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Multi-phase subsidence history of the Sarawak continental margin and its regional significance

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Abstract: Subsidence analysis of Sarawak Basin using stratigraphic data from a selection of exploration wells revealed a multi-phase history of crustal extension (rifting), subsidence and uplift. A relatively rapid subsidence during the early rift phase from Eocene to Oligocene (ca. 37–28 Ma) was followed by a gradual decrease in subsidence rate as the extended lithosphere underwent post-rift thermal relaxation (ca. 28–22 Ma). A second phase of extension during the Early Miocene (ca. 22–17 Ma) resulted in an increase in subsidence rate, which coincided with a major episode of compressional deformation, uplift and localised erosion. This deformation event culminated in a major unconformity dated ~16 Ma, known as the Middle Miocene Unconformity (MMU), which is recognised throughout the Bunguran Trough and North Luconia regions of Sarawak Basin as a major stratigraphic hiatus spanning the Early to Middle Miocene. Since the Late Miocene, there had been an increase in the subsidence rate, probably due to progradation of the Sarawak shelf to its present-day configuration. The complex subsidence history of Sarawak Basin is similar to those reported from other parts of the South China Sea margin. The subsidence histories indicate a common, underlying tectonic factor which is probably related to rifting and sea-floor spreading in the southwestern prong of the South China Sea oceanic basin.

Keywords: Sarawak Basin, rifting, subsidence, Middle Miocene Unconformity

INTRODUCTION

Understanding the origin and evolution of a sedimentary basin requires the unravelling of its subsidence history, which is closely linked to the underlying tectonic, structural and sedimentary histories. Subsidence or "geohistory" analysis (van Hinte, 1978; Steckler & Watts, 1978) was widely applied in the 1990s, most commonly to rifts, passive margins (e.g., Watts, 1988) and foreland basins (e.g., Ali & Watts, 2009). Such analysis involves restoring the present-day depth of "basement" to the original depth prior to the deposition of the overlying sedimentary layers. Restoration is done by "backstripping", a technique by which successive layers of sediment are sequentially peeled off, while keeping track of the decompacted thickness of the remaining sediment and the basement depth at every time step to derive a history of the basement subsidence (i.e., basement depth vs time) (Allen & Allen, 2013). Although the method was widely applied during the late 1970s through to the 1990s, it has not been used very much during the past 10–20 years. This is due, in part, to the lack of accurate stratigraphic age constraint and the large uncertainties especially with regard to paleobathymetry and sea level change. For the method to work, it is essential to have good biostratigraphic control on the age of the time markers in the stratigraphic succession. Nevertheless, it is also important to note that uncertainties in the input data may trigger questions that would enable the researcher to develop testable hypotheses or to plan for further data gathering in order to address those uncertainties and fill the knowledge gaps. The technique therefore remains a useful tool for understanding basin development, as it may provide valuable insights into the subsidence history and related tectonic and structural evolution of the basin (McKenzie,1978; Jarvis & McKenzie, 1980; Watts, 1988).

On the Sarawak continental margin, offshore Malaysia (Figure 1), little work has been done on subsidence history despite the large amount of data collected through decades of exploration drilling. Some analyses have been carried out in the past (Mat Zin & Swarbrick, 1997; Madon, 1999; Madon *et al*., 2013) but the mechanism of subsidence is still a subject of debate. Based largely on the interpretation of seismic reflection data, the proposed basin-forming mechanisms have included rifting (crustal extension), transtensional strike-slip tectonics (Mat Zin & Swarbrick, 1997), to foreland basin subsidence following the continental collision between the Luconia block and NW Borneo during the Late Eocene (Madon *et al*., 2013). Accurate reconstruction of subsidence history was also hampered by poor biostratigraphic control. Improved understanding of the stratigraphy over recent years (Lunt &

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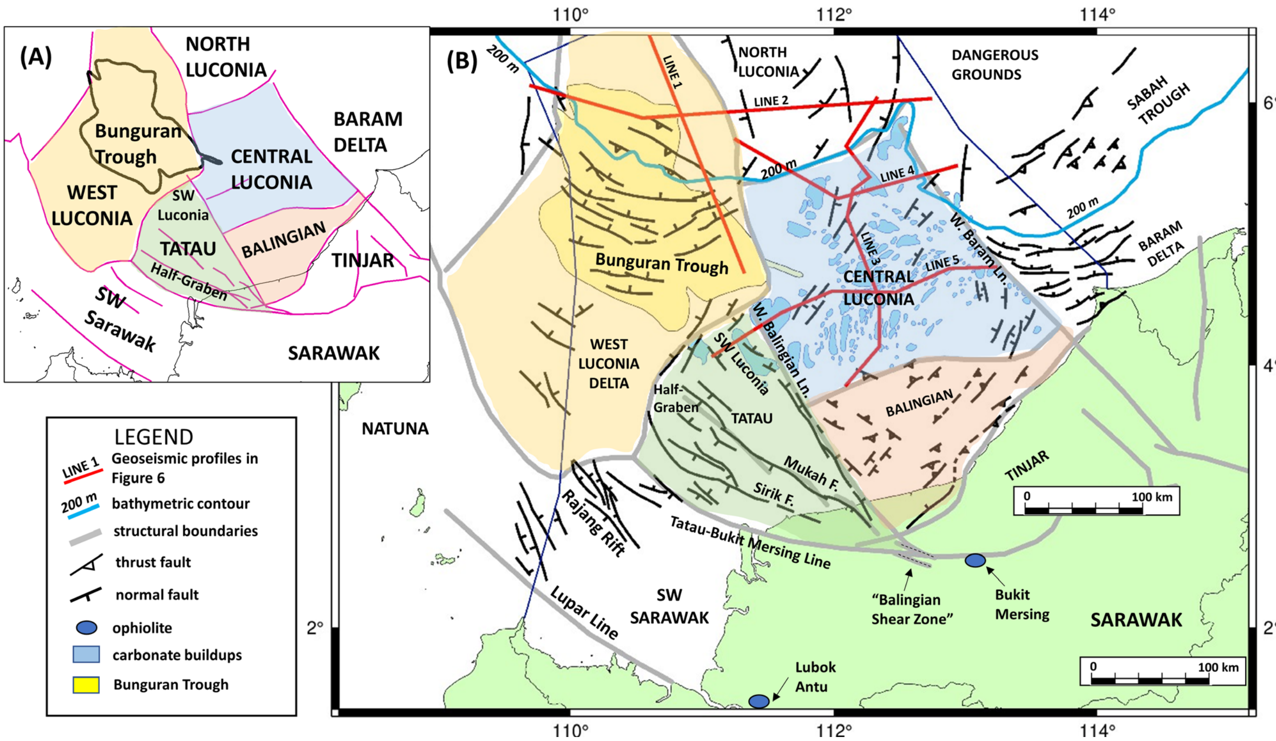


Figure 1: (A) Main tectonostratigraphic provinces of Sarawak Basin. (B) More detailed map of the tectonostratigraphic provinces and the main structural elements, including major faults. The outline of Bunguran Trough is based on the 10 km depth contour at the top of the acoustic basement. Major NW-SE trending lineaments – Lupar Line, Tatau-Bukit Mersing Line, West Balingian Line and West Baram Line. Red lines represent geoseismic profiles (Lines 1 to 5) shown in Figures 5 and 6. Map compiled and modified from Hazebroek & Tan (1993), Morrison & Wong (2003) and Madon & Jong (2022).

Madon, 2017; Lunt, 2019; Morley *et al*., 2021) has motivated us to carry out a new analysis and, as a result, we have gained further insight into the subsidence history of Sarawak Basin. In this study, subsidence analysis was carried out using available well-stratigraphic data that have been updated with the biostratigraphic framework of Morley *et al*. (2021).

GEOLOGICAL SETTING AND STRUCTURAL FRAMEWORK

Sarawak Basin lies mainly offshore beneath the broad (250–450 km) shelf north of the Malaysian state of Sarawak in NW Borneo (Figure 1). Major tectonic lineaments subdivide the basin into tectonostratigraphic provinces with their characteristic structural and sedimentation patterns, namely SW Sarawak, West Luconia, Tatau, Balingian, Tinjar, Central Luconia, West Luconia, and North Luconia (Tan & Lamy, 1990; Hazebroek & Tan, 1993). Lineaments such as the West Balingian Line and West Baram Line are fault zones believed to have had significant strike-slip histories (Tate, 1994; Mat Zin & Swarbrick, 1997; Cullen, 2010; 2014; Madon & Jong, 2022). The West Luconia and Baram provinces are major deltaic depocentres with sediment thickness in excess of 10 km and form the deepest parts of the basin. Between these deltaic provinces is Central Luconia Province which is characterised by the development of carbonate build-ups during the Middle-Late Miocene (Cycles IV to V). In the deepwater area of North Luconia, lies a Middle Miocene extended continental terrane that is contiguous with Dangerous Grounds to the east (Hutchison, 2004; Hutchison & Vijayan, 2010). Dangerous Grounds is a region of attenuated continental crust that has been interpreted as part of the rifted margin of South China, which drifted southwards as the result of sea-floor spreading in the South China Sea oceanic basin since the Paleocene (e.g., Hutchison, 2004; 2010; Vijayan *et al*., 2013; Liang *et al*., 2019).

Sarawak Basin was developed during the Late Eocene to Early Oligocene at the eastern margin of Sundaland upon the uplifted and eroded Late Cretaceous-Late Eocene Rajang Group accretionary prism that was formed by the subduction of the Paleo-Pacific oceanic crust (Burton-Johnson *et al*., 2020). Uplift of the Rajang Group culminated in the Late Eocene (ca. 37 Ma) Rajang Unconformity, which marks the so-called Sarawak Orogeny (Hutchison, 1996; Breitfeld *et al*., 2020). After a period of uplift, erosion, and probably crustal extension, sedimentation resumed with the deposition of fluvial, deltaic to shallow marine sediments over the eroded Rajang Group terrane.

The stratigraphy of Sarawak Basin is subdivided into seismically-defined "Cycles", numbered I to VIII, ranging in age from Late Eocene to Quaternary (Ho, 1978). Figure 2

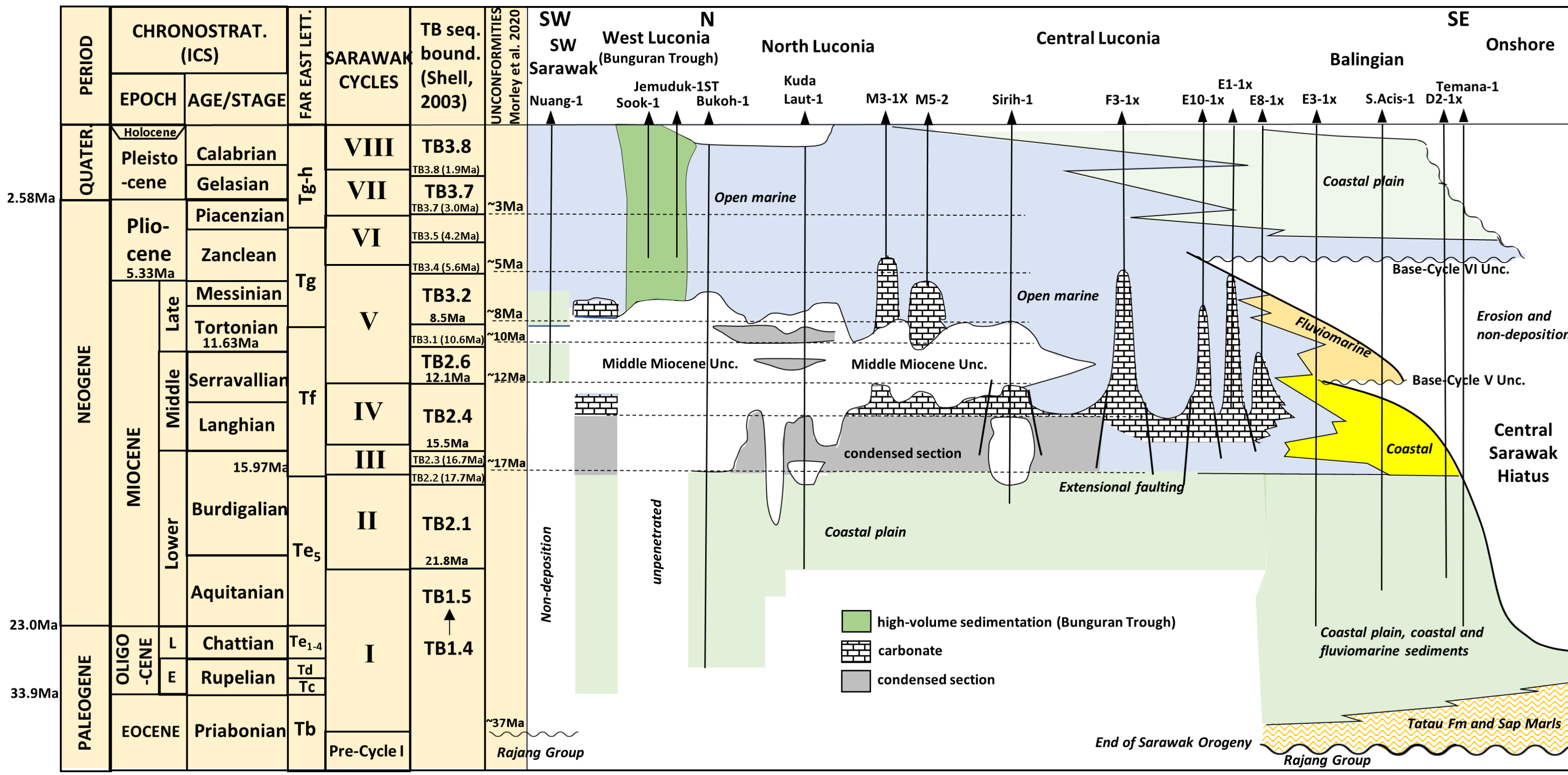


Figure 2: Stratigraphic chart of Sarawak Basin, from SW Sarawak to West and North Luconia through Central Luconia and to Balingian and Tatau provinces (see Figure 3 for the location of the profile and mentioned wells). The chart is from Madon & Jong (2022) and was compiled and modified from Madon (1999), Madon & Abolins (1999), Madon & Redzuan (1999), Jong *et al*. (2016), Lunt & Madon (2017) and Morley *et al.* (2021), adjusted to the ICS (2022) time scale. The Sarawak Cycles are correlated with Shell's sequence stratigraphic nomenclature which was based on the global TB cycles (Morrison & Wong, 2003). Chronostratigraphic ages (in Ma) of the markers down to the Oligocene follows the stratigraphic framework of Morley *et al.* (2021) and are adjusted to the ISC time scale. Note that for easy reference in the text, the Miocene is informally subdivided into "Early/Lower", "Middle" and "Late/Upper".

shows the stratigraphy along a composite profile across the various tectonostratigraphic provinces of the basin, starting from Nuang-1 well northwards, crossing the Bunguran Trough to Bukoh-1 well, and then southwards across Central Luconia towards Temana-1 well in central offshore Balingian (see Figure 3 for the location of the profile). The basin succession overlies a "pre-Cycle I basement", which in onshore Sarawak is made up of the highly deformed Upper Cretaceous–Eocene Rajang Group rocks. Cycle boundaries are, in places, marked by unconformities that represent hiatuses of varying time spans due to erosion and/or non-deposition. The unconformities are considered to be related to regionally significant events of tectonic deformation (Lunt & Madon, 2017). Some of these events appears to have been more severe towards the Sarawak hinterland, where a major compound hiatus occurs due to the multiple uplift/erosion events that had affected the basin throughout its development (Madon *et al*., 2022). The "Central Sarawak Hiatus" (Figure 2) represents an extensive basin-wide stratigraphic gap that has been recognised in onshore Sarawak and North Luconia due to the erosion and/or non-deposition during the Middle Miocene, probably as the result of a combination of tectonic deformation and uplift which continued onshore during the Late Miocene to Pliocene (Madon *et al*., 2022).

In the offshore regions, especially in the outer shelf and slope areas of West and North Luconia, a prominent unconformity is represented by a hiatus from Early to Late Miocene (Figure 2). This unconformity, generally known as the Middle Miocene Unconformity or "MMU", is widely identified on seismic sections as a distinctive seismic marker separating highly faulted Cycles I-III (Oligocene – Early Miocene) section from the overlying relatively undeformed Cycle V (Late Miocene) or younger draping hemipelagic strata, as shown by previous workers since the mid-1990s (Mohd Idrus *et al*., 1994; Abdul Manaf & Wong, 1995; Madon & Redzuan, 1999; Hutchison, 2004; Theis *et al*., 2006; Hutchison & Vijayan, 2010; Madon *et al*., 2013). The missing section at the unconformity ranges from the Upper Cycle II to Upper Cycle V, equivalent in age to the Early to Late Miocene Burdigalian to Tortonian stages (Figure 2). The vertical (or temporal) extent of the missing section varies from place to place, with a range of missing biozones, according to the scheme of Morley *et al*. (2021); from SEA 46 to SEA 72, which are equivalent in time to ca. 17.5 to 8 Ma (see Figure 4A). Biostratigraphic review by Iyer *et al*. (2015) also indicates a band of missing nannofossil (NN) and planktonic foraminiferal (N) zones in the Middle Miocene interval, due to erosion and/or non-deposition associated with the unconformity (Figures 4B and C). The missing NN zones represents approximately 2 to 6.5 Myr of equivalent missing section. In the Sarawak Cycles scheme, the unconformity is generally placed at the base of Cycle IV (Doust, 1981; Lunt & Madon, 2017; Lunt, 2019), which occurs within the NN3 to NN5 zones (ca. 19 to 13.5 Ma). Based on detailed well information, some

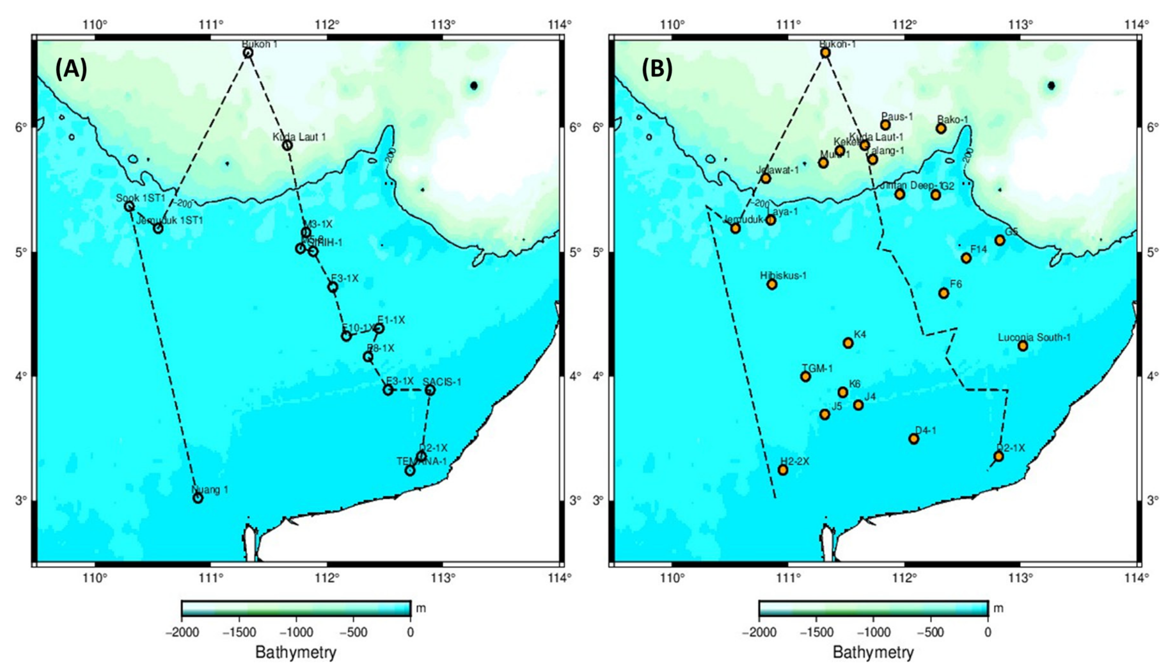


Figure 3: Location of wells used in the study and mentioned in Figure 2. (A) Stratigraphic profile and well locations in the summary chart shown in Figure 2. (B) Exploration wells used in the subsidence analysis. The stratigraphic profile in A is shown for reference. Background map is bathymetry based on Smith and Sandwell global bathymetry grid v19.1 (Smith & Sandwell, 1997). The approximate position of the shelf-slope break is shown by the 200 m isobath.

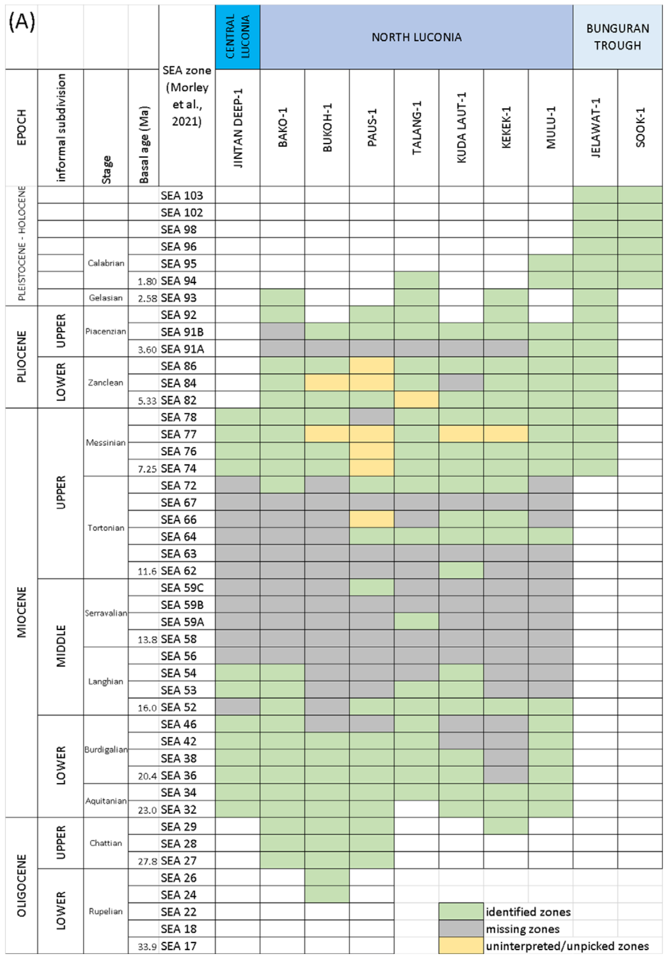
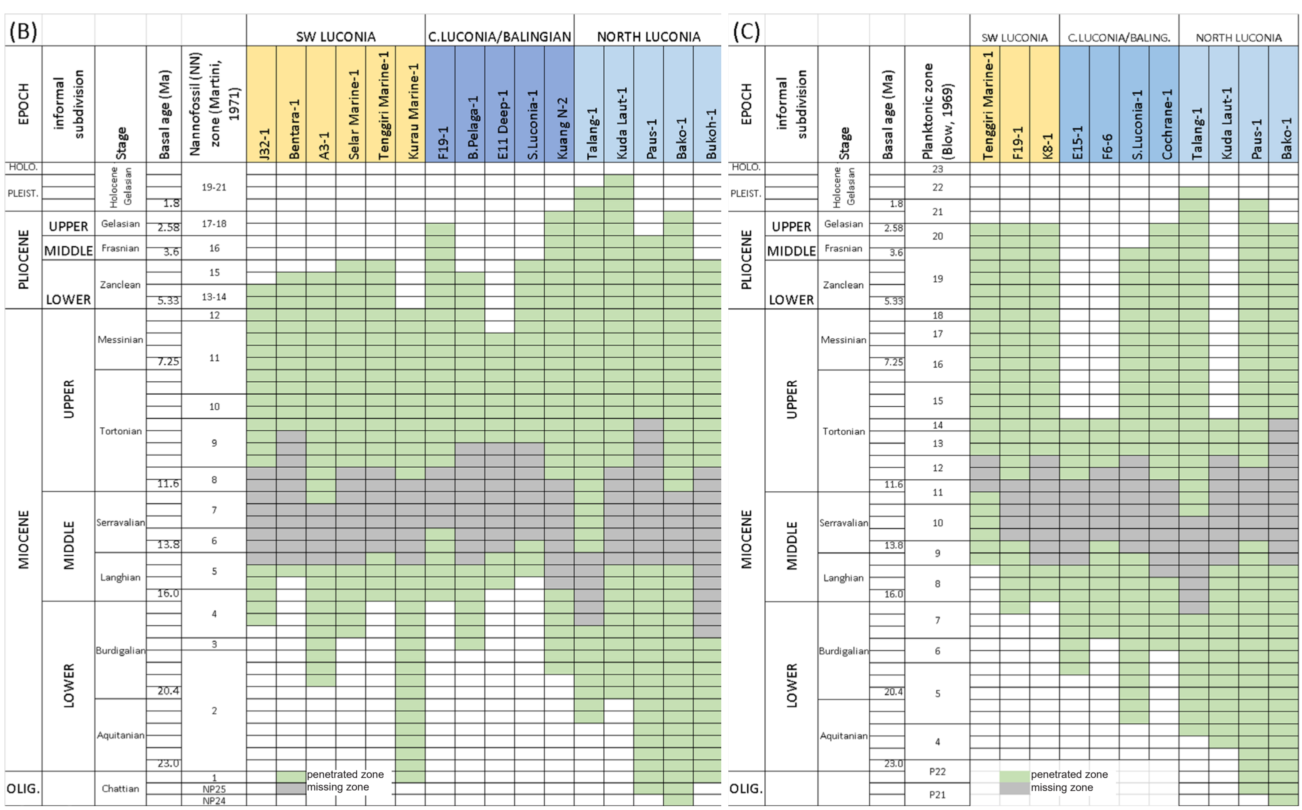


Figure 4: Well stratigraphic summaries across Sarawak Basin. (A) Well stratigraphic summary in Bunguran Trough, North Luconia and Central Luconia (Jintan Deep-1), based on the biostratigraphic zonation scheme of Morley *et al*. (2021). Note the main continuous interval of missing zones around the Middle Miocene (biozones ranging from SEA 46 to SEA 72 equivalent to ~17.5 to 8.2 Ma). Based on data compiled from internal PETRONAS reports. (B) Nannofossil biozones (Martini, 1971) in selected wells, showing missing NN zones at the MMU, especially NN6 to NN8, amounting to ca. 2–3 Myr hiatus in Central and SW Luconia. At Talang and Bukoh-1 in North Luconia, the hiatus is even larger, from NN4 to NN8, or around 6.5 Myr. (C) Planktonic foraminifera biozones (Blow, 1969) identified in selected wells, showing missing N zones (N10-N13) equivalent duration of 1.5 to 5.5 Myr at the MMU. All charts were compiled from internal reports (Iyer, 2015). Well locations are shown in Figure 3.



authors have suggested that there are actually two separate unconformities, an older one being of Early Miocene age (e.g., Morley, 2016; Lunt, 2019; Morley *et al*., 2021). The younger, more widespread unconformity shown in Figure 2 is the MMU identified on seismic throughout North Luconia and in the Dangerous Grounds region in the deepwater area off Sabah (Hutchison, 2004, 2010b; Vijayan *et al*., 2013; Morley, 2016). Following Doust (1981), the MMU is generally correlated with the Base-Cycle IV seismic marker, which has been assigned an age of 16 Ma (Thies *et al*., 2006; Lunt, 2022). Assuming that this age represents the deformational event that produced the unconformity, the missing biozones older than 16 Ma probably represent sediments that were eroded off an uplifted Cycle II terrane, whereas the younger missing biozones may have been eroded or were not deposited due to the deformation. The MMU appears to be generally coincident with the Base-Cycle IV or "basal Carbonate" seismic reflection often used as a regional seismic marker in Sarawak Basin (Koša, 2013).

Figure 5 shows the major fault trends which are related to different generations of faulting across the basin, as detailed in Madon & Jong (2022). A complex structural history is evident from the structures that have been mapped in the basin. NW-SE structures in the Tatau and SW Sarawak provinces are early rift structures developed in the southern part of the basin and had affected the Rajang Group basement during Cycles I to III times (Late Eocene to Oligocene). In the deepwater areas of North Luconia, most of the extensional faults terminate at the eroded upper part of Cycle II, and therefore the extensional event must have occurred during late Cycle II to Cycle III times (late Early Miocene to base Middle Miocene). The 16 Ma age for the deformation event is consistent with this interpretation.

As seen particularly in North Luconia, the MMU deformation event culminated in the unconformity that separates faulted predominantly pre-Cycle III strata from overlying, relatively undeformed "draping" sediments of Late Miocene age and younger (Figure 6A). The MMU surface dips westwards beneath the Bunguran Trough which appears to be bounded by major bounding faults while the post-MMU sediments onlap eastwards onto the flanks (Figure 6B). Extensional (horst-and-graben) structures were formed in Central Luconia during a later phase of extension in the Early Miocene, and became the substrate upon which the Middle Miocene Cycle IV-V carbonate reef build-ups developed (Figures 6C – E). These fault-bounded extensional structures are oriented mainly NNE-SSW, almost perpendicular to the early rift structures to the south-west (Figure 5).

Sedimentation during the post-Middle Miocene period was characterised by northward progradation of the shelf, in both the siliciclastic depocentres of West Luconia and Baram Delta, as well as in Central Luconia (Koša, 2015; see Figure 6D). Throughout the Middle to Late Miocene, Central Luconia appears to have remained relatively stable, with the growth of carbonate reefs continuing until their demise during Late Miocene to Early Pliocene due to rising sea levels (Zampetti *et al*., 2004; Che Shari, 2019). In West

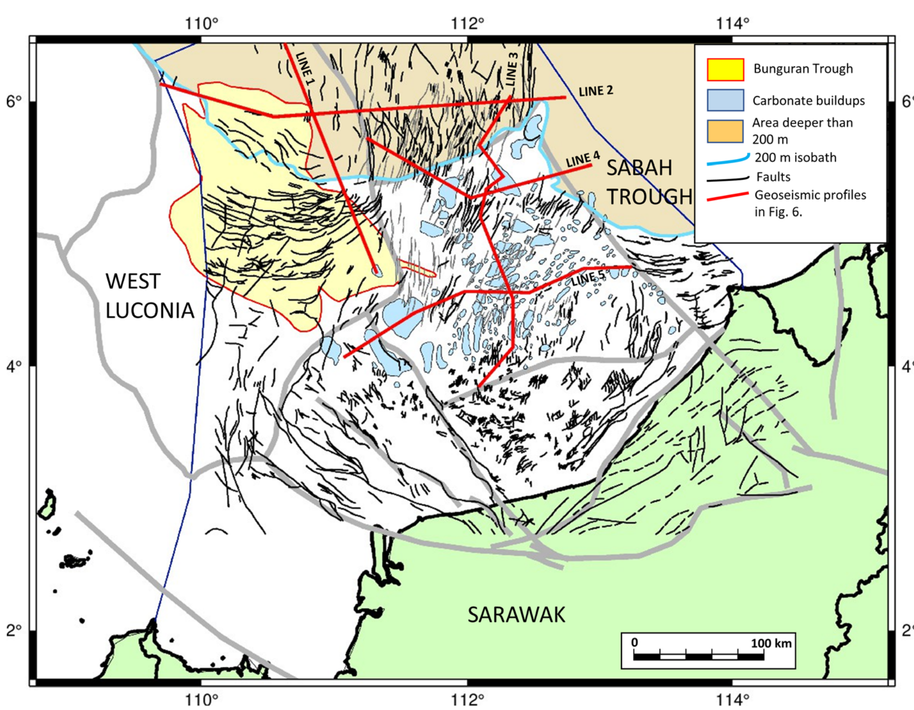


Figure 5: Map of the major structural elements, faults and carbonate build-ups in Sarawak Basin (compiled from various sources: Hazebroek & Tan, 1993; Morrison & Wong, 2003; Loftus *et al*., 2003).

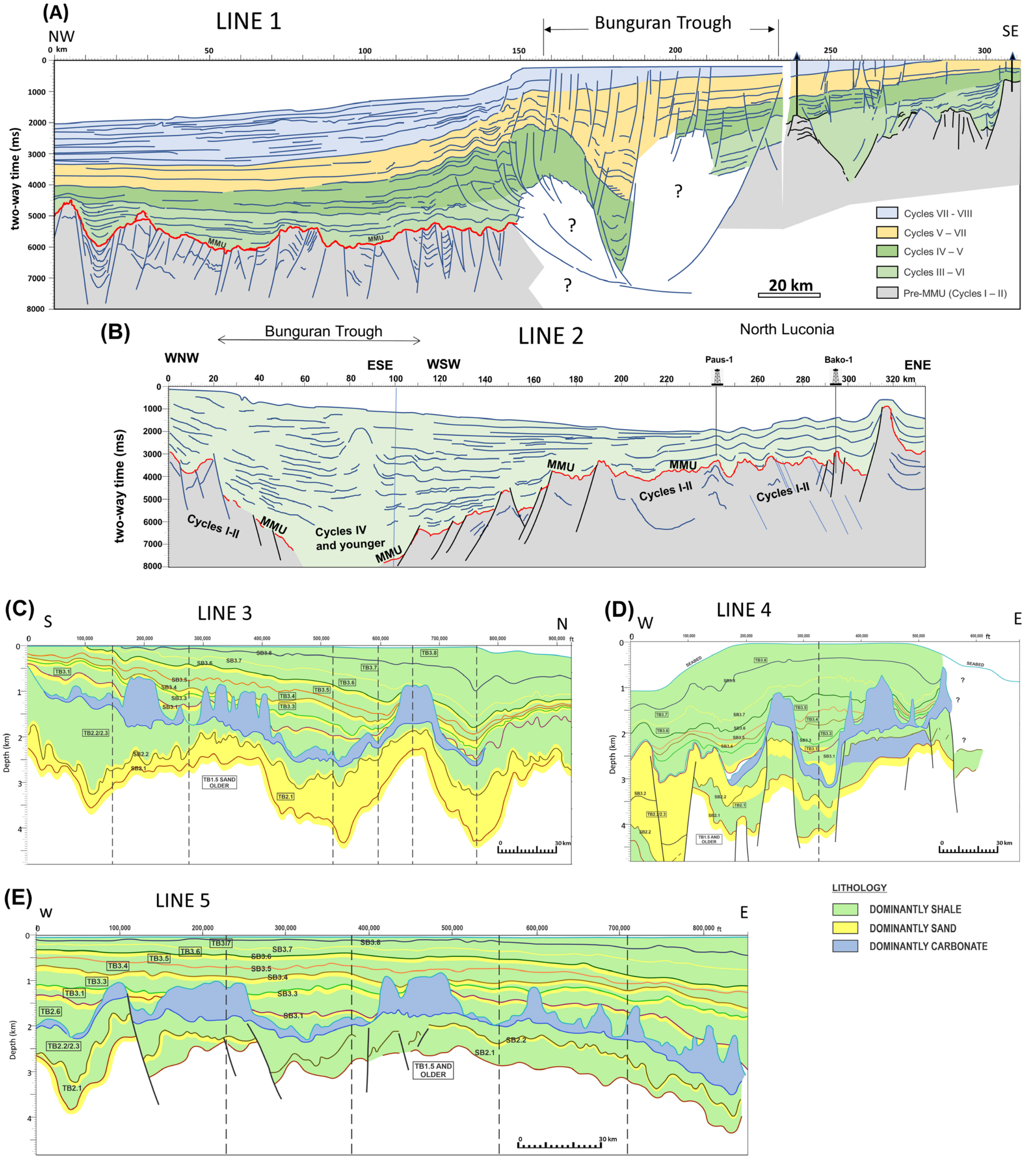


Figure 6: Geoseismic profiles across Sarawak Basin, depicting the main structural and stratigraphic features. Profile locations are shown by red lines on the map in Figures 1 and 5. (A) Line 1: NW-SE profile crossing the western Sarawak Shelf and Bunguran Trough, showing the post-MMU prograding shelf-slope sediments over highly deformed Cycles I-II sequences. (B) Line 2: WNW-ESE profile crossing Bunguran Trough and North Luconia, showing the deep Bunguran Trough and onlapping post-MMU (Cycle IV and younger) sediments filling the trough as well as draping the rifted Middle Miocene paleo-topography. (C) Line 3: Crossing the Central Luconia in roughly N-S direction, showing the prograding shelf sediments downlapping onto the basal carbonate surface upon which carbonate build-ups developed. (D) Line 4: W-E line crossing the northern part of Central Luconia separating the deep basin on either side (West Luconia and Baram deltas). (E) Line 5, also oriented W-E across the central part of Central Luconia showing the extended pre-Cycle IV section overlain by Cycle IV-V carbonate build-ups. The effect of sediment loading in Baram Delta to the east is indicate by the monoclinal pre-carbonate strata and expanded stratigraphic thicknesses in the post-carbonate section. Lines 1 and 2 were modified from Madon & Jong (2022); Lines 3, 4 and 5 from Taylor *et al*. (1977).

Luconia, the Middle-Late Miocene sediments are too deeply buried to be imaged or penetrated but structures in the post-Cycle V (Pliocene and younger) are characterised by gravitationally induced growth faults that are down-thrown northwards into the basin (Jong & Barker, 2015). Beyond the shelf edge, in North Luconia, the mainly N-S oriented faults are the continuation of the structural trends in Central Luconia, which affected Cycle III during the Early-Middle Miocene (Madon *et al.*, 2013; Madon & Jong, 2022). Due to deformation during Late Miocene-Pliocene, reverse faults and thrusts associated with compressional and strike-slip deformation characterise the proximal shelf area (Balingian and Baram Delta) as well as the adjacent onshore Tinjar Province (Madon *et al*., 2022).

DATA AND METHOD

Stratigraphic data were compiled from 25 exploration wells across Sarawak Basin, including those used in a previous study (Madon *et al*., 2013), and were updated with new stratigraphic information (Figure 3). The wells represent the different tectonostratigraphic provinces: West Luconia Delta (4 wells), North Luconia (8 wells), Central Luconia (5 wells), Tatau and Half-Graben provinces (8 wells). The well data comprise depths to the Cycle boundaries, which are assumed to be regional chronostratigraphic surfaces, and their corresponding age and paleoenvironment determined from biostratigraphic and micropaleontological analyses.

In the subsidence analysis, the "basement" of Sarawak Basin was assumed to be the Rajang Group and its equivalent, occurring below the base-Cycle I or "Rajang" unconformity. This surface is believed to represent the Late Eocene peneplanation surface of the uplifted and deformed Rajang Group accretionary prism. The age of the Rajang Unconformity represents the time of basin initiation which, following Breitfeld *et al*. (2020), was assumed to be 37 Ma. Since most wells did not penetrate this unconformity, its depth at each of well was derived from the basement depth map of Loftus *et al*. (2003). With the exception of the MMU (16 Ma), the other seismic markers and sequence boundaries were assumed to be conformable, with no significant erosional unconformities (Figure 2).

Backstripping

The 1D backstripping technique (Watts & Ryan, 1976) was employed in the calculation of the tectonic subsidence history at well locations. The technique essentially involved the successive removal of each sedimentary layer in the basin while decompacting the underlying remaining sedimentary layers, and then calculating at each time step the resultant "unloaded" depth of the basement. The backstripping algorithm effectively removes the sediment grains from the sedimentary layer while leaving the interstitial pore water, as well as the water layer above the "restored" depositional surface, i.e., the "water-loaded" subsidence. For a given sediment layer of thickness, Δh, the tectonic subsidence, ΔS, is given by (Steckler & Watts, 1978):

$$\Delta S = \Delta h\left(\frac{\rho_m - \rho_s}{\rho_m - \rho_w}\right) + W_d - \Delta d\left(\frac{\rho_w}{\rho_m - \rho_w}\right)$$

where W_d is paleobathymetry, Δd is eustatic sea level, and ρ_m, ρ_w and ρ_s are mean densities of mantle, water and sediment, respectively. The total water-loaded subsidence at any given time is obtained by summing the decompacted thicknesses of all layers at that particular time. Decompaction of the sedimentary layers is done by assuming Athy's (1930) empirical formula for the exponential loss of porosity with depth:

$$\Phi(z) = \Phi_o e^{-cz}$$

where Φ(z) is porosity at depth z, Φo is porosity at the depositional surface (z = 0) and c is the porosity decay constant. We used published values for Sarawak Basin, Φo = 0.393 and c = 0.469 km-1, based on log and core-derived porosity data (Madon *et al*., 2013).

Eustatic sea level variation was based on Hageman's (1987) sea level curve for offshore Sarawak, which is comparable to, but appears to have been amplified by, the global sea level changes (Haq *et al*., 1987; Posamentier *et al*., 1988). Hageman's paleogeographic maps were also used as a guide to estimate paleobathymetry based on the bathymetric zonation of Ho (1978). Paleobathymetric information was also obtained from Iyer (2015) which was based on micropalaeontological data derived by analysis of well samples. These data indicate that, in North Luconia, the post-MMU sediments (Cycle IV and younger) were deposited in upper to middle bathyal water depths, suggesting rapid subsidence of the region below sea level had taken place immediately after the MMU event. The well data also indicate that the upper part of Cycle II in North Luconia were deposited in deeper water environments, ranging from middle to outer neritic (Mulu-1, Bako-1, Paus-1) to upper to middle bathyal (Talang-1, Kuda Laut-1, Paus-1). This evidence seems to support Van Vliet & Krebs's (2009) interpretation that the MMU in North Luconia was mainly the result of submarine erosion, probably in bathyal water depths.

RESULTS

Figure 7 shows the subsidence history of two wells in North Luconia: Jelawat-1 at the eastern edge of Bunguran Trough and Mulu-1 further to the east in North Luconia. Mulu-1 penetrated a section down to Cycle II (Early Miocene) through the MMU hiatus that spans the Early to Middle Miocene (ca. 17–7 Ma). Due to the great thickness of sediments in Bunguran Trough, Jelawat-1 and other wells in the trough penetrate down to only Cycle VI (Upper Miocene). In the absence of data below Cycle VI, the detailed Oligocene-Miocene subsidence history in Bunguran Trough is speculative. Figure 8 shows the subsidence history for

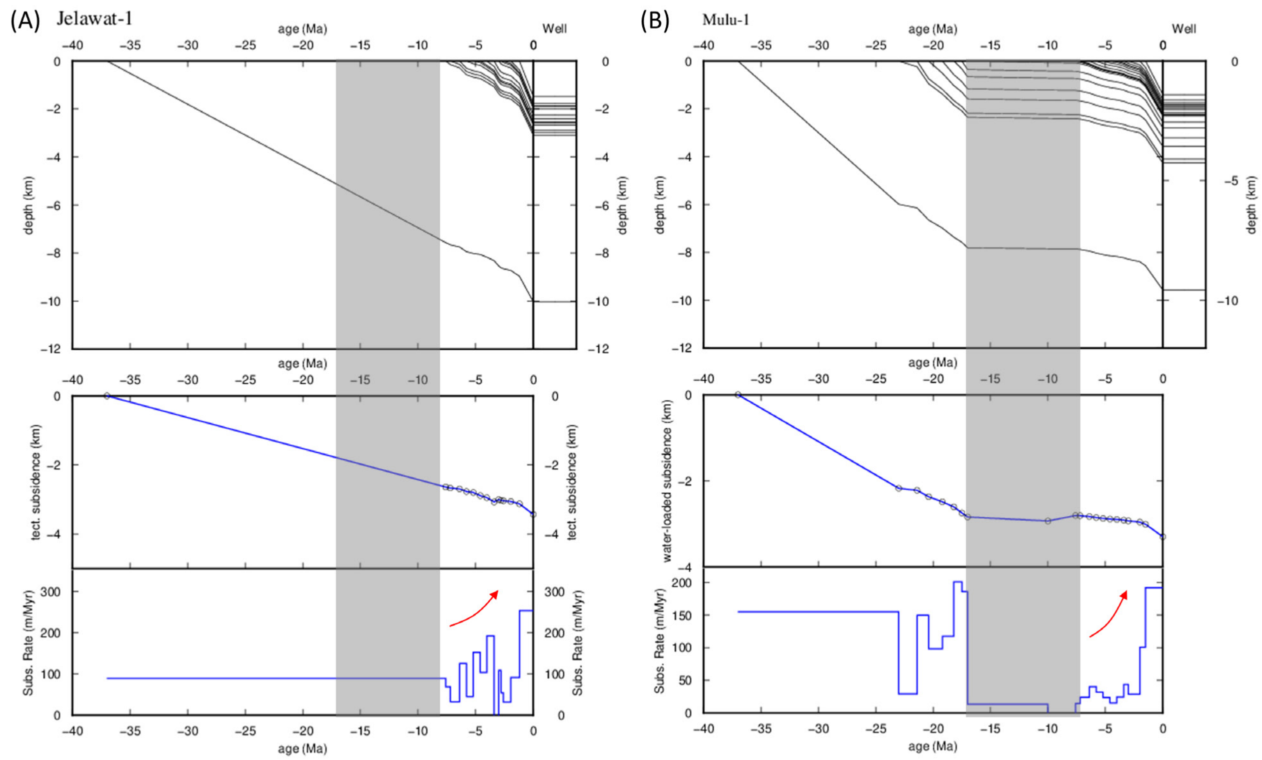


Figure 7: Subsidence history plots for wells in North Luconia. (A) Jelawat-1. (B) Mulu-1. Upper panel is geohistory plot, middle is water-loaded tectonic subsidence, and lower panel is basement subsidence rate derived from the tectonic subsidence. In Jelawat-1, data are lacking from the unpenetrated section <8 Ma. In Mulu-1, data older than 25 Ma (beyond TD) are lacking. Grey shaded rectangles represent missing section (and information) in the wells due to the MMU. Where the MMU is penetrated, as in Mulu-1, it is plotted as zero uplift/subsidence (i.e., horizontal lines within the grey rectangles).

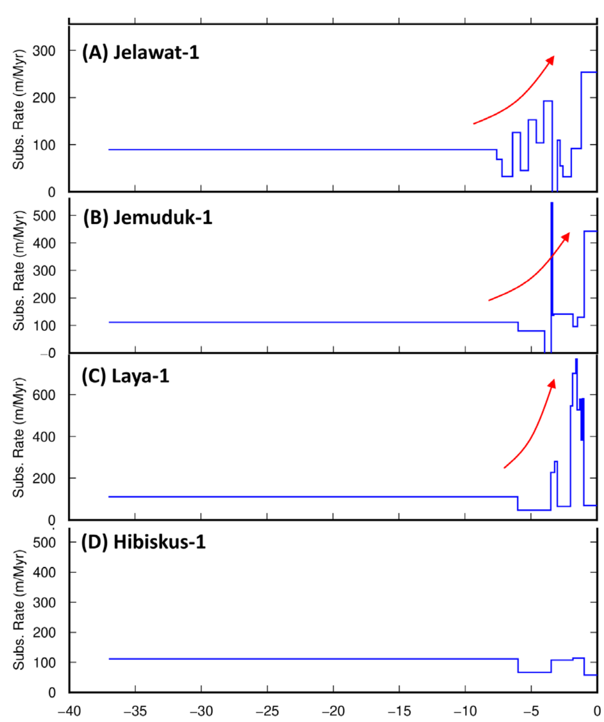


Figure 8: Basement subsidence rate based on backstripped well data in Bunguran Trough. Between 37 and ~8-5 Ma, due to the lack of data (unpenetrated section and poorly imaged by seismic), the subsidence rate is plotted as a horizontal line, which may represent the long-term average subsidence rate. With the exception of Hibiskus-1, all the wells show a sharp increase in subsidence rate since Late Pliocene times. The locations of wells are shown in Figure 3.

three wells – Jelawat-1, Jemuduk-1, Laya-1 and Hibiskus-1 – indicating rapid increase in subsidence since the Late Pliocene (~5 Ma) when the West Luconia Delta continued to prograde northward over Bunguran Trough. The data suggest that, in places, subsidence rates since the Late Miocene rose to more than ~800 m/Myr (e.g., Laya-1). In contrast, Hibiskus-1 does not show significant increase in subsidence rate, as it is located landward of the main deltaic depocentre and, therefore, was less affected by the deep basement faults and rapid subsidence in Bunguran Trough.

In Balingian, Central Luconia and North Luconia, well penetration into the Oligocene to Miocene sediments (Cycles V and older) provides a more detailed picture of the subsidence history. In particular, the North Luconia wells give some insights into the subsidence history of the Sarawak margin, which was lacking from the Bunguran Trough wells. Figure 9 (A to G) shows the subsidence histories of 7 wells in North Luconia, with a significant hiatus attributed to the MMU in the middle part of the basin history between ~17 and 10 Ma. The unconformity was a period of tectonism and relative uplift that resulted in erosion over large parts of North and Central Luconia. All over North Luconia, the wells recorded a major hiatus (shaded grey in Figure 9). In Central Luconia an intra-carbonate hiatus is inferred to be present (Figure 2; Morley *et al*., 2021). At Jintan Deep-1, in the Central Luconia carbonate province, this period of upheaval coincided with a low subsidence rate, and may have resulted in a conducive environment for the development of carbonate build-ups.

In Figure 9, increasing subsidence rates (>150 m/Myr, upward black arrows) indicate renewed extension prior to a phase of uplift and erosion that culminated in the MMU. Interestingly, all wells show an increase in subsidence rate prior to the 17 Ma hiatus. At Paus-1, Bukoh-1 and Bako-

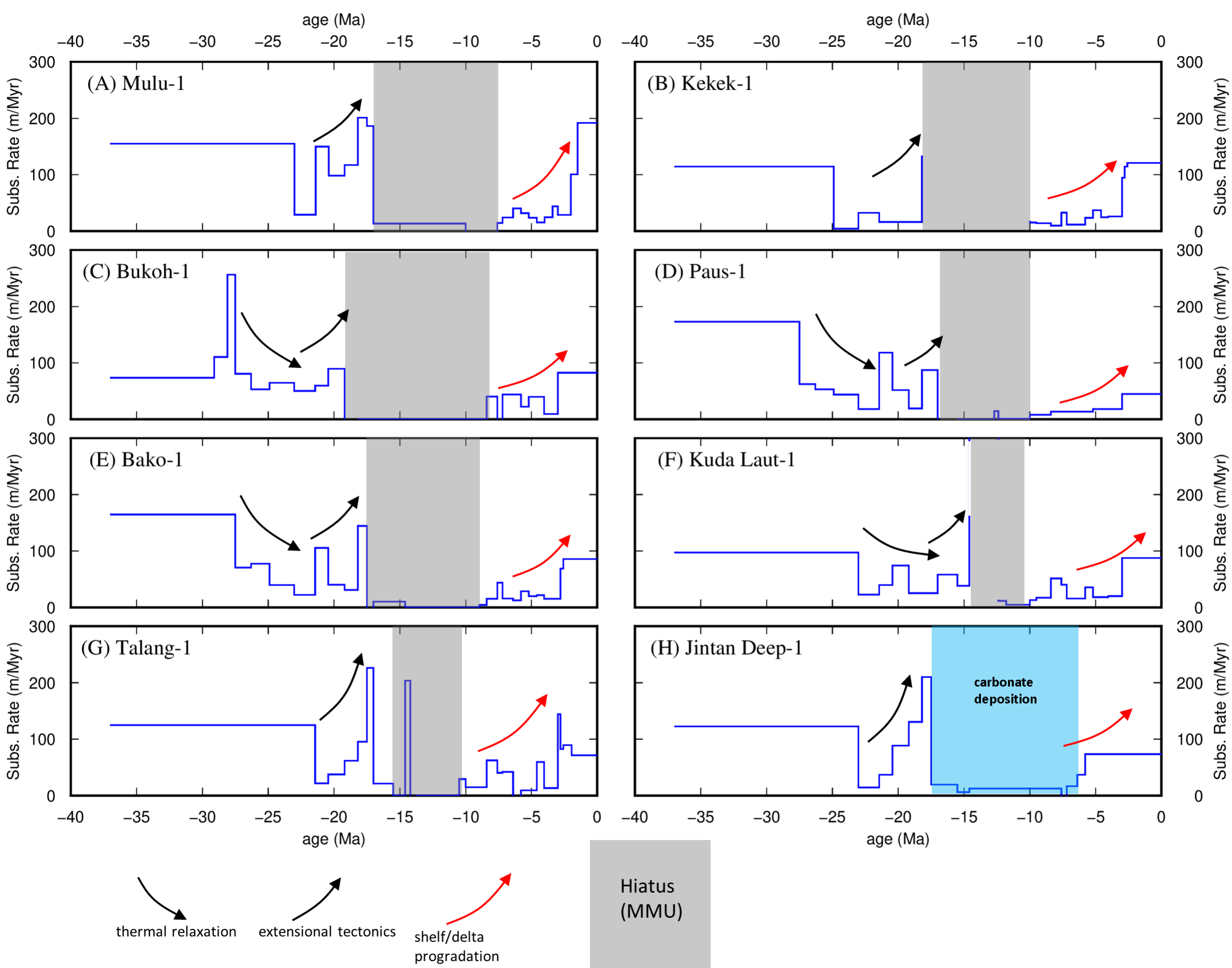


Figure 9: (A) – (H) Basement subsidence rate calculated from tectonic subsidence at selected wells in North Luconia (locations in Figure 2B). Vertical axis in m/Myr, all on the same scale for comparison. Grey shaded rectangle represents hiatus at the MMU. In (H) Jintan Deep-1 the hiatus coincides with main phase of carbonate deposition (Cycles III to V), which is characterised by very low subsidence rates (relatively stable, conducive for carbonate growth).

1, the MMU-related increase in subsidence was preceded by a steady decline in subsidence rate, probably indicating a syn-rift to post-rift subsidence. A decrease in basement subsidence rate (downward black arrows) could be indicative of the "post-rift" thermal relaxation of the lithosphere following the crustal extension phase (McKenzie, 1978) that took place until around 25-30 Ma.

Extensional tectonics at the end of Cycle III is widely recognised, with pervasive normal faulting causing the formation of horst blocks upon which carbonate reefs grew during Cycles III to V (e.g., Madon, 1999; Hutchison, 2005). For the first time, there is evidence of increased subsidence due to rifting (crustal extension) prior to a period of relative tectonic stability and carbonate platform development in Central Luconia, as uplift and erosion presumably continued in the surrounding region (Figure 9). The post-Miocene history of North Luconia shows a pattern similar to that of Bunguran Trough – a sharp increase in subsidence rate (upward red arrows, Figure 9; compare with Figure 8), signalling renewed subsidence of the margin during Early Pliocene times due to progradation of the shelf.

The early rifting history of the margin south of Bunguran Trough is based on wells in the Tatau and Half-Graben provinces and in Central Luconia (Figure 10). These wells, analysed previously by Madon *et al*. (2013), were used in this study to re-calculate the subsidence based on the revised stratigraphy. Although no obvious pattern in the subsidence history is observed in these wells in the inboard shelf areas, probably due to proximity to the Sarawak hinterland and the regional deformation related to the MMU, some wells (e.g., J4-1, K4-1, H2-2X) appear to show rapid increase in subsidence rate beginning in the Late Miocene to Pliocene. As in wells from the surrounding region (Figures 8 and 9), there was a marked increase in the subsidence rate since 8 Ma.

Subsidence rates may vary depending on the well location relative to the half-grabens: off-structure locations show relatively high initial subsidence rates (Figures 10A-B), while in other places such as on the crests of tilted fault blocks the rates were low (Figures 10C-H). The rather erratic subsidence rate patterns may be due differential movements of fault blocks caused by strike-slip tectonics in the region, as has been documented from seismic data by previous authors (e.g., Ismail, 1996; Madon & Jong, 2022).

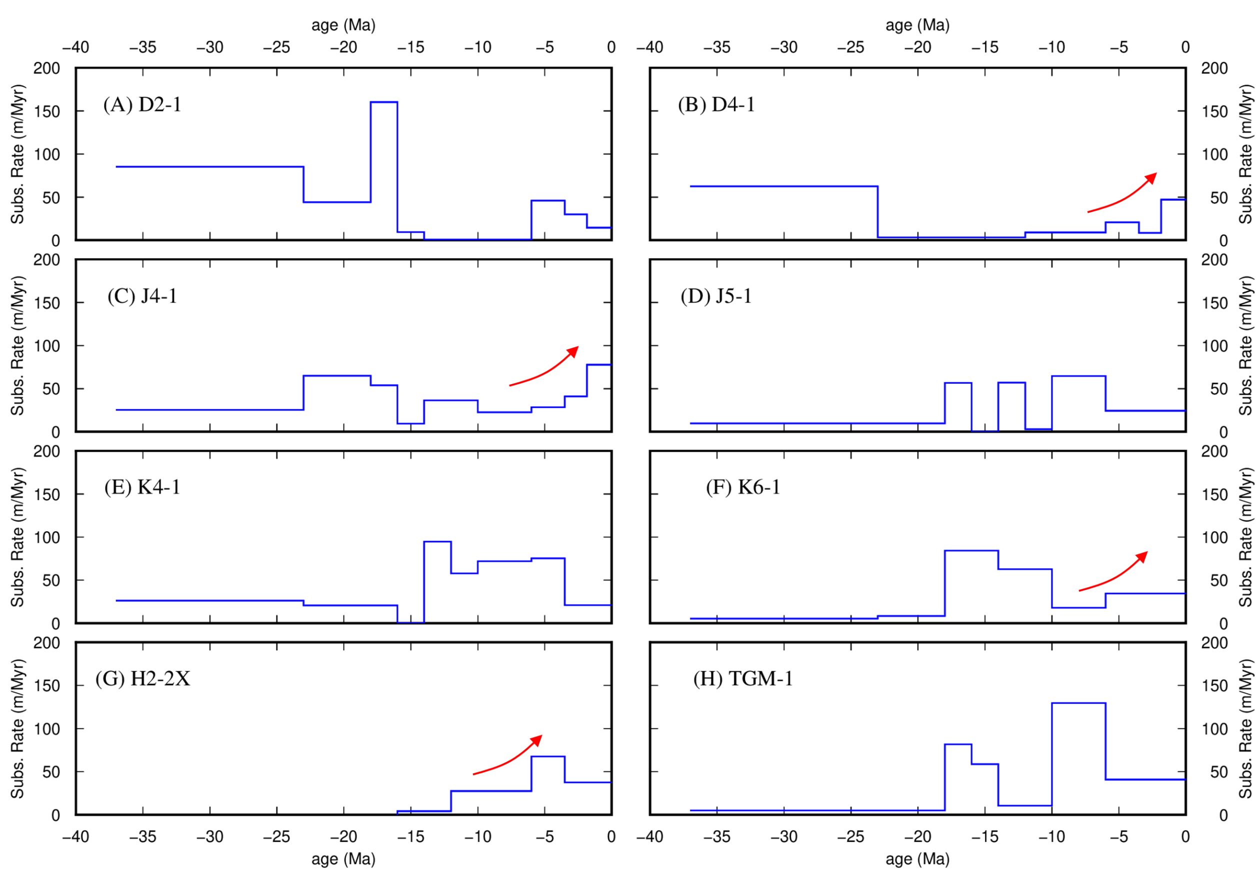


Figure 10: (A) – (H) Basement subsidence rate curves based on tectonic subsidence at well locations to the south of Bunguran Trough, mainly in SW Luconia and Balingian provinces. Well data from Madon *et al*. (2013) were re-calculated based on updated stratigraphy (Morley *et al*., 2021).

In Figures 8 to 10, due to the lack of data beneath the terminal depth of the wells, the subsidence rate was estimated from the sediment thickness down to the depth of basement and thus plotted as a uniform value starting at 37 Ma to the first well data point. This provides a rough estimate of the initial subsidence rate, which ranges from less than 25 m/Myr in Tatau Province (e.g., J4-1 and K4-1, Figure 10) to greater than 100 m/Myr in Central, West and North Luconia (e.g., Mulu-1 and Bako-1 in Figure 9). The higher rates are closely comparable to the estimated average values for the Oligocene-Miocene subsidence in Bunguran Trough derived from the basement depth map (see Figure 11). Despite the relatively high average initial rate of subsidence, the expected rift signature that may have occurred during extensional basin initiation (from 37 to 30 Ma) is not apparent, as no wells have been drilled into the extensional half-grabens.

DISCUSSION

Subsidence pattern

Figure 9 reveals a general subsidence history in all the wells analysed that comprises a high initial subsidence rate during basin initiation (ca. 37-28 Ma), followed by a rapid decrease in subsidence rate after about 10 Myr of rifting, which in turn was followed by an increase in subsidence rate due to rejuvenation of crustal extension that started at about 22 Ma, leading up to the MMU (representing the hiatus between ca. 17 and 7 Ma). The basin therefore appears to have undergone at least two major extensional episodes: one during Late Eocene-Oligocene (~37 – 27 Ma, or Priabonian to Chattian) and another during the Early Miocene (~22 – 17 Ma, or Aquitanian to Burdigalian).

The subsidence plots shown in Figures 7 to 10 also provide a regional picture of the subsidence pattern in terms of the average initial subsidence rates (Figure 11). The most obvious pattern is the low subsidence rates (<25 m/Myr) in the shallow basement region of Tatau Province, whereas high subsidence rates (90-170 m/Myr) characterise Central, West and North Luconia. The high subsidence rates in these provinces are comparable to those observed at passive margins (ca. 100 – 200 m/Myr, Xie & Heller, 2009). Anomalously high subsidence rates have been reported in SE Asian rift basins such as the Malay-Pattani (Madon & Watts, 1998; Morley & Westaway, 2006) and Yinggehai-Song Hong basins (Clift & Sun, 2006; Yan *et al.*, 2011; Zhu & Lei, 2013). In the Malay Basin, a rift basin that was strongly influenced by strike-slip faulting, subsidence rates of 173 – 221 m/Myr have been reported (Madon & Watts, 1998). Subsidence rates in strike-slip basins, such as the Dead Sea Rift and Vienna basin, are of similar magnitudes, in the order of 100s of m/Myr (ten Brink & Flores, 2012; Lee & Wagreich,

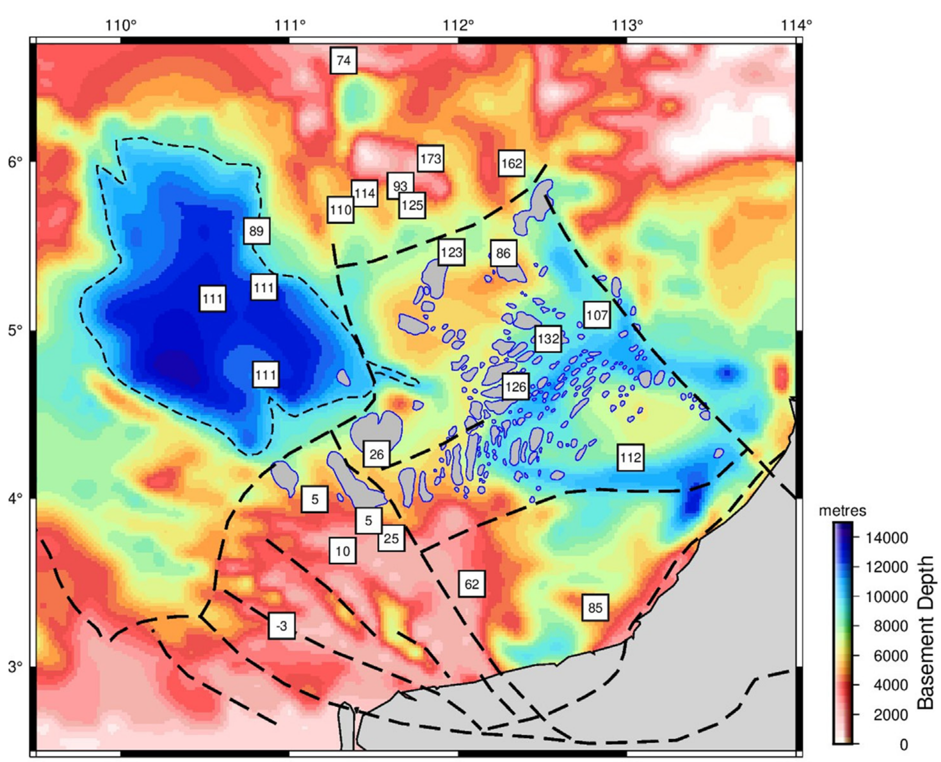


Figure 11: Map of initial subsidence rates in m/Myr (values in white boxes) estimated at the well locations based on subsidence analysis. Background map is basement depth derived from Loftus *et al.* (2003).

2016). Rapid basement subsidence in the Yinggehai Basin after around 34 Ma, was coincident with the start of pull-apart development along the Red River fault zone (Clift & Sun, 2006). The start of subsidence in Sarawak Basin is also assumed to have occurred around the same time, following the end of the Sarawak Orogeny (~37 Ma).

Based on the interpretation of multi-channel seismic reflection data, Madon & Jong (2022) summarised the structural evolution of the basin in terms of rifting phases (1 to 5), which can be correlated with the subsidence pattern revealed from the subsidence analysis (Figure 12):

1. Rift I (Lower Cycle I, Late Eocene – Early Oligocene, ca. 37 to 28 Ma). Rift-related structures are observed in the shallow basement area of SW Sarawak Shelf, Tatau and Half-Graben provinces, although are likely to be present north beneath West Luconia/Bunguran Trough.
2. Late Rift I-Early Post-rift (Upper Cycle I, Latest Oligocene-Earliest Miocene, 28 to 22 Ma). Gradual decrease in subsidence rate observed, could be the start of post-rift thermal relaxation.
3. Rift II (Cycles II/III, Early Miocene, ca. 22-17 Ma). Renewed extensional episode with increased subsidence rate, manifested structurally by E-W to NW-SE oriented extension affecting the Cycles I and II sequences prior to carbonate development, which began in Cycle III and continued widely during Cycles IV and V (Figure 5). These structures are the pervasive NNE-trending extensional faults seen in Central Luconia and have also been mapped in North Luconia. The absence of thick Cycle III in most parts of the basin (Cycle III is generally absent in West and North Luconia) indicates that they were not deposited or may have been eroded during the subsequent MMU event.
4. Post-rift Compressional phase/MMU event (Cycles III, IV and V, Middle-Late Miocene, ca. 17-8 Ma). The horst-graben paleo-topography created during the previous event provided the substrate for carbonate growth at a time when subsidence rates in Central Luconia was at the lowest and the region was relatively stable. Although carbonate buildups began to developed during Cycle III, they were most prevalent during Cycles IV and V times. Concomitant with carbonate development in Central Luconia, surrounding areas were affected by the Middle-Late Miocene compression and uplift, resulting in the erosional unconformity (MMU) and a major hiatus in the stratigraphic record. Closer to the Sarawak hinterland, compressional structures related to wrench and thrust-related movements, were particularly felt in Balingian and Baram provinces resulting in the Central Sarawak Hiatus (Figure 2).
5. Late Post-rift (Cycles VI-VIII, Late Miocene-Quaternary, ca. 8 Ma to present). Progradation of Sarawak Shelf, with pronounced subsidence in Baram and West Luconia deltaic depocentres which are characterised by syn-sedimentary, gravitationally induced growth faults. In the Baram Delta province, the wrench fault structures are superimposed upon gravitationally induced growth faults. This period was also when the buried toe-thrusts of West Luconia Delta were formed (e.g., Khoo *et al*., 2015; Jong *et al*., 2017).

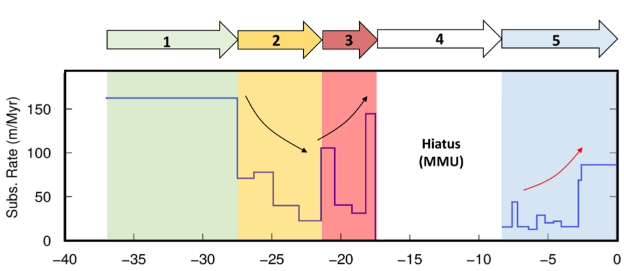


Figure 12: Generalised subsidence history of Sarawak Basin, exemplified by the results from Bako-1 well, showing the main phases of basin development (numbered 1 to 5), as explained in the text.

Significance of the MMU "event"

Although the MMU is well recognised, its origin and significance are poorly understood (e.g., Morley, 2016; Lunt, 2019; Luan & Lunt, 2022). Any reconstruction of Sarawak Basin evolution must explain the missing section and/or depositional hiatus at the MMU, which is shown as a grey rectangle in Figures 7 – 9 indicating an almost continuous section of missing biozones representing the period from 17 to 7 Ma (Iyer *et al*., 2013). But what is the nature of the MMU event?

According to Lunt (2019), the first description of a Middle Miocene unconformity in Sarawak Basin was by Doust (1981) and hence he coined the term "Doust MMU" for this widespread regional unconformity marking the base of Cycle IV. Doust (1981) stated that the Middle Miocene was the start of rapid subsidence and sedimentation in the region to the west and east of Central Luconia (i.e., West Luconia and Baram delta provinces, respectively) "at the same time as subsidence in the China basin along a network of NNE-SSW trending normal faults". Although Doust (1981) made no mention of an unconformity per se, in his Figure 8, he appeared to indicate an unconformity by a wavey line at the Cycles III to IV boundary beneath the Central Luconia carbonate province.

It is worth noting that during the 1970s and 1980s, stratigraphic analyses were mainly centred around transgressions and regressions, and less on unconformities and their tectonic causes. Furthermore, seismic data in North Luconia did not become available until the mid-1990s. The nature of the unconformity came to light when seismic sections across the deepwater area off Sarawak showed an unconformity, referred to as "horizon k" by Mohd Idrus *et al.* (1994) and Abdul Manaf & Wong (1995). In a 1996 internal report on the same region, Mobil referred to a regional seismic marker that it called the "Green Unconformity", assumed to be approximately of Middle Miocene age. The first two deepwater wells that the company drilled in that region, Mulu-1 (1994) and Bako-1 (1995), indicated the presence of a significant hiatus at the unconformity, which was labelled as the Middle Miocene Unconformity (MMU) in Figure 19.3 of Madon & Redzuan (1999).

Hutchison (2004) interpreted the MMU as the break-up unconformity in the southern margin of the South China Sea, marking the transition from Eocene to Early Miocene (~46 Ma to ~19-21 Ma) rifting to the end of Middle Miocene sea-floor spreading (~16 Ma). He noted that the MMU represents a hiatus of 3–5 Myr duration. Hutchison (2004, p. 1141) further correlated the MMU with the "spectacularly exposed" angular unconformity on the Tatau Horst, onshore Sarawak, which marks the contact between the Belaga Formation and Rangsi Conglomerate (Tatau Formation). However, that unconformity at outcrop is an older (mid-Eocene) unconformity that marks the end of the Sarawak Orogeny (Hutchison, 1996; 2004; 2008), although it could well be a compound unconformity with which the offshore unconformities merged landward as the "Central Sarawak Hiatus" (Figure 2; Madon *et al*., 2022).

The MMU was subsequently recognised as a regional unconformity across Sarawak Basin and on the margins of the South China Sea basin (Cullen, 2010; Iyer *et al*., 2012; Li *et al*., 2013). Although still not fully understood, it has generally been interpreted or assumed to be a "break-up" unconformity attributed to the end of rifting in the South China Sea basin (Hutchison, 2004; Cullen, 2010; Lunt, 2019, 2022; Kessler & Jong, 2023). Like Hutchison (2004), Cullen (2010) acknowledged that the unconformity, which he called "South China Sea Unconformity", may be diachronous, citing differences in the age of the unconformity between the northern and southern margins of the South China Sea. However, both authors considered it as a breakup unconformity associated with the diachronous rifting of the South China Sea. In a subsequent paper on the Dangerous Grounds (Spratly's), Hutchison & Vijayan (2010) suggested that the MMU may be an amalgamation of several events that occurred during Early to Middle Miocene.

The MMU in North Luconia was described in detailed by Thies *et al*. (2006), based on ~10,000 line-km of 2D seismic, well and biostratigraphic data. The unconformity was seen to overlie fault-bounded half-grabens filled with Oligocene-Early Miocene sediments (Cycles I-II). Based on the oldest age of the pre-unconformity sediments, the MMU was assumed to be ca. 16 Ma. While estimated fault-slip rates during the syn-rift phase were highly variable, as expected, and could be up to 430 m/Myr, the average sedimentation rates estimated from well data were 100–200 m/Myr (Thies *et al*., 2006). Taking into account sediment compaction, we attempted to compare the sedimentation rates obtained in this study to the basement subsidence rates reported from other regions around the South China Sea (Figure 13). On the conjugate north (Qiongdongnan Basin) and south-western margin of the South China Sea (SWSCS), there appears to be a consistent pattern of relative high subsidence rates in the early part of the history, followed by a reduced rate towards the MMU, after which there is a general increase in subsidence rate (Figure 13A). It should be noted that a direct comparison cannot be made as the data from the different basins do not have the same resolutions. On the southern side of the South China Sea basin, Fang *et al*. (2017) observed that the timing of break-up following rifting of the ocean basin was progressively delayed from Reed Bank (32–23.8 Ma) to Dangerous Grounds region (19–15.5 Ma). The age of the MMU in offshore Sarawak (16 Ma), which lies southwest of Dangerous Grounds, appears to fit well with this interpretation. Subsidence rates obtained by Fang *et al*. (2017) suggest that the average subsidence rates during the period leading to the MMU were relatively high in the Reed Bank region compared to that in the Dangerous Grounds (Figure 13B), although in the latter, the range of subsidence rates (and hence, the uncertainties) are much higher. It is interesting to note that in both regions, the average subsidence rates were high (~100 m/Myr) during the period between 15 and 10 Ma, a large portion of which is either missing from the stratigraphic record or preserved partially as a highly condensed section in offshore Sarawak. The data from Reed Bank and Dangerous Grounds may help fill the gap in Sarawak Basin and should be investigated further and integrated for the entire region.

In the inboard Tatau and Half-graben provinces, Sim & Jaeger (2004) described a "Base of Upper Miocene" unconformity (marked by sequence boundary SB 3.1, age ~10 Ma) due to a major lowstand, typified by erosional truncations and incised channels overlain by a transparent package of marine shales indicating the subsequent rise in sea level. The unconformity marks the top of fault-controlled half-graben sediment packages (syn-rift) separated from overlying "post-rift" sediments. This unconformity, which appears to represent the syn-rift to post-rift transition in this part of the basin, probably correlates with the MMU to the north.

The age of the unconformity has been a matter of controversy. Madon *et al*. (2013) suggested EMU based on Bako-1 and Mulu-1 wells and the findings of Krebs (2011) who determined that the unconformity age ranges between 17 and 19 Ma, which falls within the Burdigalian (Early Miocene). In terms of the SE Asia biozones the MMU represents a hiatus (missing section) that spans the period from ~17.5 to 8 Ma (Morley *et al*., 2021; Madon & Jong, 2022). The MMU is therefore much younger than the age of the break-up unconformity associated with the start of sea-floor spreading in the main South China Sea Basin. That age is commonly identified on seismic and supported by ODP drilling results, especially at its northern margin, to be around 32 Ma (e.g., Zhou *et al*., 2020; Wen *et al*., 2021; Chang *et al*., 2022).

The often-quoted age of 16 Ma for the MMU, based on various evidence (Thies *et al*., 2006; Lunt, 2022), lies within the time span of the hiatus observed from well data and shown as missing sections in Figures 7 and 9. Although usually assumed to be the "break-up unconformity", the cause of the deformation (compression and uplift) is still unclear. Referring to it as a "buried topography event", Lunt (2022, p. 22) described the subsidence that followed the event rather than the deformation itself: "The geographic extent of the Doust MMU subsidence can be traced by the deposition of the siliciclastic-starved Luconia limestone that followed this subsidence event." According to Lunt (2022, p. 69), the abrupt subsidence and transgression of the Doust MMU occurred between 16.4 and 15.1 Ma. Such a narrow age range implies that the hiatus (of up to 10 Myr of missing section) represents the deep vertical extent of sediment erosion, which can only be explained by an uplift and erosion event. Some studies indicate that the 16 Ma age coincided with the cessation of sea-floor spreading in the SW prong of the South China Sea (SWSCS), representing the final episode of extension and oceanic crust generation (Li *et al*., 2013; Tong *et al*., 2019). In other words, the unconformity was not due to "break-up" at the start of sea floor spreading but, rather, at the end of it (e.g., Kessler & Jong, 2023). Li *et al*. (2013) examined seismic data from the SWSCS and found that Oligocene-Early Miocene rifting was followed by mild compression and inversion prior to 16 Ma, which they related to the collision between Dangerous Grounds and Borneo (see also Wu *et al*., 2023). These deformational events may be correlated with the spreading history of the SWSCS east of about 111°E, which began at anomaly 6 (19–21 Ma) in the Early Miocene and ceased at anomaly

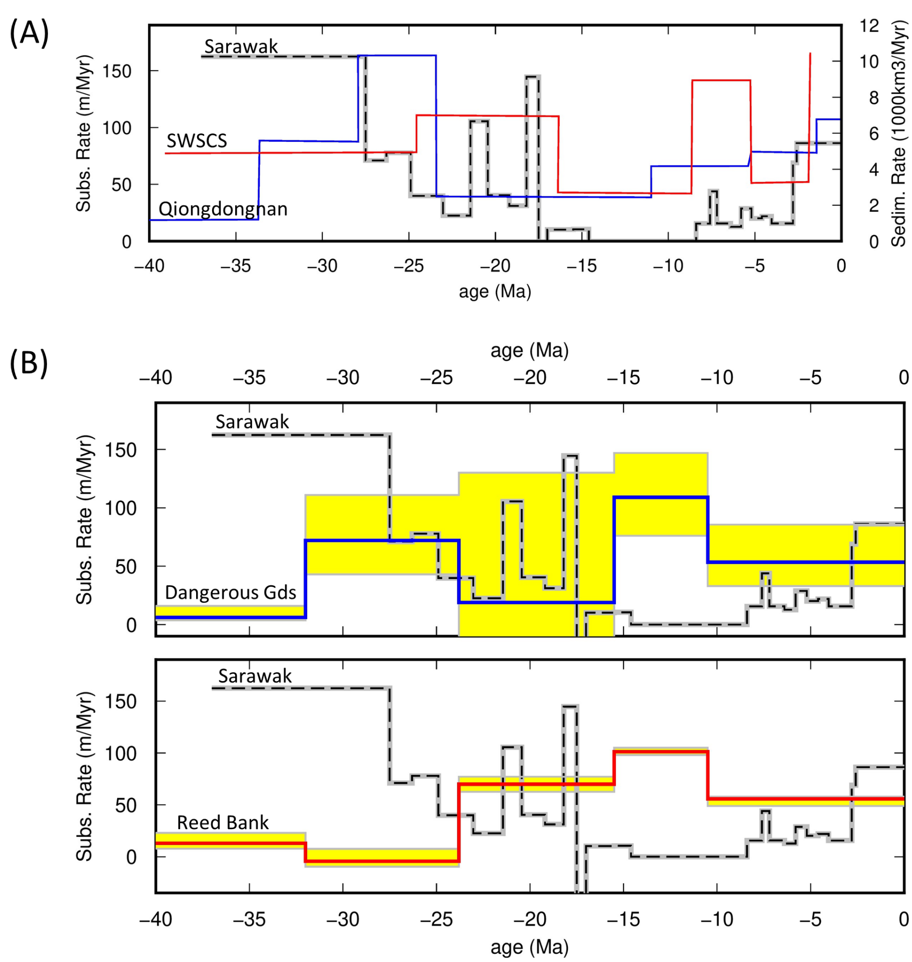


Figure 13: Comparison of subsidence and sedimentation rates over geologic time from different regions of the South China Sea. In all charts, the subsidence rate for Sarawak Basin based on the present study is shown by the black and grey dash lines. (A) Subsidence rate in Qiongdongnan basin on the northern margin of the South China Sea (from Zhu & Lei, 2013) shown by blue lines (vertical scale on the left) plotted with the sedimentation rate in 1000 km^3/ Myr from the southwestern South China Sea (SWSCS) margin (from Li *et al*., 2013) shown by red lines (vertical scale on the right). (B) Sedimentation rates based on the subsidence analysis by Fang *et al.* (2017): top chart – Dangerous Grounds; bottom chart – Reed Bank. Yellow shaded area represents the range of values obtained from the subsidence analysis.

5c (16 Ma) in the early Middle Miocene (Cande & Kent, 1995; Li *et al*., 2012; Qiu *et al*., 2023). Zhang *et al*. (2020) proposed that the break-up unconformity at the SWSCS is at 23 Ma (marked by their unconformity T4) and showed that extensional fault activity in that region continued until the Middle Miocene (15.5 Ma) or 16.5 Ma according to Wu *et al*. (2023). The results of our study have shown, independently, that the subsidence history of Sarawak Basin is remarkably similar to that of the SWSCS described by Luo *et al*. (2021, their Figure 9), with the three pre-MMU subsidence phases (Figure 10), corresponding with the T1, T2, and T3 phases (from oldest to youngest) that spanned from the Mid-Eocene rifting to the Mid-Miocene break-up. Such a protracted period of crustal extension may have been responsible for the exceptionally wide continental margins on both sides of the South China Sea basin. Numerical models by Pérez-Gussinyé *et al*. (2020) suggest that in wide rifted margins, which seems to be the case here, the focus of crustal extension migrates seaward over the syn-rift phase, resulting in diachronous "rift migration unconformities". At the point of break-up, a break-up unconformity develops at the most seaward rift zone and merges with the other unconformities to form a margin-wide unconformity. The MMU in Sarawak Basin could be such an unconformity, representing the syn-rift to post-rift transition related to the protracted history of seafloor spreading of the South China Sea basin, involving ridge-jumps and changes in spreading directions. What we are observing may be the effect of that long period of extension in its southern conjugate margin.

CONCLUSIONS

Subsidence analysis of selected wells in Sarawak Basin indicate complex history of rifting, subsidence and uplift during basin development at the southern margin of the South China Sea basin. A relatively rapid initial subsidence (interpreted as an early phase of rifting from ca. 37 – 28 Ma) was followed by a gradual decrease in subsidence rate due to post-rift thermal relaxation phase (ca. 28 – 22 Ma), which was quickly superseded by an increase in subsidence, signalling a second phase of extensional tectonics during the Early Miocene (ca. 22 – 17 Ma). A major episode of compressional deformation, uplift and local erosion, accompanied the sharp increase in subsidence rate, which culminated in the Middle Miocene Unconformity (MMU) event at ca. 16 Ma. The MMU is recognised throughout Sarawak Basin as a major hiatus spanning a large part of the Early to Middle over the Bunguran Trough and North Luconia region. The deformation probably continued into the Late Miocene, although much of the Late Miocene record may have been removed by erosion. During the post-Late Miocene period, there was an increase in subsidence probably due to the progradation of the shelf edge to its present-day configuration.

The complex multi-phase subsidence history of Sarawak Basin shows some similarities with that reported from other parts of the South China Sea margin, and indicates a common, underlying tectonic control related to the rifting and spreading histories of the South China Sea basin and their interactions with NW Borneo.

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AUTHORS CONTRIBUTION

MM - paper conceptualization, literature review, data compilation, analysis and interpretation, figure drafting, writing and editing; JJ - data access, review, and compilation, figure drafting, writing and editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in connection with this article.

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