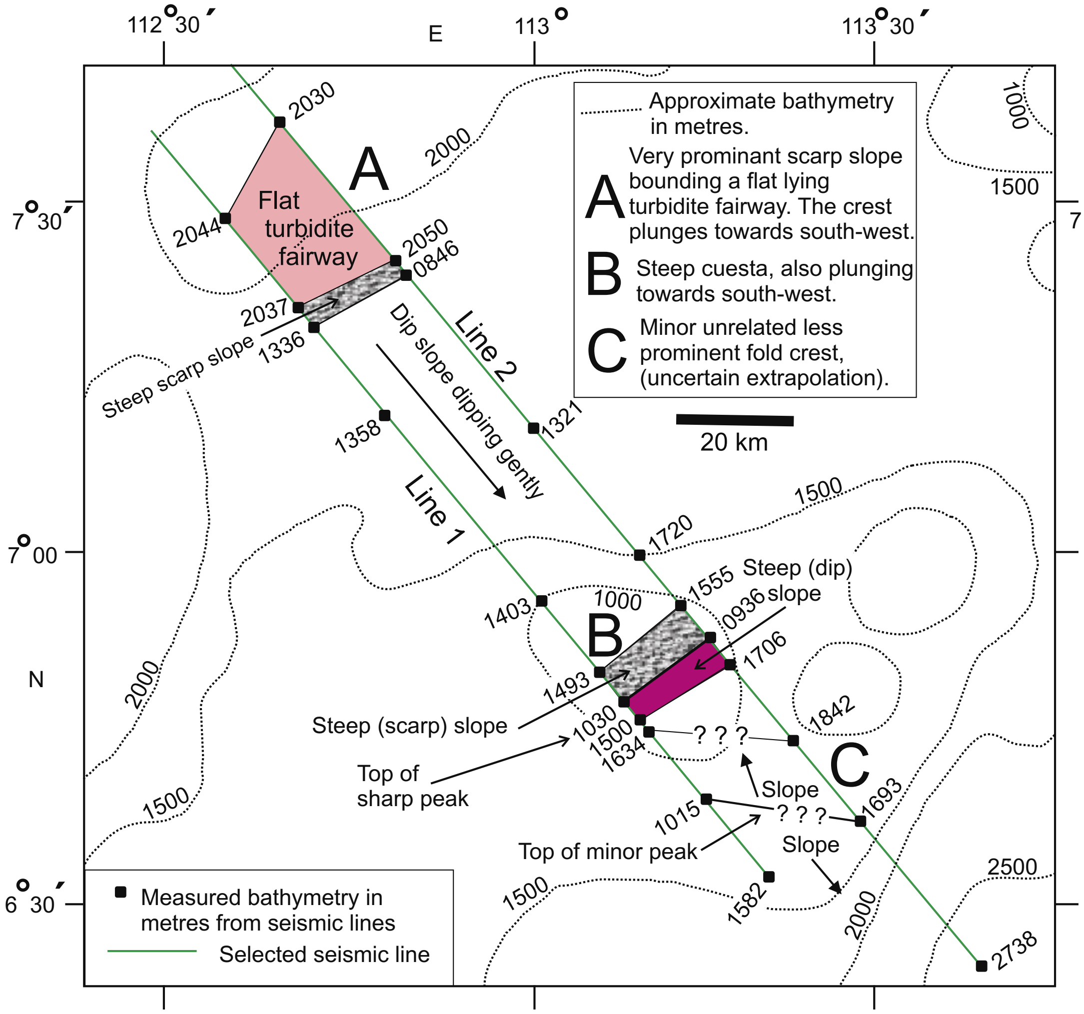


Fig. 4B. Mapped details acquired from seismic Lines 1 and 2. The sea-floor cuestas strike north-east–south-west. At example A the scarp slope acts as a bounding trap for a young turbidite fairway of impressive width.

around 1500 m. This is surprisingly deep so close to the island, but this is the general characteristic of the Spratly Islands, indicating that the build-ups constructed the whole of any Island and kept pace with the very significant amount of Dangerous Ground thermal subsidence. The sea-floor topography is very subdued with no sea-floor cuestas. This may have been due to a more crystalline crustal lithology than at Line 3, less susceptible to major faulting.

By contrast, Line 3 shows a well developed cuesta (A on Fig. 5) that rises to a water depth of only 440 m. There is no carbonate build-up upon it. It may be concluded that the only build-ups are those forming the Spratly Islands and no build-ups have been drowned by subsidence of the Dangerous Ground.

The main controlling factors must be that the cuesta crests had been at sea level at one time (probably at the MMU) to allow algae and corals to begin building a reef. The rate of post-rift thermal subsidence should not have been too fast for carbonate build-up to become impossible, but the surrounding deep water was necessary to accommodate the post-rift sediments and thereby prevent killing the reef growth.

5.3. Line 5

This line extends north-east–south-west, approximately parallel to the regional strike of the faults. Strike sections are notoriously difficult to interpret because some seismic reflections come from off-line. The line is not too distant both from Pulau Layang-Layang and the reef of Permatang Ubi. Although the two peaks A and B are not too distant from Pulau Layang-Layang, on this seismic line they lie at a water depth of 1070 m (Fig. 6).

The half grabens of the rifted basement are clearly delineated, even though the line is approximately parallel to the strike of the faults. Other elements are less clear than in a dip section.

The two clues to the proximity of Pulau Layang-Layang and the reef of Permatang Ubi are the sharp peaks A and B that are presumably elongated only slightly oblique to the plane of the paper. Their steepness makes them difficult to interpret, but the vertical exaggeration of ~8 has introduced the steepness. At this exaggeration, a sea-floor slope of 70° is actually only 19°. Peak B appears to be a fault horst. It is certainly bounded on the north-east side by an impressive fault that bounds a thick package of syn-rift strata. Peak A also has the appearance of a narrow horst, bounded on two sides by normal faults.

5.4. Lines 6 and 7

Line 6 lies extremely close to Terumbu Montanani yet the bathymetry is rather featureless, with water depth quite flat at around 1.5 km (Fig. 7). This line contains no clues to the existence of the nearby reef, a common characteristic of the region of the Spratly Islands.

By contrast, Line 7, which is farther from any island, contains two spectacular sea-floor cuestas (Fig. 7). There is nothing comparable on Line 6. The highest cuesta, with a crest water depth of only 876 m, has no carbonate build-up upon it. The scarp slopes dip steeply towards the north-west at 28–30°. The bedding dips towards the south-east with dip slopes of 2–8°. The vertical throw of these spectacular master faults is approximately 1.8 km. The overlying post-rift strata were capable of draping over the dip slopes of 2–8° but could not have settled upon a scarp slope of 28–30°. Therefore the master faults are exposed on the sea floor

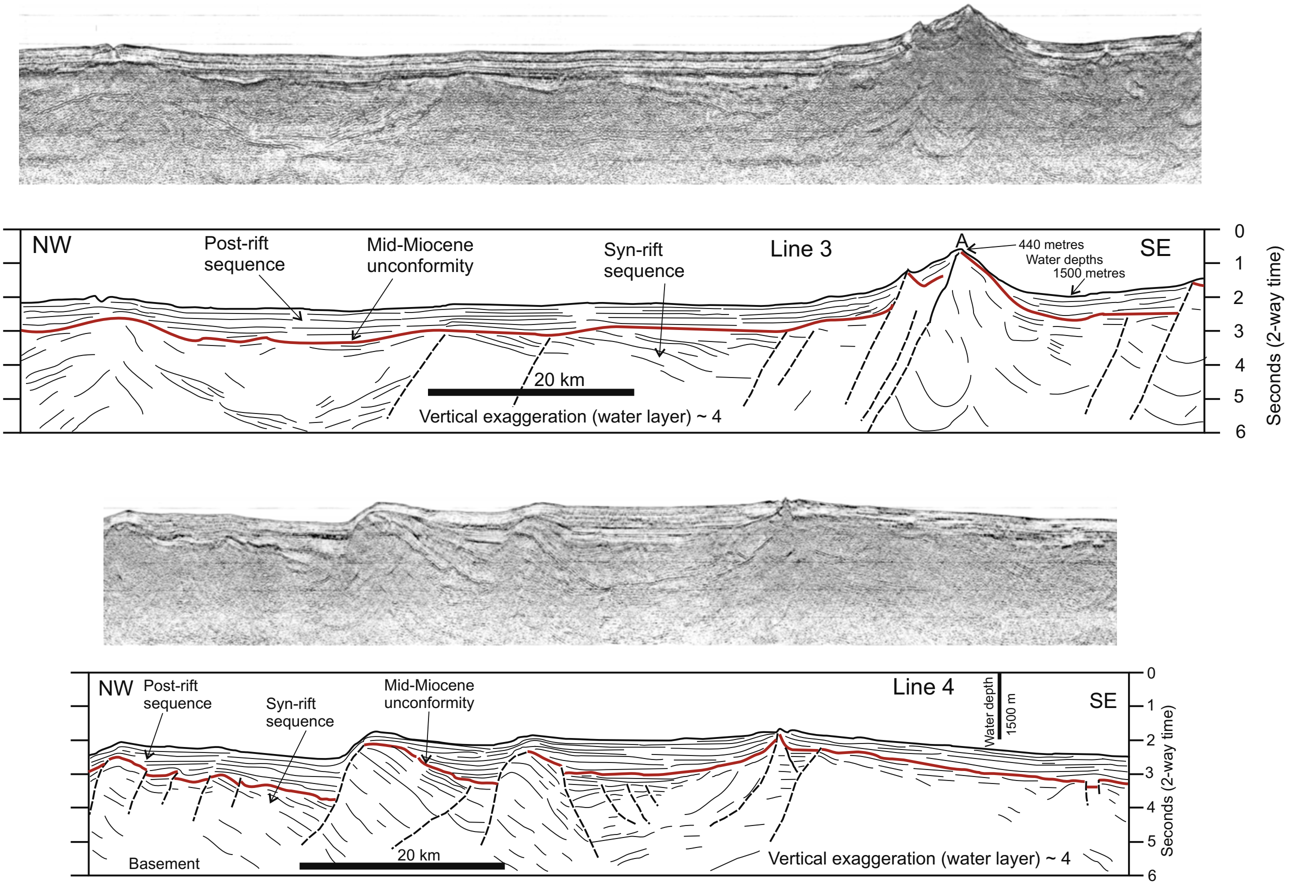


Fig. 5. Interpreted seismic Lines 3 and 4. The upper line is very close to Pulau Layang-Layang, but gives no clue of the existence of a nearby island. On the other hand the lower line is farther from any islands, but its highest point has a water depth of only 440 m. Yet, this structure has no carbonate build-up and no overlying reef. Both lines have a vertical exaggeration of ~4. Uninterpreted seismic lines are also shown.

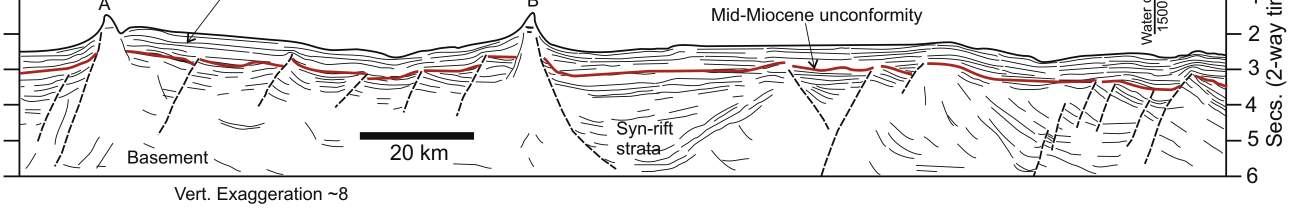


Fig. 6. Line 5, both interpreted and uninterpreted. The high vertical exaggeration of 8× has distorted the slopes. Sharp features A and B are of uncertain origin. However the geological features are rendered unfamiliar because the line is approximately parallel to the regional strike. The features at A and B are not far from the reefs of Pulau Layang-Layang and Permatang Ubi, but they underlie 1070 m of water.

in the same way that old steep-dipping fault planes onland may continue to outcrop. This does not mean that the faults are young. There is no indication that the master faults changed from normal to thrust (footwall being upthrust) as a result of possible later compression. The syn-rift strata show no dragging that would indicate such a possibility. The complicated bedding of the syn-rift strata are highly characteristic with strongly rotated bedding against the active master fault.

The contrast in relief of the Mid-Miocene Unconformity between Lines 6 and 7 is natural and results from the heterogeneity of the continental crust known from China (Yang et al., 1986) and Vietnam (Thanh and Khuc, 2006), from which the South China Sea continental slope was rifted. Semi-lithified sedimentary strata readily undergo normal faulting to form cuestas. By contrast granites and crystalline rocks, such as occur in the Precambrian Yangzi Platform or the Kontum Massif of eastern Vietnam, do not easily yield to faulting and never result in cuestas. Relatively unfaulted areas within a rifted terrane are natural and reflect the heterogeneity of the crust. Its nature cannot be identified from seismic without supplementary information and accordingly no conclusions should be drawn from the differences of rifting intensity between Lines 6 and 7 and others. The Tertiary rifts are also strongly inherited in their location and intensity from Caledonian (Devonian), Indosinian (Triassic) and Yenshanian (Cretaceous) orogenies that moulded the structural fabric of Sundaland (Hutchison, 2007).

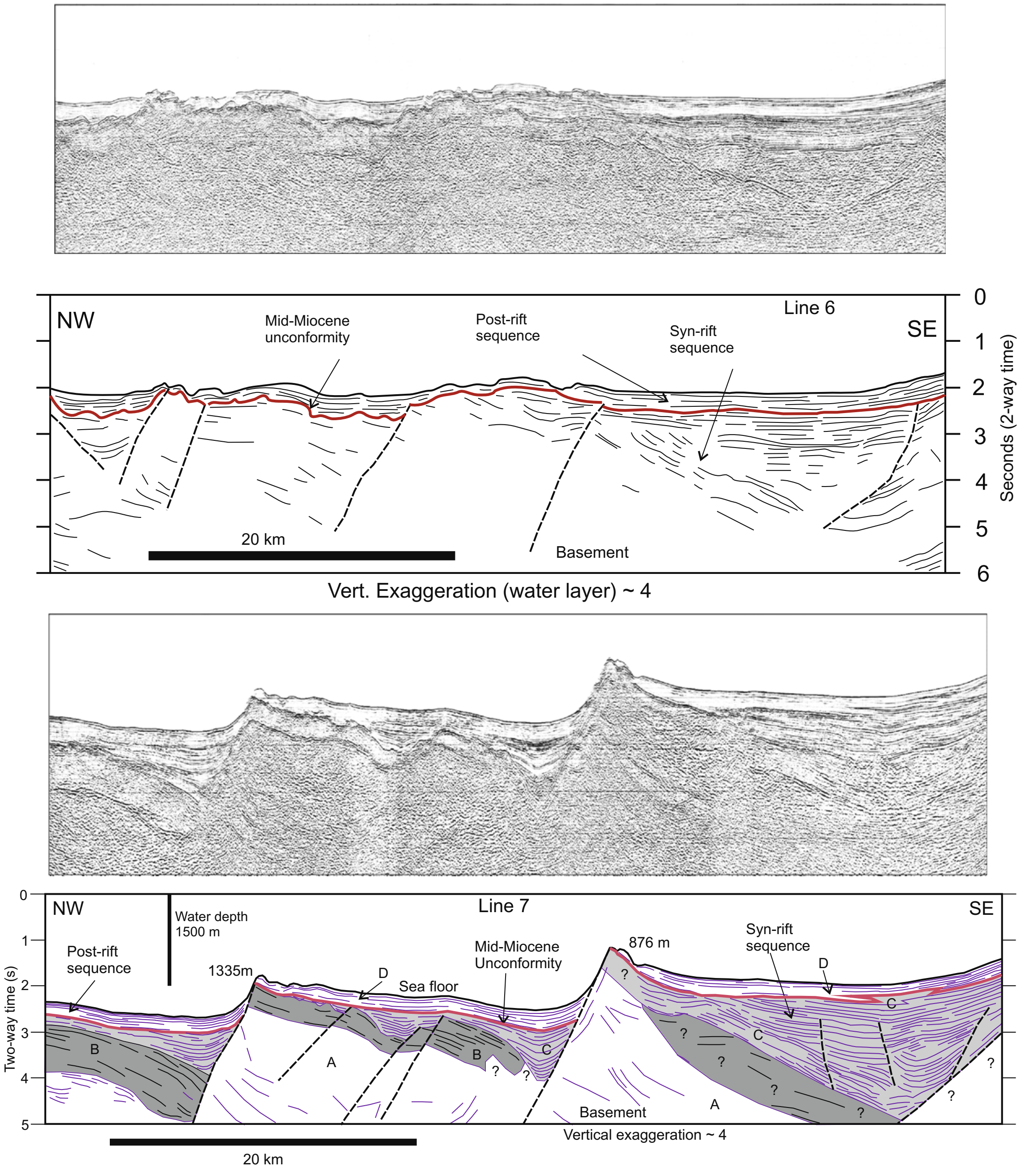


Fig. 7. Seismic along Lines 6 and 7, both interpreted and uninterpreted. Between them lies the reef of Terumbu Montanani. The spectacular cuestas of the Line 7 cannot be seen in the Line 6 that has subdued topography attributed to lithological differences. A = Basement that was subjected to rifting. B = Early syn-rift strongly rotated strata of variable thickness. C = Late syn-rift wedge-shaped half-grabens; strata strongly folded near the bounding faults. D = Post-rift draping strata. The Mid-Miocene Unconformity is taken as the C/D boundary.

5.5. Lines 8 and 9

The water over Lines 8 and 9 is generally deep, averaging 1500 m. Terumbu Peninjau lies between the two lines (Fig. 8). An approximately flat mesa-like feature is bounded along its north-west side by a normal fault and scarp slope. The exposed top of the scarp is at a water depth of 1372 m (Fig. 8). The bounding of the mesa along its south-east extent is less spectacular because it is covered over by the post-rift strata. The elevation of this south-east crest is at 1500 m water depth. The mesa-like feature sags only very slightly in the centre. Neither of the lines shows geological evidence of the reason for the existence of the nearby reef, except that it sits upon the flat-lying mesa.

Line 8 shows a similar mesa, and it may be confidently extrapolated between the two lines. In Line 8, the bounding fault scarps reach the sea-floor at elevations of 1428 and 1195 m respectively (Fig. 8). The mesa in Line 8 is nearly perfectly flat.

The geographical trend of the mesa and its bounding crests may be determined by comparing Lines 8 and 9. Terumbu Peninjau lies on the mesa. The cuesta crests at 1428 m and 1372 m (Fig. 8) give a regional trend of N56°E, similar to the trend of Fig. 5 and is approximately parallel to the magnetic anomalies of the abyssal plain of the South China Sea (Fig. 1). It may therefore be concluded that the faults all strike in a north-east–south-west direction and that the rifting belongs to one unified system that includes sea-floor spreading in the abyssal plain. The mesa is an integral part of this system. Mesas may be drowned banks, such as the Reed Bank (Fig. 1) that did not drown.

6. Seismic character of the post-rift strata

The post-rift sequence drapes over the Mid-Miocene Unconformity surface (Hutchison, 2004). Faulting is remarkably absent from

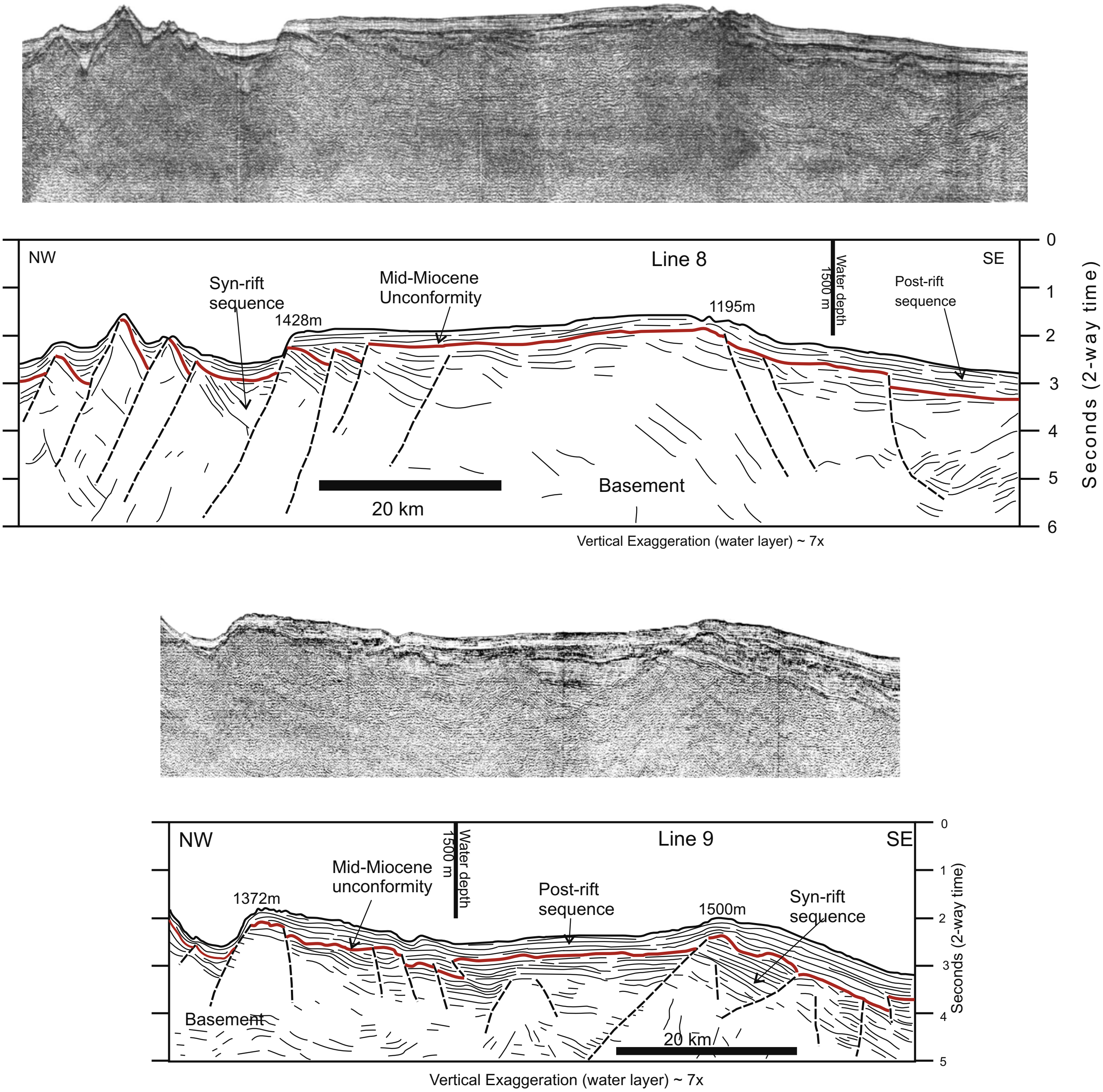


Fig. 8. seismic sections along Lines 8 and 9. Note that vertical exaggeration (water layer) of ~7 means that angles of dip that are apparently steep (75°) are in fact only 28°. Both interpreted and uninterpreted sections are shown.

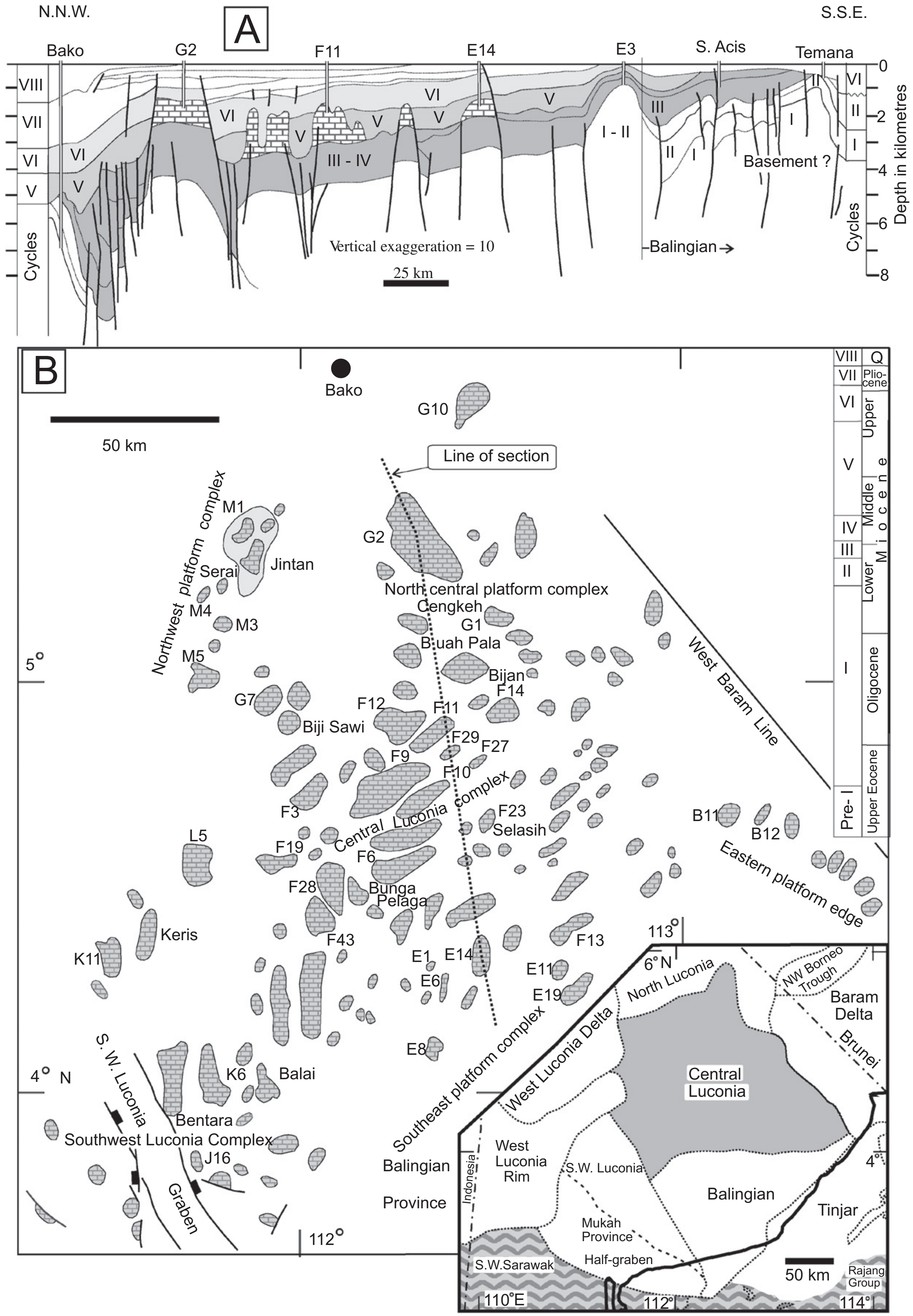


Fig. 9. The Miocene carbonate build-ups of the Central Luconia Province, based on Epting (1980) and Mohammad Yamin and Abolins (1999). (A) Structural cross section across the Central Luconia into the Balingian Province. (B) Map of the main drowned build-ups.

the post-rift sequence. The faults terminate upwards at the MMU (Figs. 5–8). The strata were deposited in bathyal water because the Dangerous Ground Province underwent post-rift thermal subsidence. In this region the post-rift sequence is thick and completely drapes over the syn-rift sequences.

The post-rift strata drape over the MMU to form a fairly uniform thickness. The sea-floor topography mimics, but in a subdued manner, the buried MMU (Fig. 8) but the draping strata may not have been able to cover over the large cuestas. Fig. 6, of only 4× vertical exaggeration, shows that the draping strata are not folded. The long amplitude wave-like structure is not tectonic folding and results from the uniform deposition upon the buried rifted topography. Differential compaction may also have enhanced this effect. Fig. 5 appears to suggest that the draping strata are folded. This is a misleading artefact of the large (~8×) vertical exaggeration.

7. Direct evidence of geology

The islands themselves are formed exclusively of carbonate build-ups (Fig. 3), thought to range from Mid Miocene to present day. A core to a depth of 165 m on the island of Taipingdao on the Zhanghe Bank (Fig. 2) logged a succession of coral-algal limestone with several caliche horizons indicating frequent subaerial exposure. Isotope dating indicates a succession from Holocene well into the Pleistocene (Gong et al., 2005). The build-ups are typical of reefs and cays and they contain no outcrops of older rocks. What lies underneath has to be inferred from the seismic records that indicate a preponderance of cuestas of bedded strata but there are no outcrops from which to deduce the chronostratigraphy. The dredging programme of Kudrass et al. (1986), summarised by Hutchison (2005), provide real evidence of the nature of the underlying rocks. Only three dredges were accomplished within

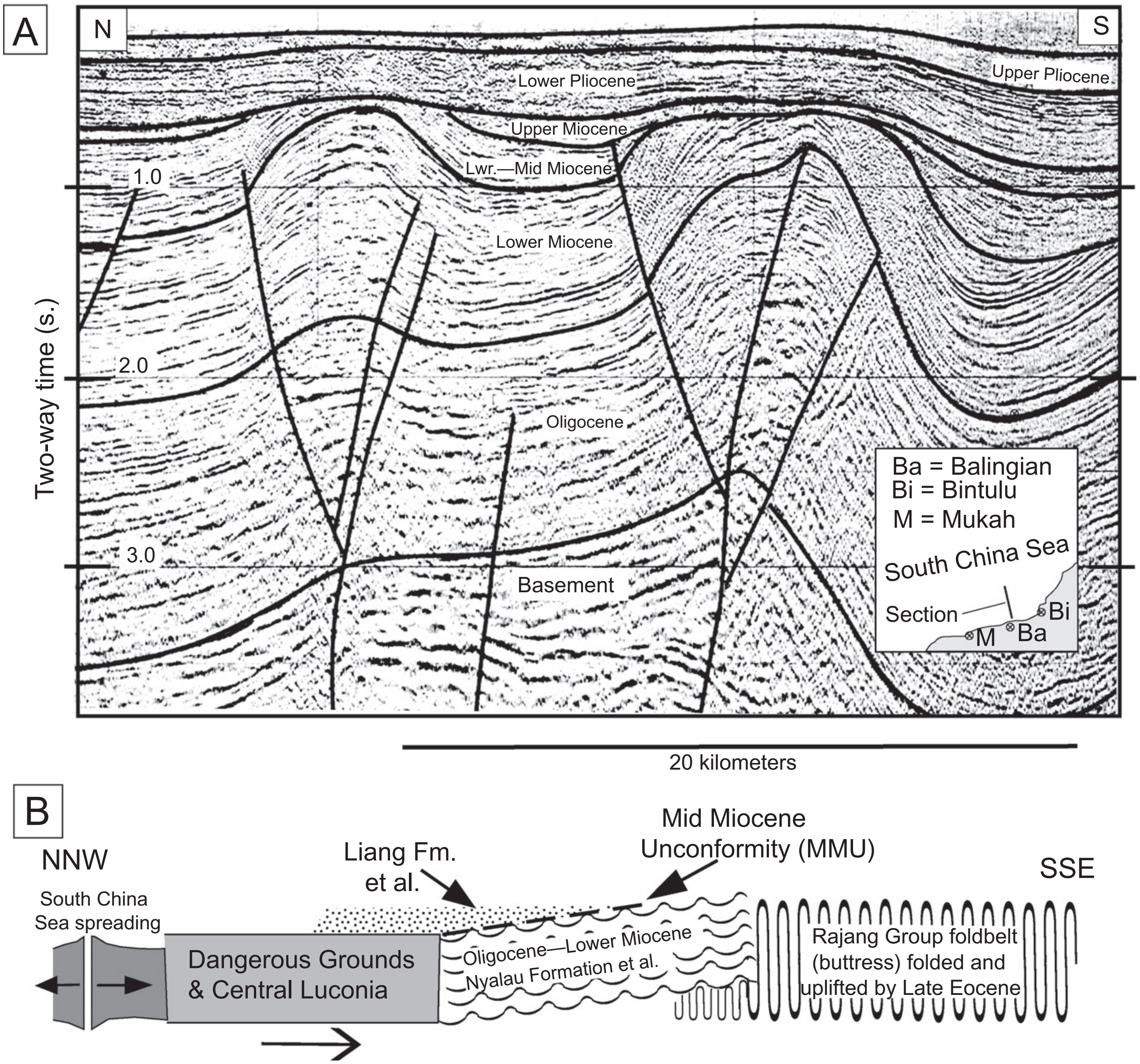


Fig. 10. (A) Seismic section immediately south of Central Luconia, showing the tightly compressed and eroded anticlines as a product of the Mid-Miocene Unconformity, after Mat Zin and Tucker (1999). The thrust-up and eroded anticlines have been commonly mistaken for horsts (Hutchison, 2005). (B) Cartoon to suggest the cause of folding within the Balingian, Central Luconia and Miri Zones.

the Malaysian EEZ (Fig. 2) and no additional work has been carried out. They all cluster north-east of the Commodore Reef. However, the area immediately to the east, north and north-east of the Malaysian EEZ, towards Mischief Reef, is of more interest where reefs are more numerous and the dredged samples more varied.

Kudrass et al. (1986) selected the slopes that support topographic highs such as banks, reefs and islands. They tabulated and described the large collection of rocks without making any geological analysis, but now it is possible to understand their collection by reference to the seismic lines of Figs. 5–8.

7.1. Pre-rift basement

The pre-rift basement is exposed beneath the sea on the scarp slopes and has been sampled around Mischief Reef (Fig. 2). The following sedimentary rocks have been dredged: light brown–grey siltstone and sandstone containing *Clathropteris* fern leaves of Upper Triassic–Lower Jurassic age were dredged at locality TR (Fig. 2). The strata have a vitrinite reflectance of 1.0–2.5%, resulting from loading by the rock and the water column. This range is equivalent to medium volatile bituminous coal–anthracite and is generally over-mature for oil – the oil-window is 0.5–1.35 (Hutchison, 1983). Dark grey claystone contains moulds resembling Upper Triassic *Halobia* and *Daonella,* abundant in Triassic rock outcrops in Peninsular Malaysia and Vietnam. Grey–black siliceous shale, of unknown age, contains radiolarian relicts.

The following metamorphic rocks have been dredged: biotite–muscovite–feldspar–quartz migmatitic gneiss has yielded a K/Ar date on muscovite (122 Ma) suggesting Lower Cretaceous metamorphism (Kudrass et al., 1986); garnet-mica schist containing sillimanite and one sample contained andalusite. K/Ar dating on muscovite (113 Ma) suggests the same metamorphic event; quartz-phyllite gave a K/Ar date on muscovite (113 Ma) also indicating Cretaceous metamorphism; and amphibolite schist in which the amphibole gave a K/Ar date of 146 Ma (Jurassic). However low credence must be given to K:Ar dates on random samples that have been altering on contact with sea water. The ages should be interpreted with caution.

The following plutonic rocks have been dredged: boulders of dark green diorite, of unknown age, are composed of plagioclase, clinopyroxene, ilmenite and some quartz. The plagioclase and pyroxene are much replaced by epidote, prehnite and chlorite; blocks of intensely altered olivine gabbro, of unknown age, in which the olivine is almost completely replaced by aggregates of chlorite, talc and montmorillonite.

The dredged rocks are not unusual in the context of continental Southeast Asia. The contiguous landmasses of Vietnam, South China, Peninsular Malaysia and western Sarawak have abundant outcrops of similar Triassic strata (Hutchison, 1989; Hutchison, 2007). As examples, the coal-bearing Van Lang, Hon Gai and Ha Coi formations of the An Chau depression of north Vietnam contain identical Tonkin flora to western Sarawak (Thanh and Khuc, 2006; Kon'no, 1972). Rhyolitic tuffaceous strata in south and south-west Vietnam are closely similar to the Semantan Formation of central Peninsular Malaysia (Nuraiteng, 2009). The continental terranes also contain significant belts of Triassic and Late Cretaceous granites and localised metamorphic rocks bear witness to older sutures and deformed belts. It may, therefore, be concluded that it is the typical continental crust of Southeast Asia that has been rifted to form the basement of the shelf and continental slope of the southern South China Sea.

7.2. Syn-rift rocks

Kudrass et al. (1986) have included dredge samples that date the rift related strata of the included seismic lines as Upper Oligocene to Lower Miocene. The specimens are as follows: light-grey–green slightly consolidated siltstone containing siliceous sponge spicules, radiolaria and planktonic Foraminifera, and Middle to Upper Oligocene nannoplankton; shallow-marine carbonates sampled at 23 sites, containing Late Oligocene to Early Miocene (Te) Foraminifera and Nummulites.

The well cemented syn-rift shallow-marine Oligocene–Early Miocene carbonates have not been identified on regional seismic records and therefore their stratigraphic significance is unknown.

7.3. Middle Miocene to Recent post-rift draping strata

Ocean Drilling Program (ODP) Site 1143 has provided information only about the Upper Miocene to Recent post-rift strata (Fig. 1), drilled as part of Leg 184 (Shipboard Scientific Party, 2000). 500 m of clay and highly calcareous nannofossil ooze with Foraminifera were recovered.

Many other sites yielded dredges of Pliocene ooze, ranging from grey–green clay to light-grey foraminiferal ooze. Coccoliths indicate a full Pliocene age range. Upper Pliocene ooze fills the outer vesicles of submarine basalt (Kudrass et al., 1986).

The following igneous rocks have been dredged: porphyritic basalt; vesicular basalt containing olivine, clinopyroxene and plagioclase gave a K/Ar Pliocene date of 2.7 Ma. However the K/Ar dating values should be given low credence. Porphyritic and vesicular basalt, containing olivine, clinopyroxene and plagioclase, gave a K/Ar Pliocene date of 2.7 Ma. Vesicular olivine basalt tephra surrounds lumps of Pliocene carbonaceous ooze. The basalt gave a K/Ar date of 0.42 Ma. Red and green massive dacite is of unknown age. The groundmass contains large plagioclase and small alkali feldspars. Secondary alteration to sericite and chlorite replace clinopyroxene. There is an extensive Pliocene–Pleistocene rift-related basalt province extending from Peninsular Malaysia, through Thailand to Vietnam and eastern China. As Hutchison (2007) has discussed, these gemstone-bearing alkaline basalts are associated with the major rifts that were active during development of the Tertiary basins of the South China Sea.

Li et al. (2005) have shown from Foraminifera studies that there is an unconformity-free 500 m cored sequence, from late Middle Miocene (12 Ma) to the present day so it may be assumed that the post-rift strata have been deposited without any tectonic interruption except for occasional basaltic eruptions in the Pliocene.

7.4. Granites from the continent–ocean boundary zone

Yan et al. (2009) described I-type tonalite-granodiorite dredged from near the continent–ocean boundary to the north of the Spratly Islands at 11°47′N, 114°56.5′E and 11°28.3′N, 114°04.6′E. These samples have been dated by zircon U–Pb at 127–159 Ma by Yan et al. (2008). Such Mesozoic granites may be correlated with the abundant Yenshanian granites (Xu and Zhu, 1988) of eastern mainland China as would be expected from the rifting history of the South China Sea.

The Yenshanian (Jurassic–Cretaceous) dredged granites lend some support to the theory of Taylor and Hayes (1983) that an Andean-type continental margin was rifting.

8. Comparison with Central Luconia

The Central Luconia Province (Fig. 1) contains ~200 carbonate build-ups and 43 have been drilled and proven to be a very significant gas province (Epting, 1980). Some build-ups began in the Early Miocene (Late Cycle III, 20.5 Ma). Most of the Cycle V build-ups were developed in the Messinian and Tortonian (10–5 Ma). Their extinction has been attributed to an influx of post-rift Cycle VI Upper Miocene siliclastic sediments (Fig. 9) but away from the sediment supply in deeper water, some of the build-ups were not terminated by muddy water and have continued active even until the present day (Mohammad Yamin and Abolins, 1999).

The build-ups are generally interpreted to have developed upon horsts, but seismic resolution beneath the build-ups is very poor. Mat Zin and Tucker (1999) and Hutchison (2005) showed that tectonic events around Mid-Miocene Unconformity time caused folding of the Balingian Province and the onland Miri Zone. The tightly folded and faulted anticlinal crests were eroded and deeper basement thrust-up, as shown by flower structures (Fig. 10), to resemble horsts (e.g. Tatau Horst), as discussed by Hutchison (2005).

Build-ups continue to survive in deepening water, but in shallow water a high influx of siliciclastic sediments causes their extinction. The tectonic scenario of the well studied and extensively drilled Central Luconia Province should be taken as a guide for interpretation of the Spratly Islands.

9. Conclusions

It seems reasonable to conclude that the Spratly Islands have resulted from carbonate build-ups upon the higher crests of major sea-floor cuestas whose axes generally plunge towards the south-west. The trends of the cuesta axes are parallel to the magnetic anomalies of the south-west prong of the contiguous abyssal plain (Briais et al., 1993; Barckhausen and Roeser, 2004) showing that all are part of a single rifting system. Seismic profiles show that their present crests may reach as high as present-day elevations of around 400 m below sea level towards the Spratly Islands, though the majority are much deeper. Sea-floor cuesta crests that were suitable for coral-algal growth would have been at sea level before the Dangerous Ground region began post-rift thermal subsidence. The build-ups kept pace with subsidence to form islands and reefs now known as the Spratly Islands. A mesa-like feature around Investigator Shoal now rests under about 1200 m of water. Unlike the Central Luconia Province, the reefs of the Spratly Islands were protected from extinction because of the deepening water of the region, within which the post-rift strata were fully accommodated, and the reefs were able to continue to build-up in clear water, even to the present day.

The preponderance of sea-floor cuestas indicates that the region is dominated by well bedded strata and dredging suggests they are mainly of Triassic–Cretaceous age. Such rocks are widespread onland China, Vietnam, Thailand, Peninsular Malaysia and western Sarawak (Hutchison, 2005). It is concluded, admittedly on limited information, that the Spratly Islands infrastructure is not exotic to the region of Southeast Asia and that the rifting was of a large part of eastern Sundaland.

Yan et al. (2006) correctly concluded from their review that the South China Sea margins are non-volcanic. They listed the dredge samples by Kudrass et al. (1986) as the only examples. Unfortunately the K/Ar dates cannot be reliably accepted, so that no meaningful statement can be made of the sparse occurrences of volcanic rocks. However Yan and Liu (2004) and Hutchison (2004) presented seismic interpretations of sea-floor edifices that have no structural elongation and might be interpreted as volcanic features that rise from around the Mid-Miocene Unconformity or from a lower level. However they remain untested. There are also conical edifices, as yet unpublished, within the North-West Borneo Trough that are now conclusively shown by Hutchison (2010) to be drowned carbonate build-ups.

Acknowledgement

We are grateful to PETRONAS for allowing us to study, interpret and publish the seismic lines included in this paper.

References

Barckhausen, U., Roeser, H.A., 2004. Seafloor spreading anomalies in the South China Sea revisited. In: Clift, P., Wang, P., Kuhnt, W., Hayes, D. (Eds.), Continent–Ocean Interactions within East Asian Marginal Seas. Geophysical Monograph, vol. 149, pp. 1–5.

Briais, A., Patriat, P., Tapponnier, P., 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: implications for the Tertiary tectonics of Southeast Asia. Journal of Geophysical Research 98, 6299–6328.

Clift, P., Lin, J., Barckhausen, U., 2002. Evidence of low flexural rigidity and low viscosity lower continental crust during continental break-up in the South China Sea. Marine and Petroleum Geology 19, 951–970.

Clift, P., Lee, G.H., Anh Duc, N., Barckhausen, U., Van Long, H., Zhen, S., 2008. Seismic reflection evidence for a Dangerous Grounds miniplate: no extrusion for the South China Sea. Tectonics 27, TC3008. doi: 19.1029/2007TC002216.

Darwin, C., 1842. The Structure and Distribution of Coral Reefs. University of California Press, Berkeley (reprinted 1962) 214p.

Dzurek, D.J., 1996. The Spratly Islands Dispute: Who's On First? Maritime Briefing, vol. 2 (No. 1). International Boundaries Research Unit, Mountjoy Research Centre, University of Durham, Durham, England, 67p.

Epting, M., 1980. Sedimentology of Miocene carbonate build-ups, Central Luconia, offshore Sarawak. Geological Society of Malaysia Bulletin 12, 17–30.

Gong, S.Y., Mii, H.S., Wei, K.Y., Horng, C.S., You, C.F., Huang, F.W., Chi, W.R., Yui, T.F., Torng, P.K., Huang, S.T., Wang, S.W., Wu, J.C., Yang, K.M., 2005. Dry climate near the Western Pacific warm pool: Pleistocene caliches of the Nansha Islands, South China Sea. Palaeogeography, Palaeoclimatology, Palaeoecology 226, 205–213.

Hancox, D., Prescott, V., 1995. A Geographical Description of the Spratly Islands and An Account of Hydrographic Surveys Amongst Those Islands. Marine Briefing, vol. 1 (No. 6). International Boundaries Research Unit, Department of Geography, University of Durham, Durham, England, 88p.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1166.

Hutchison, C.S., 1983. Economic Deposits and Their Tectonic Setting. The MacMillan Press Ltd., London.

Hutchison, C.S., 1992. The Eocene unconformity in Southeast Asia and east Sundaland. Geological Society of Malaysia Bulletin 32, 69–88.

Hutchison, C.S., 2004. Marginal basin evolution: the southern South China Sea. Marine and Petroleum Geology 21, 1129–1148.

Hutchison, C.S., 2005. Geology of North-West Borneo. Elsevier, Amsterdam. 421p.

Hutchison, C.S., 2007. Geological Evolution of South-East Asia, second ed. Geological Society of Malaysia, Kuala Lumpur. 433p.

Hutchison, C.S., 2010. The North-West Borneo trough. Marine Geology 271, 32–43.

Kon'no, E., 1972. Some Late Triassic plants from the southwestern border of Sarawak, east Malaysia. Geology and Palaeontology of Southeast Asia 10, 125–178.

Krebs, W.N., Van Vliet, A., 2009. The Middle Miocene Unconformity (MMU): neither Middle Miocene nor unconformity. Petroleum Geology Conference and Exhibition 2009 Programme, Geological Society of Malaysia, Paper 16, p. 27.

Kudrass, H.R., Wiedicke, M., Cepek, P., Kreuzer, H., Müller, P., 1986. Mesozoic and Cainozoic rocks dredged from the South China Sea (Reed Bank area) and Sulu Sea and their significance for plate-tectonic reconstructions. Marine and Petroleum Geology 3, 19–30.

Li, B., Jian, Z., Li, Q., Tian, J., Wang, P., 2005. Paleoceanography of the South China Sea since the middle Miocene: evidence from planktonic foraminifera. Marine Micropaleontology 54, 49–62.

Mat Zin, I.C., Tucker, M.E., 1999. An alternative stratigraphic scheme for the Sarawak Basin. Journal of Asian Earth Sciences 17, 215–232.

Mazlan, bin Haji Madon, 1999. North Luconia Province. In: The Petroleum Geology and Resources of Malaysia. PETRONAS, Kuala Lumpur, pp. 443–454.

Mohammad Yamin, bin Ali, Abolins, P., 1999. Central Luconia Province. In: The Petroleum Geology and Resources of Malaysia. PETRONAS, Kuala Lumpur, pp. 371–392.

Nuraiteng, Tee Abdullah, 2009. Mesozoic stratigraphy. In: Hutchison, C.S., Tan, D.N.K. (Eds.), Geology of Peninsular Malaysia. Geological Society of Malaysia and the University of Malaya, Kuala Lumpur, pp. 87–131 (Chapter 6).

Purdy, E.G., Winterer, E.L., 2001. Origin of atoll lagoons. Geological Society of America Bulletin 113, 837–854.

Robinson, K., Baltensperger, P., Thomas, A., Noon, S., 2009. The Middle Miocene unconformity (MMU) and *globigerinid* sands in deepwater Sarawak. Petroleum Geology Conference and Exhibition 2009, Programme, Geological Society of Malaysia, Paper 17, pp. 28–29.

Shipboard Scientific Party, 2000. Site 1143. In: Wang, P., Prell, W.L., Blum, P., et al. (Eds.), Proc. ODP, Init. Repts. 184, pp. 1–103 ([CD-R] available from: Ocean Drilling Program, Texas A&M University, College Station, Texas 77845-9547, USA).

Taylor, B., Hayes, D.E., 1980. The tectonic evolution of the South China Sea Basin. In: Hayes, D.E. (Ed.), The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands. Geophysical Monograph, vol. 23. American Geophysical Union, Washington, pp. 89–104.

Taylor, B., Hayes, D.E., 1983. Origin and history of the South China Sea Basin. In: Hayes, D.E. (Ed.), The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands, Part 2. Geophysical Monograph, vol. 27. American Geophysical Union, Washington, pp. 23–56.

Thanh, T.D., Khuc, V., 2006. Stratigraphic Units of Vietnam. Vietnam National University, Hanoi.

Vahrenkamp, V.C., 1998. Miocene carbonates of the Luconia Province, offshore Sarawak: implications for regional geology and reservoir properties from Strontium-isotope stratigraphy. Bulletin of the Geological Society of Malaysia 42, 1–13.

Xu, K., Zhu, J., 1988. Time-space distribution of tin/tungsten deposits in south China and controlling factors of mineralization. In: Hutchison, C.S. (Ed.), Geology of Tin Deposits in Asia and the Pacific. Springer-Verlag, Heidelberg, pp. 265–277.

Yan, P., Liu, H., 2004. Tectonic-stratigraphic division and blind fold structures in Nansha waters, South China Sea. Journal of Asian Earth Sciences 24, 337–348.

Yan, P., Deng, H., Liu, H., Zhang, Z., Jiang, Y., 2006. The temporal and spatial distribution of volcanism in the South China Sea region. Journal of Asian Earth Sciences 27, 647–659.

Yan, Q.S., Shi, X.F., Wang, K.S., Liu, X.M., 2008. LA-ICPMS dating of zircon U–Pb and tectonic significance of granitic rocks from Nansha Block, the South China Sea. Acta Geologica Sinica 82 (8), 1057–1067 (in Chinese with English Abstract).

Yan, Q.S., Shi, X.F., Liu, J., Wang, K.S., Bu, W., 2009. Petrology and geochemistry of Mesozoic granitic rocks from the Nansha micro-block, the South China Sea: constraints on the Basement Nature. Journal of Asian Earth Sciences. doi:10.1016/j.jseaes.2009.08.001.

Yang, Z., Cheng, Y., Wang, H., 1986. The Geology of China. Oxford Monographs on Geology and Geophysics, vol. 3. Clarendon Press, University of Oxford.