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South China Sea carbonate build-up seismic characteristics

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Abstract: More than 600 active reefs in the Spratly Islands and 200 build-ups in Central Luconia, buried in the Upper Miocene, all begun at the Middle Miocene Unconformity. Their seismic character results from the subsidence regime of the marginal basin. Central Luconia build-ups within the continental shelf remained in shallow water and were buried by an Upper Miocene influx from nearby Sarawak, known onland as the Setap Shale. Build-ups within the continental rise (Dangerous Grounds) and North-West Borneo Trough were drowned by rapidly deepening water then occasionally draped over by a thin layer of deep water sediments. Spratly Islands reef builders colonized cuesta highs and kept pace with the deepening sea. The build-ups now continued to be active and none were drowned. Young sediment influx could only settle as thin ponded turbidites within the sea between the reefs that had deepened to at least 1.8 km.

Keywords: South China Sea, carbonate, Spratly Islands, Luconia Province

INTRODUCTION

The purpose of this paper is to illustrate the seismic characteristics displayed by the range of carbonate build-ups in the southern part of the South China Sea marginal basin. In a regional review, Wilson (2002) noted that, apart from the Central Luconia Province offshore Sarawak, there is a general absence of publications on the carbonate build-ups of the South China Sea. Epting (1980) illustrated diagrammatically the behaviour of algal-coral reefs in response to changing sea-levels. Sea-level changes may be worldwide eustatic, or have regionally resulted from tectonic events such as post-rift thermal subsidence that has been very important in the South China Sea. The categories of reef behaviour discussed by Epting (1980) are:

1. Build-up — balance between rate of reef growth and that of water deepening.
2. Build-out — the growth rate of the corals/algae exceed the rate of water deepening resulting in upwards widening of the build-up.
3. Build-in — growth rate cannot keep up with the rate of water deepening
4. Reef extinction — ultimately a build-in results in extinction of the reef. The top of the dead submerged carbonate bank will become topped by spikes of restricted coral/algal colonies, calcareous algal balls, or diverse marine fauna/flora. I refer to this extinction mechanism as drowning.

To be complete, two additional categories should be added:

5. Reef exposure — Tectonic uplift of a region (equivalent to falling sea-level). The living reef is raised progressively above sea level and dies off. These are commonly referred to as “raised coral reefs”. No examples have been found in the South China Sea. The large island of Timor and the smaller islands such as Wetar to the north in the Banda Sea offer excellent examples.
6. Reef burial because of an influx of muddy sediment causing the water environment to become unsuitable. The build-ups die and become buried.

The three regions of South China Sea carbonate build-ups are:

1. The Central Luconia Province, described by Epting (1980) and Mohammad Yamin and Abolins (1999), was included by Wilson (2002) in her summary. This is the best known of the three because the build-ups contain commercial gas and accordingly have been extensively drilled. However seismic illustrations of the build-ups have not been published. These build-ups have been buried by Upper Miocene sediments.

2. The Spratly Islands, referred to by many but not adequately studied because of the lack of seismic analysis and ownership dispute. The build-ups are topped by present¬day reefs surrounded by very deep water. Accordingly no reef appears on any seismic line (Hutchison & Vijayan, 2010).

3. Within the North-West Borneo Trough. Large sea-floor conical edifices rise above the flat ~2 km deep trough (Hutchison, 2010a) and are now analysed for the first time as 64 drowned carbonate build-ups. These build-ups initially occurred as scattered individuals within the marginal basin continental rise (Dangerous Grounds).

Each of these provinces will be described.

GEOLOGICAL ENVIRONMENT

Hutchison (2004) has analysed the South China Sea as a marginal basin that rifted the marginal continental crust of the Southeast Asian Sundaland continent. Rifting began locally in the Eocene and became widespread by the Oligocene, predominantly in the form of half grabens. A universally present Middle Miocene Unconformity marked the end of rifting. It continues to be referred to as the MMU, although Krebs and Van Vliet (2009) and Robinson *et al*. (2009) have shown from the palaeontology of cores that the unconformity is indeed late Lower Miocene.

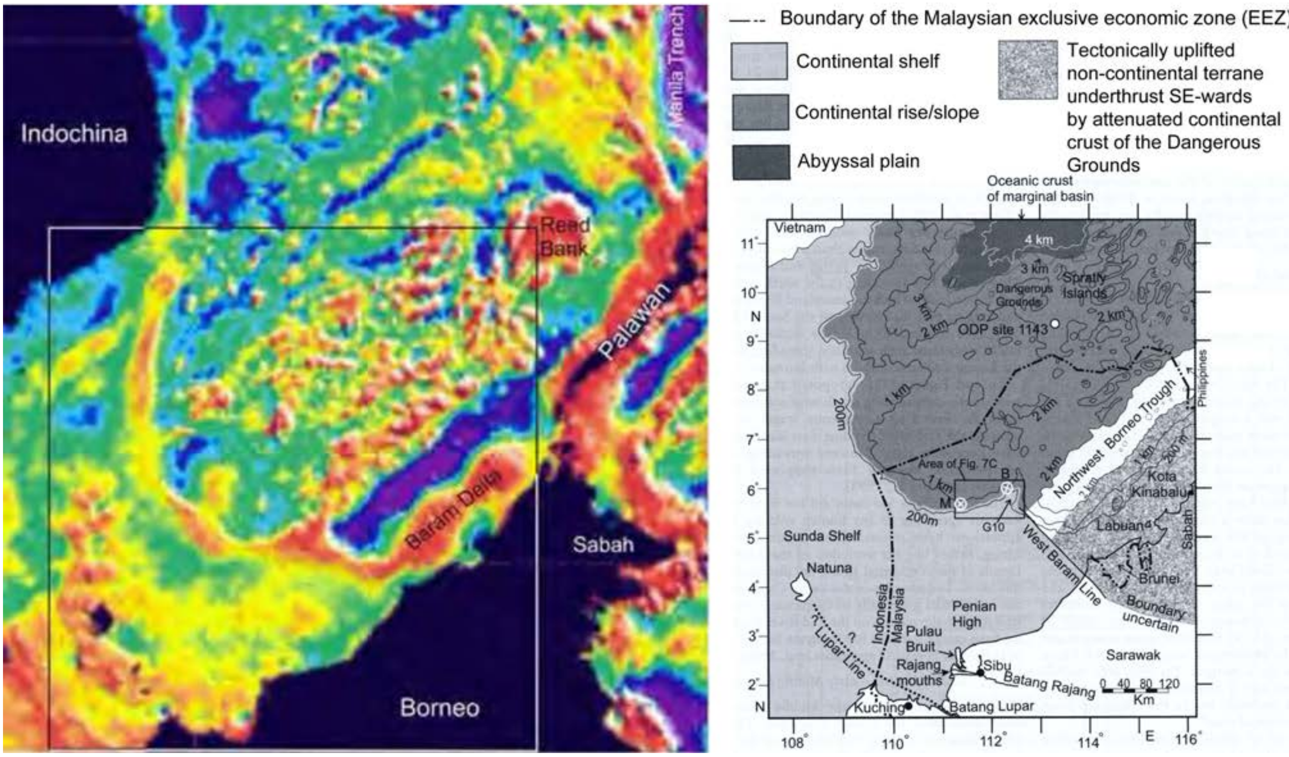


Figure 1: Left: SEASAT marine gravity anomaly map of selected part of Southeast Asia, downloaded from Oxford University earth sciences department web site http://www.earth.ox.ac.uk/~geodesy/downloads.html Right: Major tectonic elements of the southern South China Sea outlined area and their relationship to bathymetry, after Holt (1998).

The bathymetry of the South China Sea has been analysed by Holt (1998) but his major thesis was never published (Figure 1). A three-fold geographical division, in common with all passive margins, is readily visualised. The present day coastline is of no geological significance, being a product of sea level change resulting from the amount of water locked up in the ice sheets during glaciations (Hanebuth *et al*., 2000). The older continental geology of northwestern Borneo clearly continues under the sea (Sunda Shelf) towards Vietnam (Hutchison, 2005). Borneo Island, just like the smaller island of Natuna, does not have its own continental shelf but forms an integral part of the continental shelf of Eurasia.

As a generalisation, the shallow water continental shelf extends from the coastline to the 200 metre isobath (Figure 1). A prominent change in gradient of the sea-floor is seen at this depth, but in many localities it may be deeper. In Southeast Asia, the shelf is known as the Sunda Shelf. Holt (1998) has shown that on average the Sunda Shelf is characteristically of crustal thickness between 25 and 30 km but may locally be as thin as 16 km beneath the deeper basins, such as the Malay Basin.

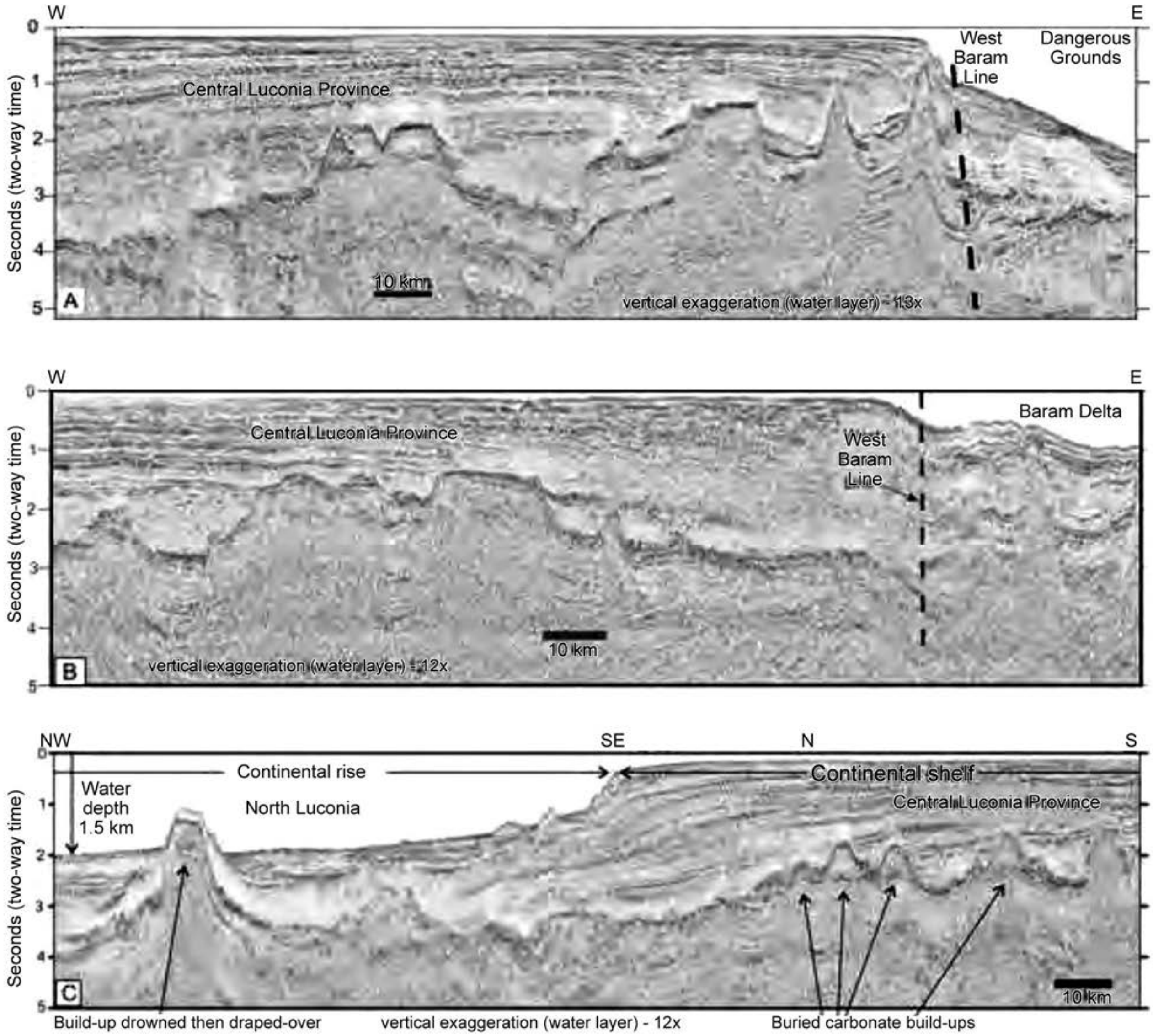
As a result of more advanced rifting and crustal attenuation, the crust of the succeeding continental rise has subsided to an isostatic depth of between 200m and 3.5 km (Figure 1). It is not possible to map separately a continental slope, so I have combined it with the rise. It is discussed generally by geomorphologists but the distinction slope/rise cannot be made in the South China Sea. The continental rise/slope is known as the Dangerous Grounds and Spratly Islands regions (Figure 1). The abyssal plain is characterised by water depths in excess of 3.5 km. It is the region of sea-floor spreading where the continental crust has been completely attenuated. Sea floor spreading has been dated by magnetic anomalies between Oligocene and Lower Miocene but the abyssal plain has nowhere been drilled.

DATA

A wide selection of unpublished 2D seismic lines from within the Malaysian Exclusive Economic Zone (EEZ) have been studied for carbonate build-ups and examples of the different varieties are published herein.

CENTRAL LUCONIA PROVINCE

The Central Luconia Province lies entirely offshore Sarawak within the Sunda Shelf. Its geology has been summarised by Epting (1980) and Mohammad Yamin and Abolins (1999). There are more than 200 carbonate build-ups and Vahrenkamp (1998, 2000) has described their stratigraphic dating and Volker *et al*. (1998) has discussed their porosity, stratigraphy and origin. Figure 2 gives the typical seismic characteristics of the Province and Figure 3 shows the areal distribution and chronostratigraphy. Large platform-type build-ups developed on pre-MMU highs whereas pinnacle-type build-ups developed in adjacent areas where subsidence was slightly more pronounced. The build-ups are dated Middle to Upper Miocene, but die out in the Upper Miocene. By this time the environment



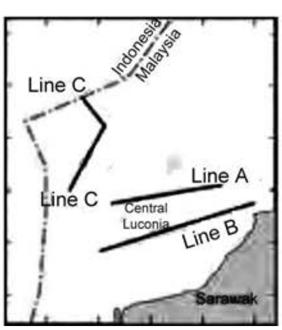


Figure 2: Three seismic profiles across western Sarawak. A and B illustrate the buried gas¬ bearing Miocene carbonate build-ups of the Sunda Shelf Central Luconia Province. C illustrates a more isolated carbonate build-up in the less well known deep water Northern Luconia Province. The location map shows the approximate positions in relation to the Malaysian EEZ boundary and the coast of Sarawak.

was unfavourable for continuing coral survival in a shelf open marine environment with an influx of predominantly muddy sediment from the Sarawak landmass. The build-ups of Figure 2 were all buried and the argillaceous Upper Miocene mudstones (= Setap Shale onland) that caused the burial also provided a good seal causing trapping of the hydrocarbons within the carbonates.

The Central Luconia Province is separated abruptly from the Baram Delta by the West Baram Line. West of the Line the average geothermal gradient is 43°C km^{-1} and east of the line the average geothermal gradient is only 28°C km^{-1} (Hutchison, 2007). Accordingly the Central Luconia Province is underlain by thick continental crust and commonly referred to in the literature as a microcontinent.

The beginning of the carbonate build-ups results from the prominent Middle Miocene Unconformity (MMU) that most likely occurred in the very late Lower Miocene (Figure 3). Before the MMU, Sarawak did not exist as a landmass, and land lay to the west in the Penian High and Sundaland (Hutchison, 2007). The sand-dominant coastal formation that underlies the MMU is known onland as the Nyalau Formation. The MMU is marked by the end of rifting and the uplift of what is now known as the Sarawak landmass.

NORTH LUCONIA PROVINCE

In response to more advanced rifting and crustal attenuation, the sea became as deep as 1.5 km in the Continental Rise to the north of the Central Luconia Province after the MMU, as compared with a maximum 200 m over the Sunda Shelf (Figure 2 seismic section C). There are a small number of isolated carbonate build-ups. The deeper water protected the build-ups from possible burial as the Upper Miocene continent-sourced sediment was dispersed by turbidity currents in the deeper water.

The illustrated build-up showed that it continued to grow as the water deepened, as shown by distinct bedding. Eventually the build-up was drowned by the too rapid subsidence and is now covered over by a thin veneer of younger sediments (Figure 2, section C).

NORTH-WEST BORNEO TROUGH

The North-West Borneo Trough has been interpreted as an extinct convergent plate margin (trench) in which the continental rise of the South China Sea (Dangerous Grounds Province) once subducted southeastwards beneath Sabah and the thrust sheet complex may be interpreted as the related extinct accretionary prism (Hutchison, 2010a). The Trough may then be referred to as a foredeep. It terminates abruptly southwestwards at the West Baram Line. Post-MMU uplift of the Western Cordillera (Deep Regional Unconformity) of Sabah (Hutchison, 2007) resulted in the major Miocene Baram Delta, the ultimate destination of whose sediments is the North-West Borneo Trough (Figures 4 and 5). Oil has been trapped not only in the shallow water nearshore parts of the delta but also in folded turbidites of the fold thrust toe zone of the delta as it actively builds out into the North-West Borneo Trough (Ingram *et al*., 2004).

The build up (1) shown in Figure 4 is identical to that shown in C (Figure 2), although the present water depths are different. However build-up 1 was not yet within the Trough when it was growing. Both were part of the Dangerous Grounds. Generally carbonate build-ups have no seismic resolution underneath, but a high such as the crest of a half graben is likely. The thin veneer of young draping strata may be attributed to proximity to sediment supply from a shallow shelfal area.

Profiles 2 and 3 (Figure 4) are of a very large build-up. Profile 3 is a recently acquired high resolution seismic record and it clearly shows that the build-up was drowned as the water deepened. The features to expect in a drowned build-up were enumerated by Epting (1980) but never seen in the Central Luconia Province where the build-ups were buried. The top of a reef, that is dying because of over deepening water, should be characterised by dead corals and debris as well as scattered balls of algae. These accumulations form spikes on top of the dead reef and this is clearly shown in profile 3 (Figure 4). It is the only profile of its kind after an extensive search through the seismic records. Because it is a very large build-up eventually positioned in very deep water in the North-West Borneo Trough, and because the sediment supply from onland (front of the Baram Delta) was insufficient, this large build-up could not have been draped over.

SPRATLY ISLANDS PROVINCE

There are more than 600 reefs and islets in the southern South China Sea. Most lie between 7–12° N and 112–116° E (Figure 6). The naming is not internationally agreed because there is an ongoing unresolved territorial dispute. A general description has been given by Hutchison and Vijayan (2010).

The reefs occur within a province of very deep water, commonly as deep as 1.9 km (Figure 6) and this is strange because carbonate build-ups require shallow water and the active tops of the reefs are currently at sea level and a danger to shipping, hence the name Dangerous Grounds. Seismic profiles across the reefs do not exist but there are several that were surveyed between the reefs. They show spectacular half grabens and sea floor cuestas and it is assumed that the build-ups became established upon the crests of shallower cuestas following the MMU at the early stages of rifting. But there are no drowned build-ups and all survived to the present day. The post-rift sedimentary drape is thin because the province is far from a possible provenance and the corals and algae thrive at the surface in adjacent very clear deep water.

Only one reef has been drilled. A core to a depth of 165 m on the island of Taipingdao on the Zhanghe Bank (Figure 6) 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). However the total build-up remains unpenetrated. It seems very unlikely that any of the build-ups would have reservoired hydrocarbons because of the absence of a seal and frequent subaerial exposure.

Onland carbonates of long duration

The nearest analogue to the Spratly Islands could be the Melinau Limestone of the Mulu Caves district of Sarawak (37 km long in a NE–SW direction by a maximum width of 8 km, occurring at 114°50′E, 4°10′ N). Descriptions are by Adams (1965) and Wannier (2009). The carbonate extended as a platform from Upper Eocene (Priabonian, 37.2 Ma) through to Lower Miocene (Aquitanian, 20.42 Ma), an extent of 16.77 m.y. and a total thickness of 1997 metres (Adams, 1965). Coral reefs (build-ups) have been described only around the top in the Lower Miocene (Wannier, 2009). The Melinau Limestone unconformably overlies the Mulu Formation, which may be correlated to the turbiditic Rajang Group of Sarawak. The change from turbidite to shallow water limestone marks the regionally

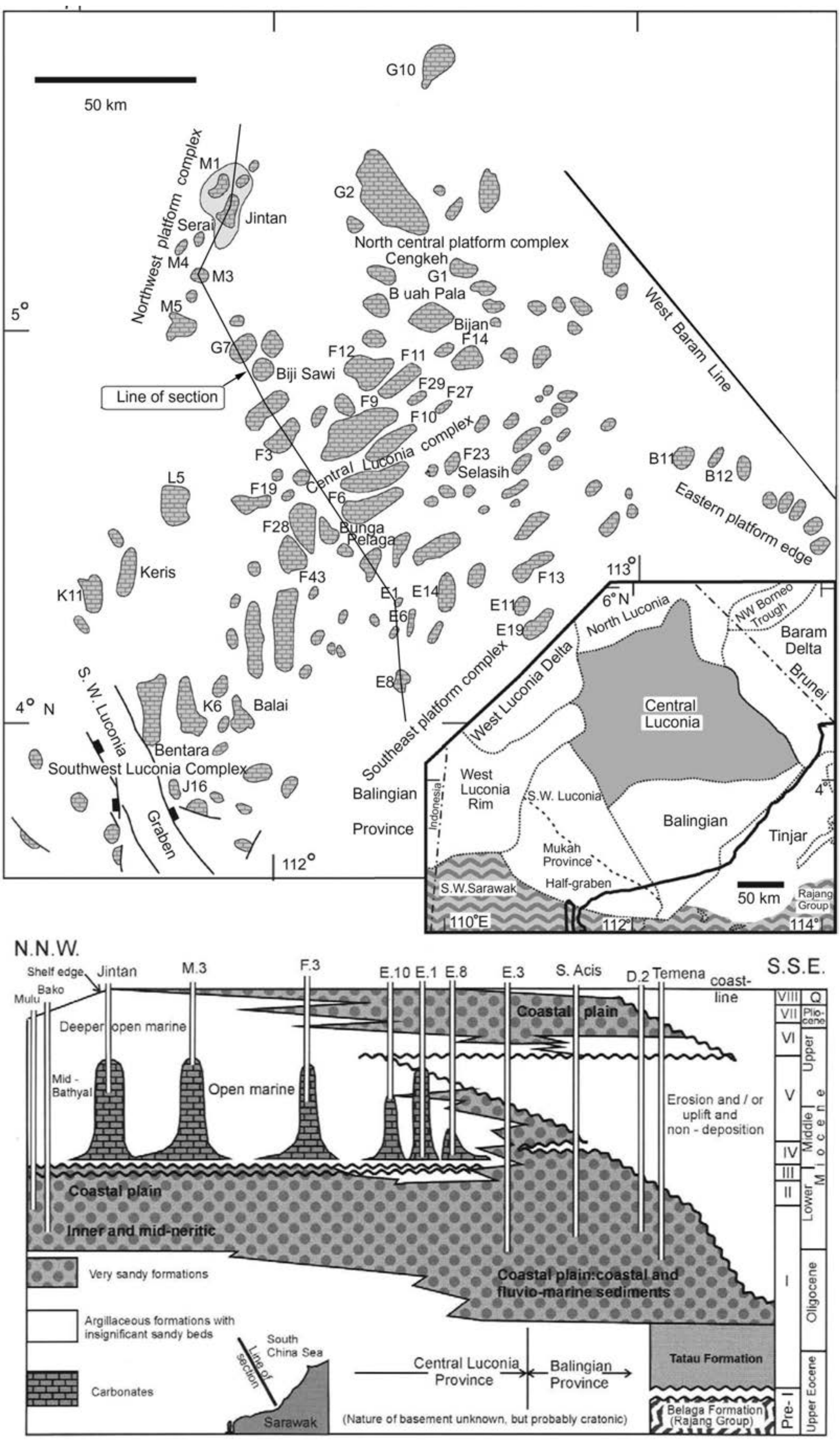


Figure 3: Upper: Distribution of the Miocene carbonate build-ups of the Central Luconia Province. Lower: Chronostratigraphic cross section (after Hutchison, 2007).

important Sarawak Orogeny (Hutchison, 2010b). Wannier (2009) showed the Upper Melinau Limestone is overlain by a very muddy formation. I would disagree with his naming it as the Temburong Formation (a very confusing term meaning different things in Brunei and in Sabah) and would rather choose the name Setap Shale, which is not universally of deep water environment. However the muddy environment would have caused extinction of Melinau Limestone deposition. By comparison with the Melinau Limestone, the Spratly Islands build-ups are assumed to have begun in the Middle Miocene (Langhian 15.97 Ma) persisting actively to the present day. This is comparable to the Melinau Limestone, but Spratly Islands thickness cannot be quantified.

CONCLUSIONS

Hundreds of carbonate build-ups characterize the southern South China Sea, concentrated in two areas—more than 600 presently active as reefs in the Spratly Islands and more than 200 buried build-ups in the Central Luconia Province. There are also scattered occurrences of drowned build-ups elsewhere. All may be concluded to have begun at the Middle Miocene Unconformity (Langhian, 15.97 Ma). The seismic character of the build-ups results directly from the subsidence regime of the South China Sea marginal basin. Build-ups within the Sunda continental shelf (Central Luconia carbonates) remained in shallow water and were buried by an Upper Miocene sediment influx from nearby Sarawak. Build-ups within the continental rise, where crustal attenuation and subsidence was greater, may have been drowned by too rapidly deepening water and even draped over by a thin layer of post extinction sediment. This includes build-ups that ended up within the deep North-West Borneo Trough. The Spratly Islands is a special category of build-ups that occur within the continental rise. The corals and algae were able to keep up with the deepening sea and to be active as reefs to the present day. Great distance from landmass-provenanced sedimentary influx prevented the build-ups from burial and the meager sediment supply could only settle as thin turbidite within the sea that had deepened to at least 1.8 km between the reefs.

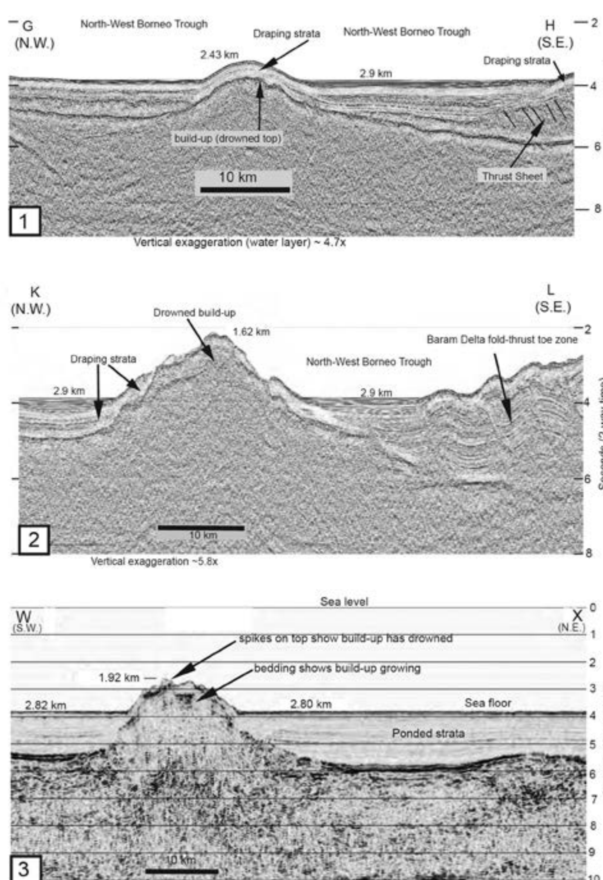


Figure 4: Three seismic profiles showing drowned carbonate build-ups within the North-West Borneo Trough, based on Hutchison (2010a). Locations are shown in Figure 5.

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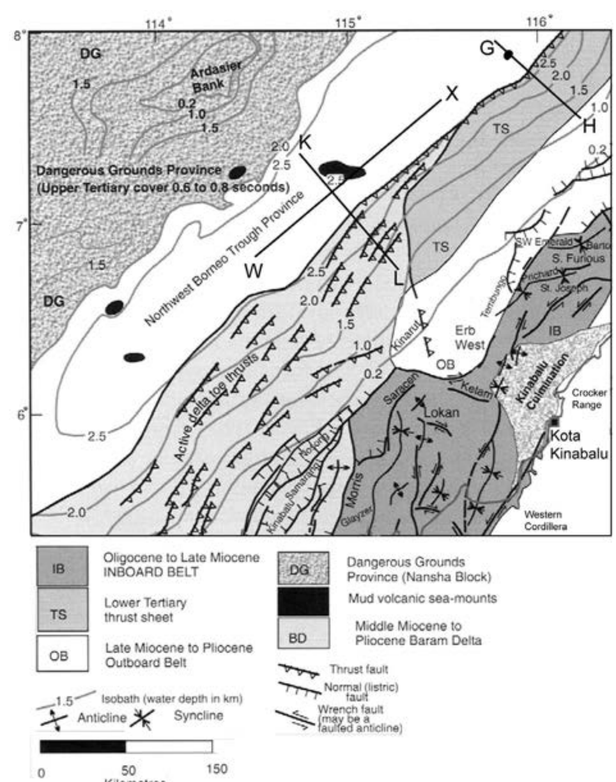

Figure 5: The North-West Borneo Trough and its relation to the Baram Delta and other tectonic belts of coastal Sabah, based on Hazebroek and Tan (1993). The positions of the three seismic profiles of Figure 4 are shown.

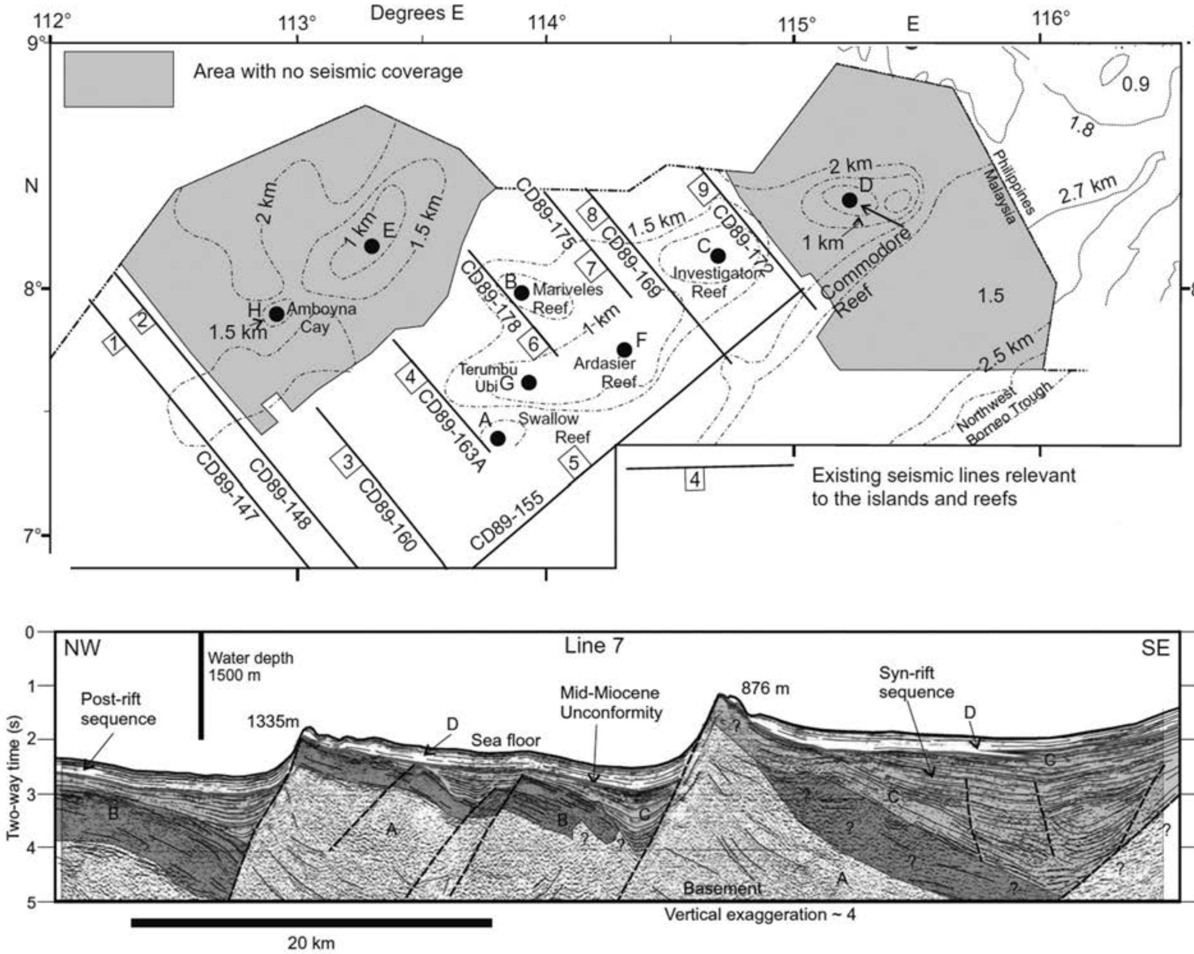

Figure 6: Upper: Map showing the distribution of active reefs of the Spratly Islands. Lower: Bathymetric survey by the Royal Malaysian Navy showing details within the Malaysian EEZ. Names of islands: A=Swallow Reef (Terumbu Layang-Layang), B=Mariveles Reef (Terumbu Montanani), C=Investigator Shoal (Terumbu Peninjau), D=Commodore Reef (Terumbu Laksamana) said to be occupied by the Philippines, E=Barque Canada Reef (Terumbu Perahu) said to be occupied by Vietnam, F=Ardasier Reef (Permatang Ubi) claim/occupation is uncertain but named Bai Kieu Ngua by Vietnam, G=Ardasier Reef (Terumbu Ubi), H=Amboyna Cay (Pulau Kecil Amboyna) said to be occupied by Vietnam. Reef without annotated comment are claimed/occupied by Malaysia.

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