The South China Sea: Sub-basins, Regional Unconformities and Uplift of the Peripheral Mountain Ranges since the Eocene

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ABSTRACT

This paper reviews the complex interaction of basin subsidence, erosion and uplift of mountain ranges that enclose the South China Sea (SCS). We found that recent uplift is a feature occurring dominantly at the fringes of the Sundaland Plate, around Sumatra/Java, Borneo, the Philippines and Taiwan. More significantly, there is a positive age correlation between regional unconformities, formation of oceanic crust and uplift of the peripheral mountain ranges. However, the magnitude of erosion related to each major unconformity can vary regionally, and could partly be subjected to climatic influence. The oldest truly regional unconformity recognizable is of very Late Oligocene age, and acts as an angular unconformity in Sabah, Sarawak, and the Malay/Penyu Basins (at Base 'K' level), at or very close to the base of the Miocene sedimentary package. We call this unconformity the Base Miocene Unconformity (BMU). Other than the BMU, the widely-known seismic event called the Mid-Miocene Unconformity (MMU) could be correlated with the end of proto-SCS spreading, and uplift may have occurred only in segments of the SCS, in particular at the southern fringe. The Late Miocene Shallow Regional Unconformity (SRU) points to a short compressive pulse that affected mainly areas of Sabah and Sarawak. The more recent Intra-Pliocene unconformity (IPU), commonly forming the base of some uplifted coastal terraces can be seen in particular in the south and eastern parts of the SCS, and correlates with uplift of areas such as NW Borneo and Taiwan. The event is a likely consequence of the Taiwan collision interplayed with the docking of the Philippines Plate in the Early Pliocene with NW Borneo at the Palawan/Philippines Margin. The Malay, Penyu, Natuna Basins and Vietnam Margin are predominantly Oligocene to Lower Miocene fills, whereas the NW Borneo Foredeep/Palawan Trough, deepwater Nam Con Son Basin and the Bunguran Trough have predominantly a Neogene fill.

This observation points to a reduced extensional regime if compared with the south-eastern margin, where fault activity continued to the Mid/Late Miocene. The compiled uplift data in the surroundings of the SCS, as well as the presence of seismically mapped regional unconformities suggest that the greater Sundaland Plate has seen a number of extensions and compression/inversion/rotation phases; however there appears to be no positive evidence for the presence of microplates and/or subduction during the Oligocene/Miocene. In summary, crustal stretching, uplift and the resulting unconformities can be compared to different instruments of an orchestra playing individually; no harmonic tune can be achieved and there is little merit in looking at each contributing factor in isolation.

Keywords: *Eocene, erosion, sea-level changes, sediments, South China Sea, subsidence, unconformity, uplift, Tertiary.*

INTRODUCTION

Geological Background

The South China Sea (SCS) was formed by rifting of the continental lithosphere of Sundaland (Hutchison, 2005; Figure 1). According to Pubellier et al. (2015), some sub-basins of the SCS are marked by extremely stretched crust (Phu Khanh, West Natuna, NW Palawan, Taiwan's Tainan), where upper mantle may be in contact with the sediments. Therefore, we can distinguish between an early extensional process which started during the Late Cretaceous and possibly Paleocene, during which the basement and the Mesozoic granitoids were exhumed, and an Early Eocene to Middle Miocene rifting, which stretched the crust to a 12 km thickness over a large area by a boudinage process. Previously, good attempts were made to characterize ages and uplift data of the SCS (e.g., Hall & Morley, 2004; Figures 2a, b), however without incorporating seismic data.

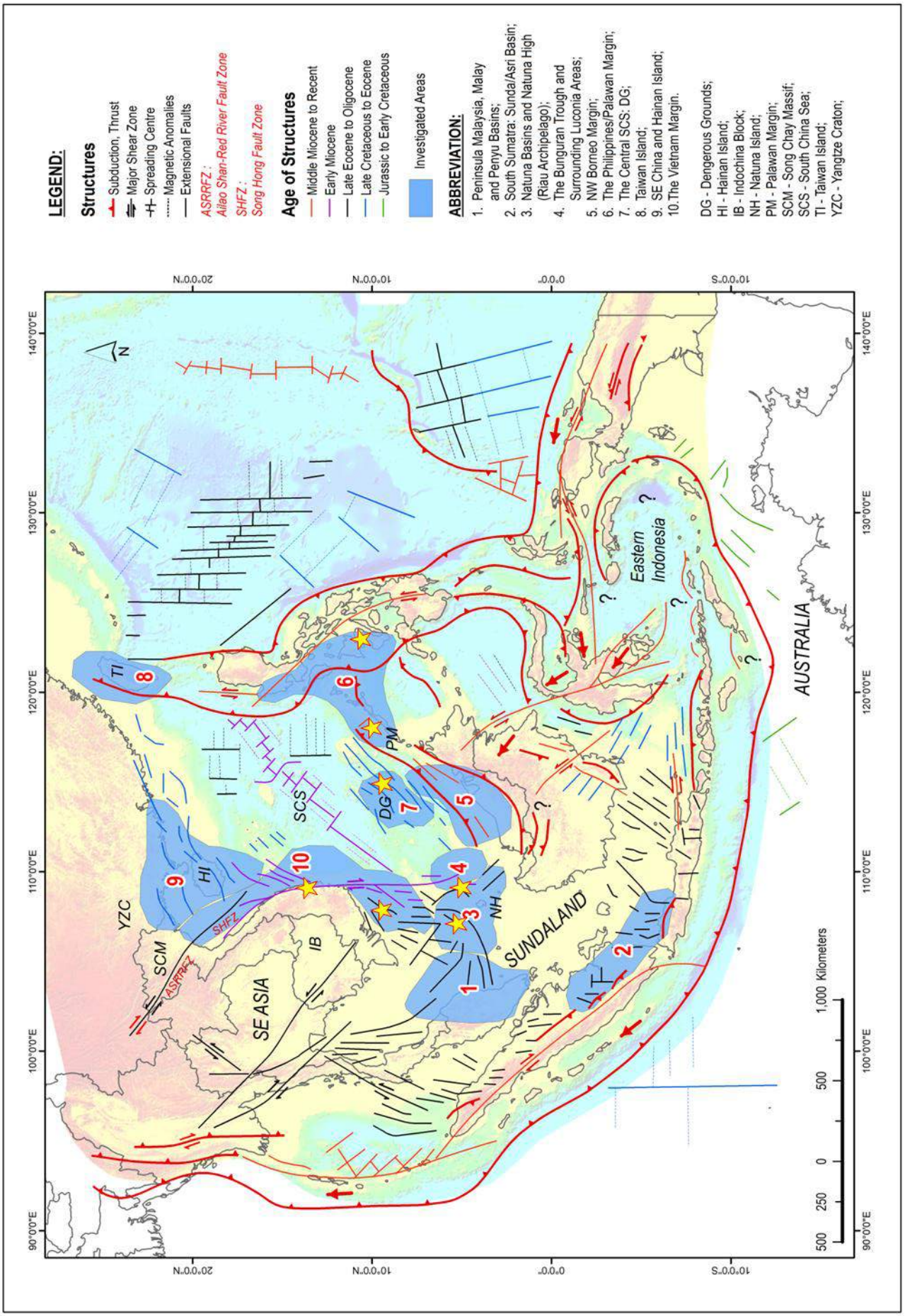


Figure 1. *Investigated sub-basins for understanding the subsidence history of SCS. Uplift data were compiled where available from the study areas and the periphery mountain belts. Areas annotated by the yellow stars are lacking in uplift data, which might have been compiled in unpublished sources and other publications under preparation. The availability of these data will help to further reduce the knowledge gap on the tectonic evolution of SCS and uplift mechanism of the periphery mountain ranges.*

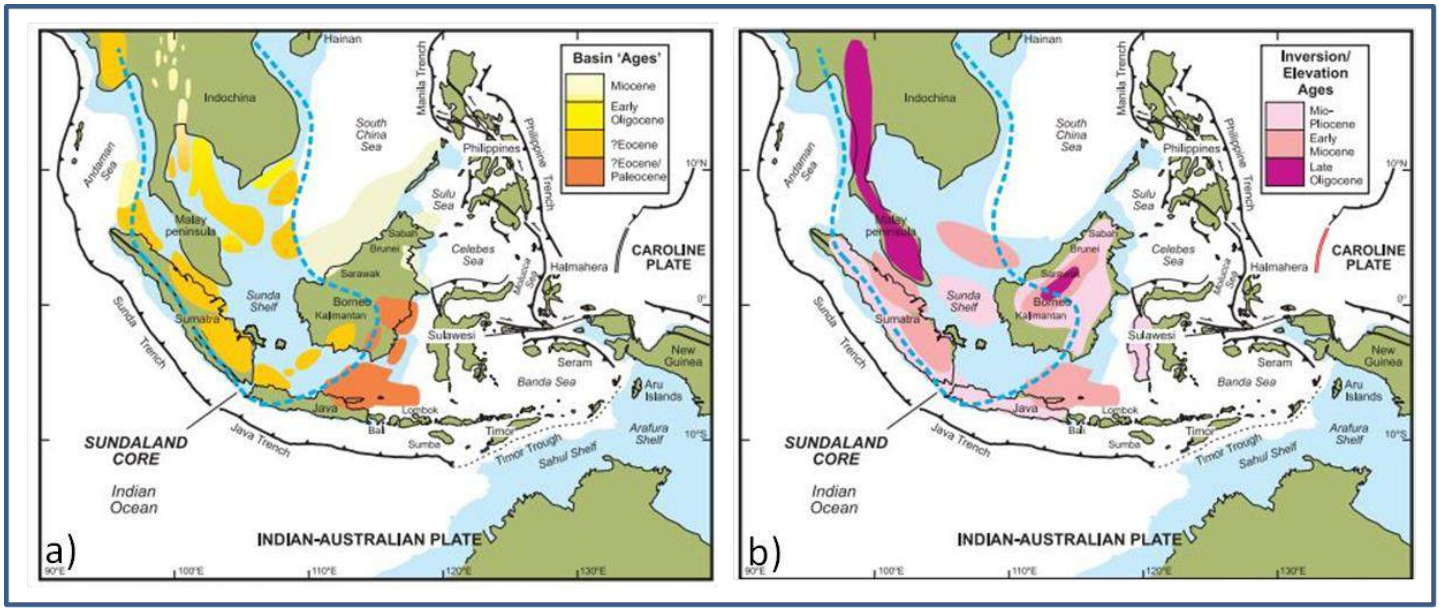


Figure 2. *a) Ages of basin initiation in Sundaland. The record typically begins in the Eocene or Oligocene although since the older parts of most sequences are terrestrial, and deeper parts of many basins are not drilled, most are relatively poorly dated. b) Ages of basin inversion or elevation due to tectonism in and around Sundaland. After Hall & Morley (2014).*

An area of apparent high geological complexity, the SCS is formed by several Mesozoic continental blocks that protrude from the southern part of the Eurasian Plate as a wedge between the Indo-Australian and Philippine Plates. This peninsular continental extension from Eurasia was, during the Paleocene, characterized by an extensive landmass, probably exposing crystalline rock, as well as Mesozoic meta-sediments at the paleo-surface. Several Late Tertiary sub-basins rim the older interior highlands and, in turn, are flanked by marginal seas underlain by oceanic crust (SCS, Sulu Sea and Celebes Sea: Cullen et al., 2010).

At least two episodes of rifting have occurred in the region. The older 'Eocene' event is associated with a regional episode of extension recognized in Luconia (Hutchinson, 1996), the Dangerous Grounds (Thies et al., 2005), the Phu Khanh Basin (Fyhn et al., 2009a), onshore Kalimantan (Barito, Kutei and Tarakan basins; Satyana et al., 1999), and the Makassar Straits (Guntoro, 1999). Remnants of otherwise eroded Eocene sediments have also been drilled by oil exploration wells in the Penyu Basin, suggesting that this region also saw Eocene rifting in contrast to the Cuu Long Basin in Vietnam (Donny et al., 2015). Although these basins demonstrate widespread extension of the Sundaland crust, the Celebes Sea is the only documented area where sufficient extension has occurred to result in Eocene seafloor spreading (Rangin & Silver, 1991). This episode of rifting has been attributed to back-arc extension related to subduction processes, such as slab roll back, around greater Southeast Asia (Doust & Sumner, 2007; Hall, 2013). The second younger rifting event, although not as regionally extensive as the Eocene event, culminated with seafloor spreading in the SCS. It has been interpreted to have opened in several stages during the Oligocene and early Mid-Miocene, *ca.* 32 Ma to 16 Ma (Taylor & Hayes, 1983; Ru & Pigott, 1986; Briais et al., 1993; Longley, 2014). Later work, based primarily on additional ship-borne magnetic data, allows a refinement of those earlier models (Huchon et al., 2001; Barckhausen & Roeser, 2004; Hsu et al., 2004). North of Palawan, north-south extension occurred from *ca.* 37 Ma to 24 Ma, followed by NW–SE-orientated extension from *ca.* 24 Ma to 20 Ma as the rifting separated the Reed and Macclesfield Banks and then propagated to the southeast. A recent study by Morley (2016) suggests a westward propagation of oceanic crust between 25 and 23 Ma, and a termination of seafloor spreading sometime between 20.5 and 16 Ma. It may have triggered faulting in the Qiongdongnan and Nam Con Song Basins. In the Dangerous Grounds area however, extension continued until about 16 Ma, ending in the 'Red Unconformity'.

Seafloor Spreading Models for the South China Sea

Two end-member models for opening of the SCS have been proposed and their differences are not yet resolved. Extrusion-based models (e.g., Briais et al.,1993; Replumaz & Tapponier, 2003) show opening of the SCS as driven by the SE displacement of the Indochina Block along the Mae Ping and Ailao Shan-Red River Fault Zones following India's collision with Asia. Subduction-based models (e.g., Hall 2002; Hall et al., 2008) suggest the SCS opened in response to slab pull during subduction of proto-SCS oceanic crust. A variation on these models suggests additional crustal thinning related to a mantle plume is required to initiate seafloor spreading (Xia et al., 2006). An alternate model proposed by Cullen (2010), interprets minimal Neogene subduction under Borneo and suggests a hybrid model of extrusion and crustal shortening that needs to be

considered. Nonetheless, some persistent problems with the evolution of the SCS remain, such as the timing of fault displacement vs. continental extension and the timing of seafloor spreading. It is noted, that ages of formations (Cretaceous vs. Palaeogene) and paleogeography of the proto-SCS ocean differ considerably in the proposed models (Morley, 2016).

Detailed understanding of proto-SCS development remains uncertain and controversial. Regardless of the choice of models portraying the opening of the SCS, it is important to keep several model-independent points in mind. First, beyond the present-day continent–ocean boundary the width of rifted continental crust (*ca.* 600 to 1200 km; Hayes & Nissen, 2005) suggests a ductile, mechanically weak, upper mantle prior to rifting (Gueydan et al., 2008); this may reflect earlier Eocene rifting. Secondly, the elastic thickness of the rifted continental crust in the SCS is thin and therefore different from other continental plates. Its thickness was calculated as 8-10 km from geo-mechanical modelling (Clift et al., 2002), and 4–6 km from inversion of marine gravity data (Braitenberg et al., 2006). Accordingly, dynamic tectonic models from other areas of the world should be applied with caution.

STUDY OBJECTIVES

The idea appears obvious that unconformities within the SCS and mountain-building processes such as inversion, folding and uplift must be related to each other. In the periphery of the SCS sub-basins/mountain belts, there is a reasonable coverage of published uplift data in the literature such as Apatite Fission-Track Analysis (AFTA) plus other absolute age dates. This said, the regional context of uplift and unconformities has rarely, or only partly been addressed. In this paper we explore and examine this relationship encompassing the entire SCS, trying to resolve the following questions:

i. Are there any particular pulses of uplift that can be recognized?
ii. Are major unconformities recognized on seismic established in the entire basin area, or of local dimension?
iii. Can the uplift data be reconciled with unconformities?
iv. If regional unconformities are indeed correlated with uplift data, then how is the nature of such a correlation?
v. How is the context between the opening of the SCS rifting and timing of uplift and unconformities in the sub-basins?

Although there is a shortage of uplift data (Figure 1), particularly in areas such as Natuna and the Philippines (albeit with some publications forthcoming as mentioned in Pubellier et al., 2015), we hope that this paper could help bring forward a better integration of the mentioned basin parameters. Accordingly, we want to briefly detail and compare area specifics (basin/hinterland pairing) in anti-clockwise fashion extending from Malay and Penyu Basins then southward to South Sumatra's Sunda/Asri Basins, thence upward to Natuna High, Bunguran Trough and surroundings. We continue our discussion with the NW Borneo Margin, extending to the Philippines/Palawan Margin and to the Dangerous Grounds in central SCS. The investigation follows eastward to the north-western periphery of SCS covering the Taiwan Island, Hainan Island/SE China and the Vietnam Margin such that it becomes clear which features are common, and which features are distinctive (Figure 1).

METHODOLOGY AND RATIONALE

When it comes to regional stratigraphic correlation, there are essentially two schools of thought:

(i) Those who applied the sea-level fluctuation concept first published by the Esso geologists such as Peter Vail and Bilal Haq (e.g., Vail et al., 1977; Haq et al., 1987). In theory, this method should allow perfect sequence to sequence correlation, and from sub-basin to sub-basin. In practical geology, this concept has often failed given the proposed (synchronous) boundaries are not as widespread as claimed or cannot be resolved on seismic.
(ii) Researchers who divided stratigraphy by unconformities. This concept has been applied with good results, as far as the coarse Tertiary stratigraphic framework is concerned. However, more detailed subdivisions such as sediment cycles could not be applied regionally with satisfactory results. Furthermore, uplift data had not been taken into account in this approach.

We have largely followed the second concept, mainly because of the importance of hinterland uplift in the SCS region. There might be, however, a strong element of diachronism. Avoiding looking at unconformities in isolation, we are also comparing these with the uplift data in the periphery of the SCS. The rationale being that unconformities and uplift should be correlated since both are expressions of the buoyancy within the Sundaland Plate. Accordingly, we have compiled regional data such as AFTA, Zircon Fission-track data, absolute cooling ages for magmatic rocks, vitrinite reflectivity data, and other indirect measurement data derived from morphology and terrace studies (e.g., Liu, 1982; Tsao, 1986; Swauger et al., 2000; Maluski et al., 2001; Hutchison, 2005; Li et al., 2005; Viola & Anczkiewicz, 2008; Yan et al., 2011; Cottam et al., 2013a, b; Cullen, 2013; Guo, 2014; Wang et al., 2014; Kessler & Jong, 2014, 2015a, b, c; Jong et al., 2016).

- Fission-track dating is a radiometric dating technique based on analyses of the damage trails, or tracks, left by fission fragments in certain Uranium-bearing minerals and glasses.

The method involves using the number of fission events produced from the spontaneous decay

of Uranium-238, by alpha emission into Thorium-234 in common accessory minerals to date the time of rock cooling below closure temperature (Wagner & Haute, 1992). Fission-tracks are sensitive to heat, and therefore the technique is useful in unraveling the thermal evolution of rocks and minerals. For this study we relate mainly to AFTA. As Apatite crystals cool down to less than 92 ^{0}C, they record radioactive crystal fabric damage. In such ways, one can estimate the amount of uplift, as the clocks start ticking some 3 km beneath surface (assuming a temperature gradient of *ca.* 30 ^{0}C/1000 m). Other fission-track analysis tools can also be used, for instance zircon, but these crystals 'freeze/anneal' at a far higher temperature, which means that the clock is reset (at least for plutonic rocks) at a far higher depth than minerals of the Apatite Group.

- Vitrinite reflectance measurement (VRM) is a method originally applied in the coal mining industry, built on the observation that the appearance of coals changes with increasing temperature and overburden rock thickness. In sedimentary basins, VR shows and preserves the maximum amount of temperature that the rock has endured. If the regional temperature gradient is known, VRM can give a precise notion of burial. Coals exhumed on a sedimentary surface allow for estimates of erosion/uplift (= the missing overburden).
- Terraces. River terraces form when coarse sediments (sands, conglomerates) cannot be held any longer in suspension, and drop out. Incised terraces may indicate uplift in the hinterland, or a lowering of the sea-level. Changes in climate can play a role too. We also observed that many Borneo terraces dated as Pleistocene in age are found significantly above the current river beds (Kessler & Jong, 2015b).

In the respective sub-basin of SCS, we reviewed the expression of unconformities as observed on seismic, trying to establish the age of the eroded formation below the unconformity ('younger than'), and the ages of the formations above the unconformities ('older than'). Our data are derived mainly from seismic data calibrated to well results from Sabah, Sarawak, the Penyu and Malay Basins, and other published sources from the Philippines/Palawan Margin, Hainan, Taiwan and Vietnam Margin. If there is a change of dip (= angular unconformity) between pre-unconformity and post-unconformity, it indicates a direct link between tectonic processes and the nature of the unconformity. In such cases one might argue, that both events are caused by plate-tectonic events that affected the Sundaland Plate or at least segments of it. As a result, the post-uplift (and unconformity) sediment supply would also be widespread over the SCS. If uplift were to be observed in isolated blocks, possibly driven at least partly by climatic factors (e.g., Kessler & Jong, 2015a), this might result in strong and localized sediment supply to the nearest sub-basin.

OBSERVATIONS FROM SOUTH CHINA SEA REGIONAL SUB-BASINS

An earlier review of principal hydrocarbon-bearing basins around the SCS has been conducted by Du (1985). Doust & Sumner (2007) and Longley (2014) provided excellent summaries on the genetic and geodynamic relationship of the petroleum systems of SE Asian basins. Evolution of the Sundaland basins were reviewed and summarized by Hall & Morley (2004), and more recently by Morley (2016). The tectonic history of structural domains surrounding the SCS with the exception of the Philippines, Taiwan and SE China areas has been recently documented by Jong et al. (2014), and is briefly highlighted below with a focus on the documentation of mapped regional unconformities and timing of key uplift events recorded from published data.

Peninsula Malaysia, Malay and Penyu Basins

The area is characterized by intense lateral movements (Madon & Anuar, 1999; Tan, 2009; Donny et al., 2015). Data presented by Kraehenbuehl (1991) and Cottam et al. (2013a) suggest uplift in Peninsular Malaysia occurred mostly during Oligocene times. In the Malay and Penyu Basins transtensional tectonics led to horst and graben structures (Figures 3 & 4), offsetting granitoids, volcanics and metamorphic Mesozoic phyllites and slates in elongated slivers, particularly at the end of the Oligocene. After post-Early Miocene, the Penyu and the Malay Basins practically formed a fused sedimentary system of mainly fluvio-terrestrial and shallow marine deposits sourced from the north, which culminated in a major inversion episode in the study area. Both basins are extraordinary in the sense that subsidence and sedimentation remained balanced from this time onwards until present-day (Donny et al., 2015).

The shale (commonly called K shale) above the K1 sand is 'transgressive' marine and dated as Lower Miocene. The K shale extends throughout most of the Malay and Penyu Basins, and forms a good stratigraphic marker. The K level also separated the older (Oligocene or syn-rift) sequence, although most, if not all of the fills originated in pull-apart basins rather than in rift grabens. Accordingly, the so-called syn-rift sequence may have originated as a hybrid between crustal stretch and pull-apart signatures. This said, the rifting mechanism remains poorly understood.

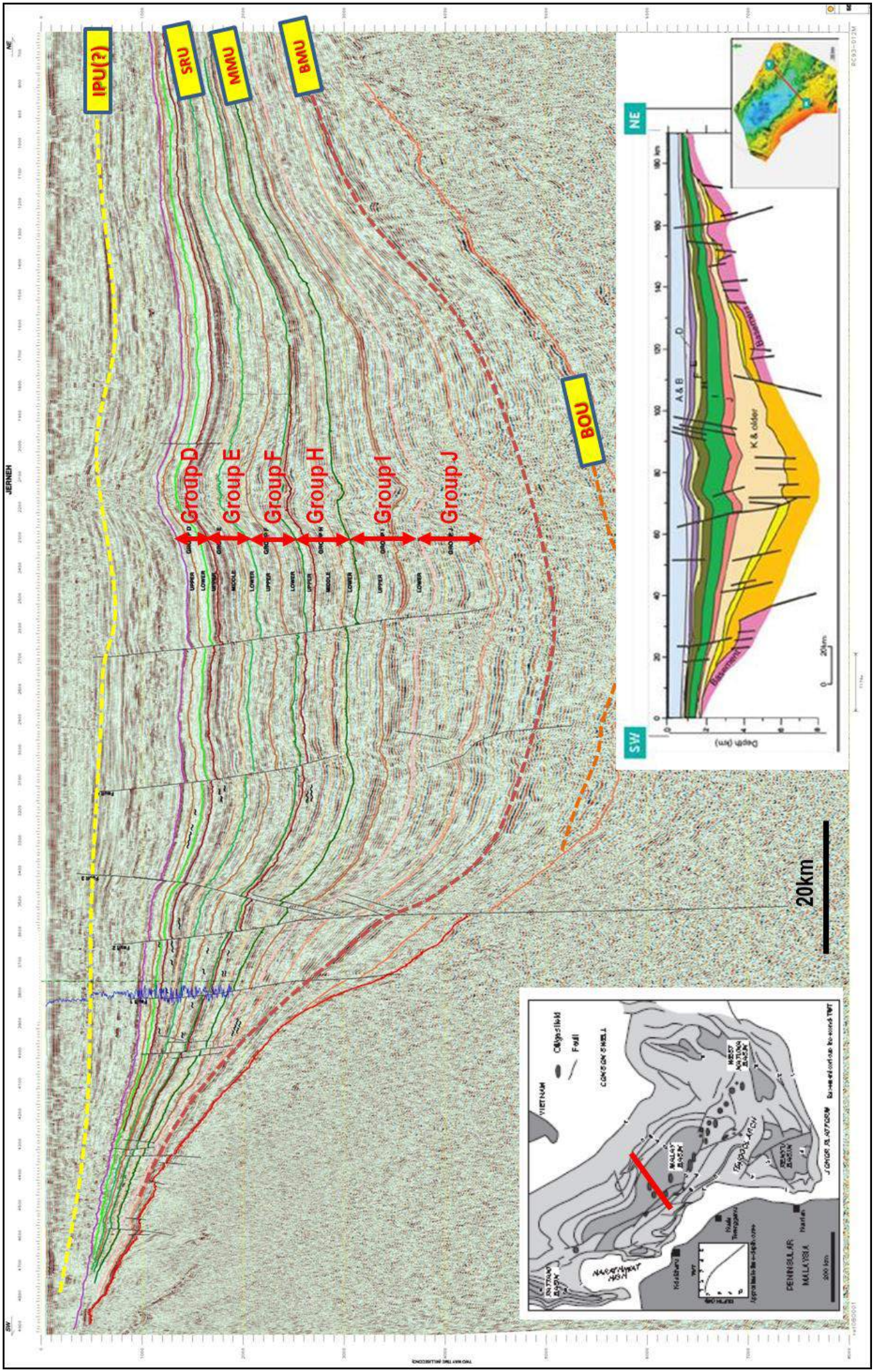


Figure 3. *Malay Basin regional type seismic section illustrating the sequence intervals of Group J to Group D from Lower Miocene to the Upper Miocene. The K, L and M Groups are difficult to correlate on this section. Tentative positions are shown for IPU, SRU, MMU, BMU and BOU, after Donny et al. (2015). Insert cross section shows steer's head geometry with deep, poorly resolved syn-rift basin at centre overlain by thickening and onlapping post-rift strata. Note the inversion folds at the centre (after PETRONAS, 2015).*

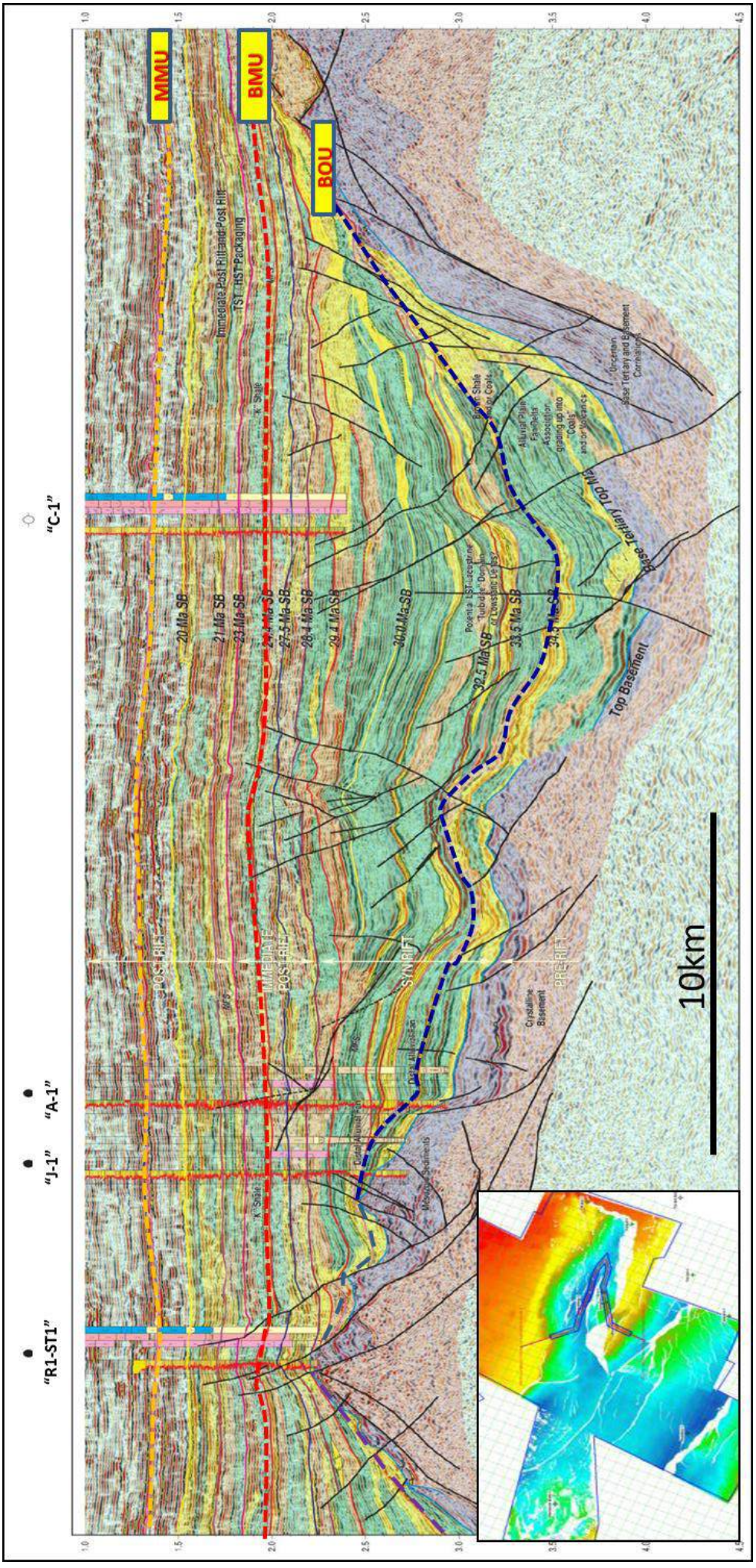


Figure 4. *Penyu Basin regional seismic section illustrating mapped sequence boundaries (SB) and related depositional facies; yellow = sandy facies, green = lacustrine shales, purple = meta-sediments. The depositional system of the Penyu Basin is mainly restricted lacustrine facies up to Base Miocene, near Top L event and was isolated from the fluvial sedimentary pulses of the Malay Basin until this time, after Barber (2013) and Donny et al. (2015). Locations of regional unconformities BOU, BMU, MMU are annotated. A hiatus of ca. 1200 m (= eroded sediments) is based on a significant increase of VRM from the Oligocene layer to the Eocene and older remnants below.*

Recent spurious data suggest that there may be remnants of eroded Eocene deposits in the centre of graben areas, beneath a marked Intra-Eocene or Base Oligocene unconformity (BOU); whilst the Base Miocene Unconformity (BMU) and the Mid-Miocene Unconformity (MMU) are tentatively assigned to near Top Group L and near Top Group H, respectively (Figures 3 & 4). The younger unconformities in the basins, especially the Intra-Pliocene Unconformity (IPU) are inferred mainly from seismic interpretation of the nearby Natuna area and Bunguran Trough to the east.

The stratigraphy in the basins is well known given a multitude of oil and gas wells. There are also a number of fission-track points located on the peninsula, indicating mainly an Oligocene (Rupelian) uplift history (Cottam et al., 2013a).

South Sumatra: Sunda/Asri Basin

The South Sumatra area (Figure 1) was formed by three major tectonic phases: 1) extension during Late Paleocene to Early Miocene forming north-trending grabens that were filled with Eocene to Early Miocene deposits; 2) a relative quiescence period with late normal faulting from Early Miocene to Early Pliocene; and 3) basement-involved compression, basin inversion, and reversal of normal faults in the Pliocene to Recent forming the anticlines that are the major traps in the area (Suhendan, 1984). Many of the normal faults that formed the depositional basins in South Sumatra have been reactivated and some were reversed during Miocene to Plio-Pleistocene compression and basin inversion (Sudarmono et al., 1997).

In absence of published seismic data/calibration points, unconformities could not be mapped and synchronized with neighboring areas, albeit regional events such as the MMU and Shallow Regional Unconformity (SRU) affecting nearby Borneo would have likely been experienced. Although further away from the margin of the SCS, it is interesting to take note of the various uplift events recorded in the area, a likely consequence of the continued Indo-Australian Plate subduction beneath the Sumatra Trench, and the relationship to the tectonic events of the SCS. AFTA data from 17 wells in the Sunda-Asri, NW and SW Java Basins were dated by Soenandar (1997) and appear to indicate a Paleogene, as well as a Lower Miocene period of uplift probably due to the collisional impact from the Indo-Australian Plate. However, additional and detailed studies in the same South Sumatra basin by Sutriyono (1998), point to much younger uplift with ages ranging from the Late Miocene to the Pliocene, likely a result of the subduction further to the west.

Natuna Basins and Natuna High (Riau Archipelago)

Late Eocene to Mid-Oligocene transtensional rifting created a complex network of grabens in the West Natuna and Malay Basins (Tjia, 1998), followed by Miocene to Recent compression and inversion (Figure 5). The original grabens were formed through extension, but it appears that at least some of the extension was removed by the subsequent inversion. Good definition of Base Tertiary in most of the area allows for interpretation of the syn-rift sequence and economic basement (Figure 5b). From the earliest Miocene, the grabens were inverted to form folds and wrench zones as a result of a right-lateral stress regime (Burton & Wood, 2010). The nature of the inversion is strongly controlled by the orientation of underlying rift faults. Rift basins with a strike oriented at a high angle to the principal compressional stress form folds through reactivation of graben-bounding faults. In these rifts the syn-rift graben fill is inverted over the graben footwall, often along a fault with a convex upward geometry. The magnitude of inversion is closely correlated to the heave of the initial extensional faults; large extensional faults often have large inversion folds associated with them and vice-versa. Within any one graben, inversion appears to commence at younger ages away from these large faults.

In the East Natuna Sokang Basin (Figure 5b), Longley (2014) has suggested an Early Oligocene uplift and incision (canyons) in the hinterland as a consequence of 'Luconia Block' collision (37 – 32 Ma), whilst the Malay Peninsula also saw contemporaneous uplift during the same period. However, these areas seem to be less affected by the Miocene inversion tectonism, in contrast to the West Natuna area. The key unconformities established in the investigated area include the BMU, MMU and the equivalent SRU, whilst the youngest IPU can be correlatable from the nearby Bunguran Trough.

We are not aware of any published AFTA data from the Riau Archipelago. In summary, with only seismic evidence, and lacking credible fission-track data, the timing of structural history and tectonic evolution of the Natuna area remains a challenging topic for further research. The greater Natuna is particularly tough to interpret in the context of regional unconformities due to the impact of multiple inversions, which reshaped the basin geometry.

The Bunguran Trough and Surrounding Luconia Areas

The relatively under-explored and little known Bunguran Trough can be described as a roughly triangular crustal depression, wedged between the Terumbu Platform in the west, Central Luconia Platform to the east, the Rajang Shelf to the south and the Dangerous Ground Massif to the north and northeast. It is flanked by two lineaments, the West Baram and Lupar Lines and located at the southern end of the transform margin of the SCS (Jong et al., 2014, 2015; Harun Alrashid et al., 2015).

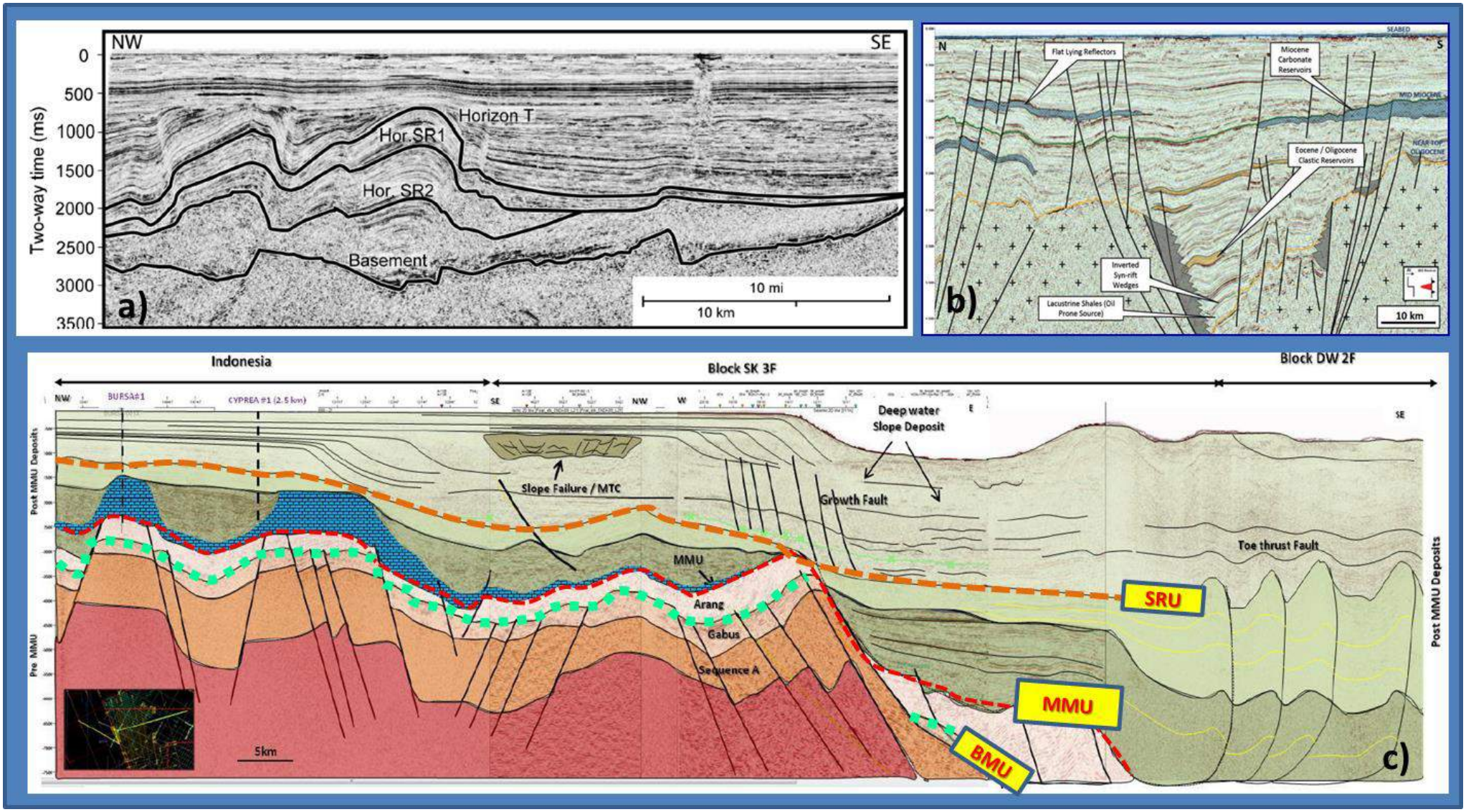


Figure 5. *a) Vertical seismic section from the West Natuna Basin showing four regional horizons mapped, including a lower syn-rift horizon SR2, an upper syn-rift horizon SR1 and the top of the syn-rift horizon T. Inversion started in the Early Miocene and continued to Late Miocene (after Burton & Wood, 2010). b) A seismic profile from the East Natuna Sokang Basin with a rift graben, the area is less affected by the Miocene inversion tectonicism (after PGS, 2012). c). A composite W-E seismic profile across the Natuna High to deepwater Bunguran Trough with MMU marked the start of post-rift carbonate growth (in Natuna High) and clastic sedimentation. Inversion in deepwater Bunguran Trough continued well into the Pleistocene.*

A recent study by Iyer et al. (2012) of nearby areas of West Luconia, northern Central Luconia and North Luconia suggested basins in the study area were initiated as intracratonic rifts on attenuated continental crust, on a foreland bulge of offshore Sarawak, ensuing from Phase-I NW-SE to north-south extension, during Late Cretaceous(?) to Late Eocene. The general structural style during this stage is characterized by north-south and NE-SW-trending half-grabens, dipping to the east and southeast. The phase of extension continued (into Phase-II), with the opening of the SCS during Early Oligocene, and also during a subsequent drift phase up to early Mid-Miocene. Transtensional rifting formed the basin at the end of the Oligocene, accelerated during the Early Miocene and continued in periodic pulses into the late Middle Miocene (Hutchison, 2004). Unequal subsidence in the half grabens during this stage, accommodated variable thickness of infill sequences of Oligocene to Mid-Miocene Cycles I to III, showing diverse facies distributions as evidenced by the well results. Lower Miocene deposits are buried to a depth of 6000 m, and the fill above is constituted by mostly muddy Neogene and Quaternary deposits.

Subsequent regional uplift in the area associated with plate convergence during late Early Miocene to Mid-Miocene, resulted in the regional MMU, which are well expressed on the flanks of the basins (Figures 6 & 7). Towards the western part of the study area and substantiated by seismic sequence mapping, an Early Miocene age for the MMU can be inferred (Madon et al., 2013, Figure 7). This is associated with uplift and erosion, aided by a major tilt to the east from East Natuna Hinge Zone. The age of the MMU progressively becomes younger eastwards. A major NW-SE transtension episode close to the MMU time along SW Luconia Fault Zone transecting the study area resulted in the formation of the West Luconia/Bunguran Trough, accommodating a huge pile of post-unconformity section. Northeasterly sag of the basin through Late Miocene to Recent led to a deepwater setting, resulting in deposition of mainly hemipelagics, interrupted by mass transport-dominated sequences (Figure 8). Recently, based on well drilling outcomes, a younger erosional event can be identified at the Upper Miocene Top Cycle V section and is moderately expressed on seismic. This erosional event has been dated with biofacies technique and is established in this paper as the IPU (Figure 8).

Given the area's position in the centre of the SCS, there are no fission-track data available; however the area is well constraint by good seismic coverage and well calibration such as those documented by Madon et al. (2013).

NW Borneo Margin

NW Borneo is formed (from south to north) by four arcuate belts that extend from Sarawak to Brunei and into Sabah. The southernmost block is formed by the Schwaner Mountains, a Gondwana terrane (e.g., van Hattum et al., 2006, 2013; Setiawan et al., 2013).

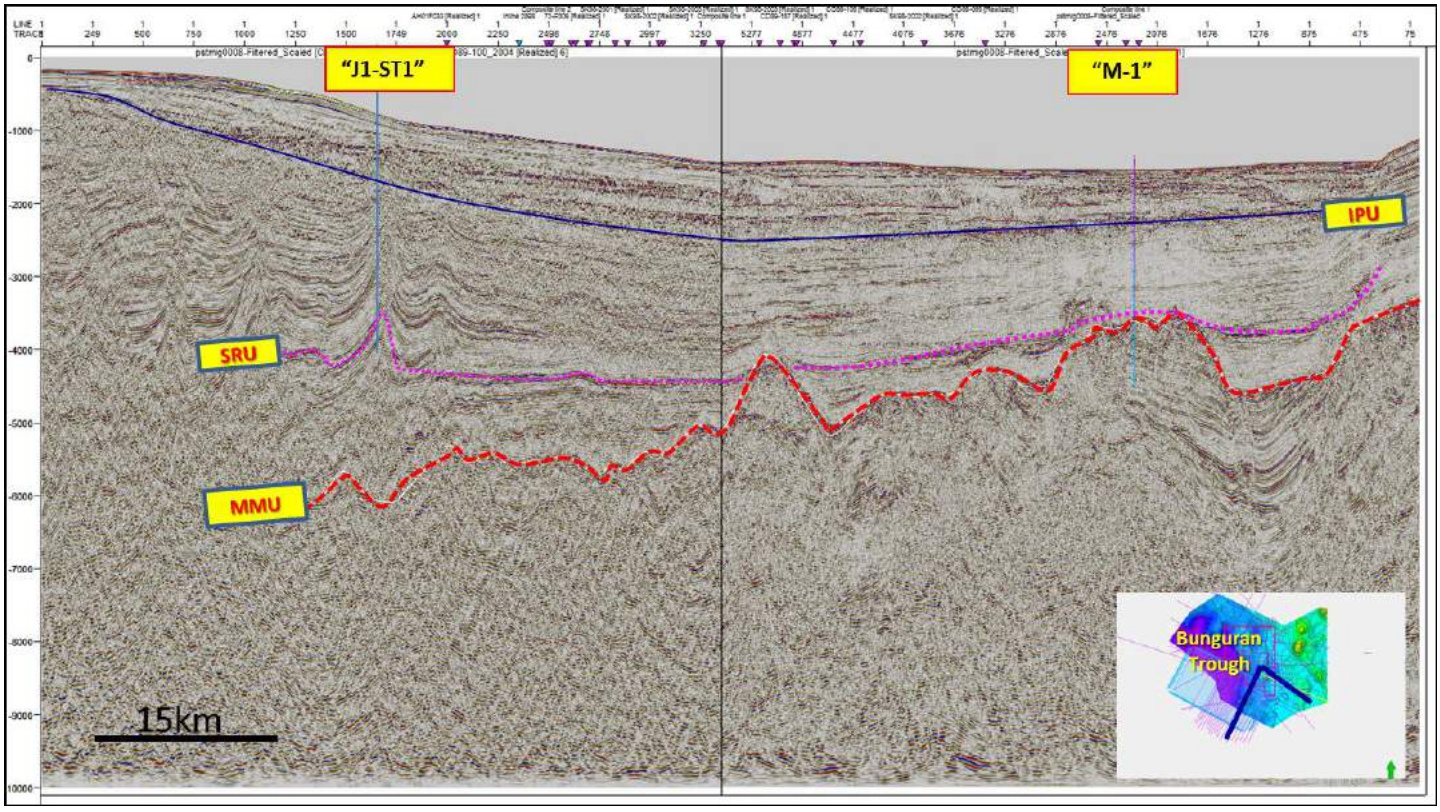


Figure 6. *Composite seismic section from 'J-1ST1' to 'M-1' across the Bunguran Trough. MMU, marked by dashed red line is diachronous in nature with dashed pink line representing Top Cycle V (Late Miocene) and the dark-blue event a Pleistocene erosional event, with the section dominated by muddy lithology.*

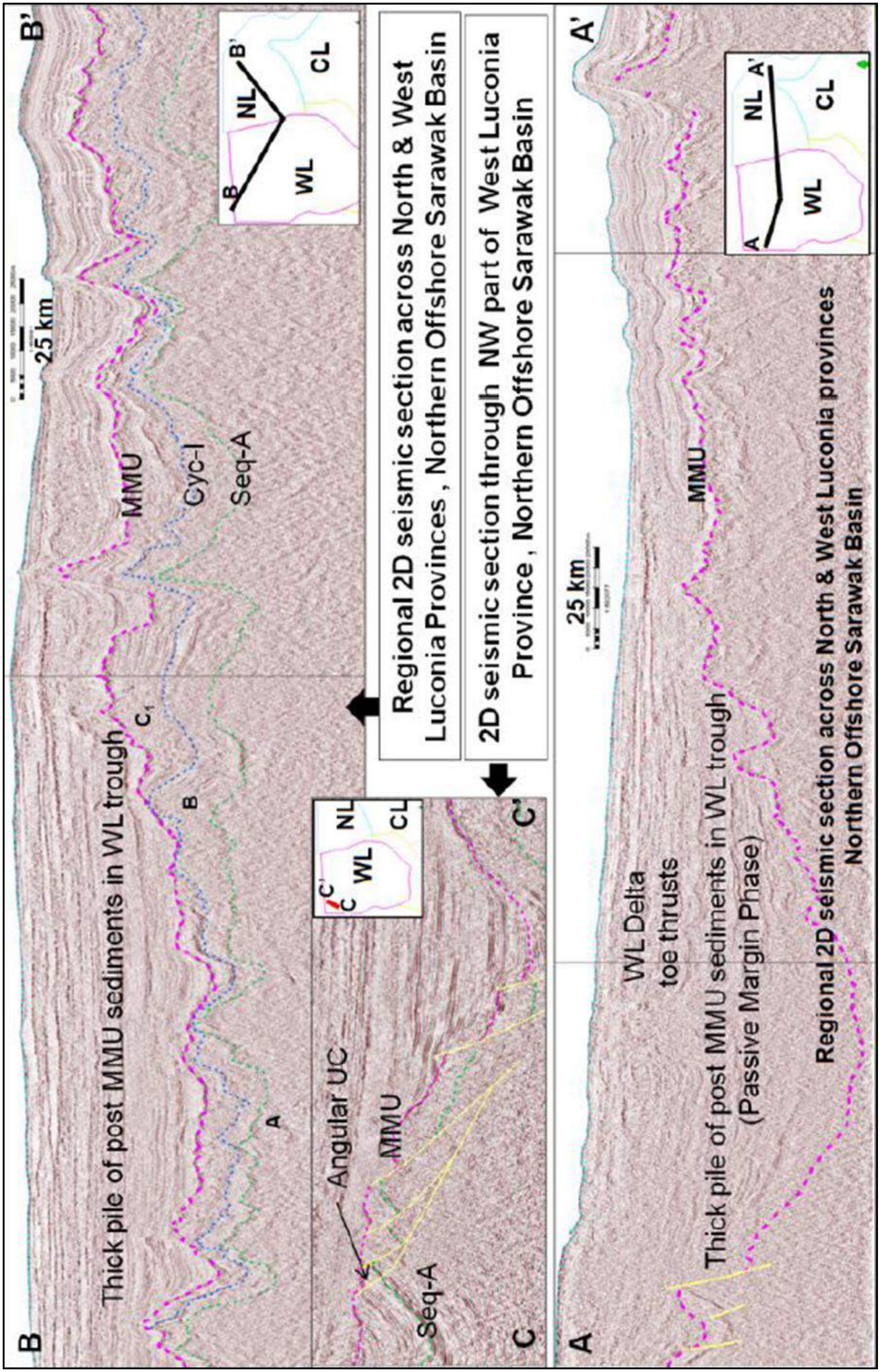


Figure 7. *Representative seismic profile across northern offshore Sarawak demonstrating the highly diachronous nature of the regional MMU. Missing section based on existing well data varies from 2 – 8.5 Ma (from south to north) but more well penetrations are essential to constraint the MMU time gap. CL=Central Luconia, WL=West Luconia and NL=North Luconia. (after Iyer, 2012). Post-MMU section is dominated by hemipelagics, interrupted by mass transport-dominated sequences.*

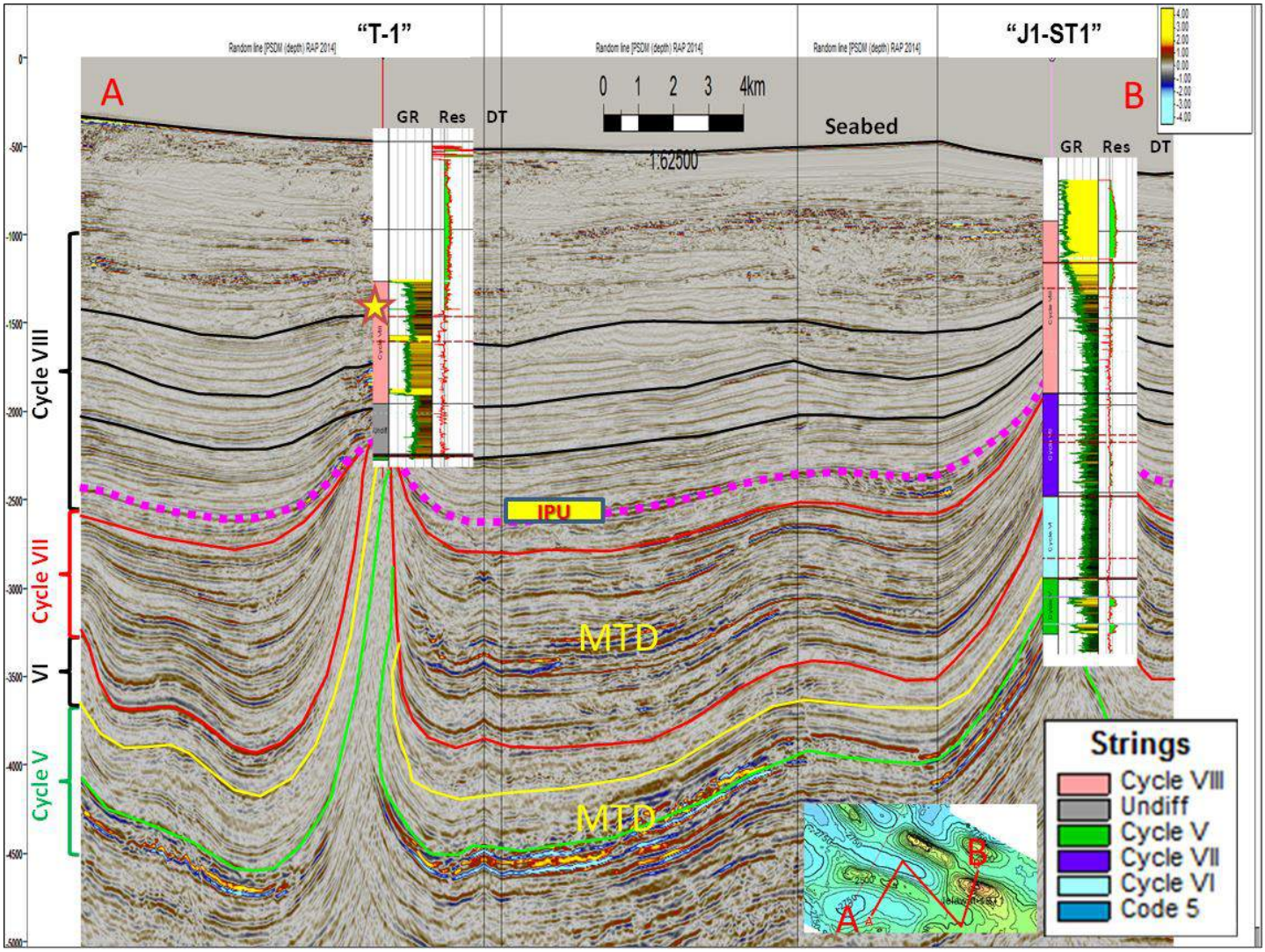


Figure 8. *Composite seismic section from 'T-1' to 'J-1ST1' across the Bunguran Trough. At 'T-1' well location an undifferentiated section at the base of the well TD was later dated as Upper Miocene Cycle V, whilst the overlying section is mainly Pleistocene Cycle VIII sequences. The dashed pink line is potentially the Intra-Pliocene unconformity (IPU) observed in this area.*

The second belt is formed by inverted, Late Mesozoic anchi-metamorphic flysch deposits that encompass the Rajang, Belaga and West Crocker Formations. Volcanics and granites have intruded this belt as illustrated in Figure 9. Mainly the first and second belts appear to have seen significant uplift (= denudation/erosion) and acted as potent sources of sediment for the NW Borneo Foredeep basin (van Hattum et al., 2013; Kessler & Jong, 2015a). The third belt is the Tinjar Block, formed by denudated Mesozoic cover and remnants of the Tertiary overburden. The fourth belt is located mainly in Sarawak and is formed by both folded and unfolded Tertiary molasse. In general, rocks on the surface are getting younger from south to north. The northernmost belt is formed by unfolded, folded and inverted molasse of Neogene age, which extends into the much thicker trough called the NW Borneo Foredeep. The Balingian Province is characterised by a complex structuration dominated by transpressive movements and by essentially clastic deposition. East Balingian is an area of strong Late Miocene to Pliocene wrench related deformation, inversion tectonism and uplift which resulted in significant erosion of the younger sequences (Figures 10 & 11). Inversion features of the Baram Delta and offshore Brunei are relatively recent compressional features (Figures 12 & 13). Across the border on the Sabah Shelf, a compressive regime is also evident with mud volcanoes and diapiric mud intrusions occurring along a suture, where a partly inverted basin flank is seen colliding with the Sabah Orogeny thrust front (Figures 14 & 15). The suture appears to have a multi-phase history dominated by strike-slip movements.

Due to the paucity of deep well penetrations, there is little knowledge regarding the oldest chapter of basin development. The few available data are suggestive for the presence of basin development in the Eocene, but it cannot be assessed whether this was caused by either conventional rifting or transpressional tectonics. Nonetheless, NW Borneo Margin represents a type area where the key regional unconformity discussed in the studied area are recognized and established (e.g. Figures 11 & 14).

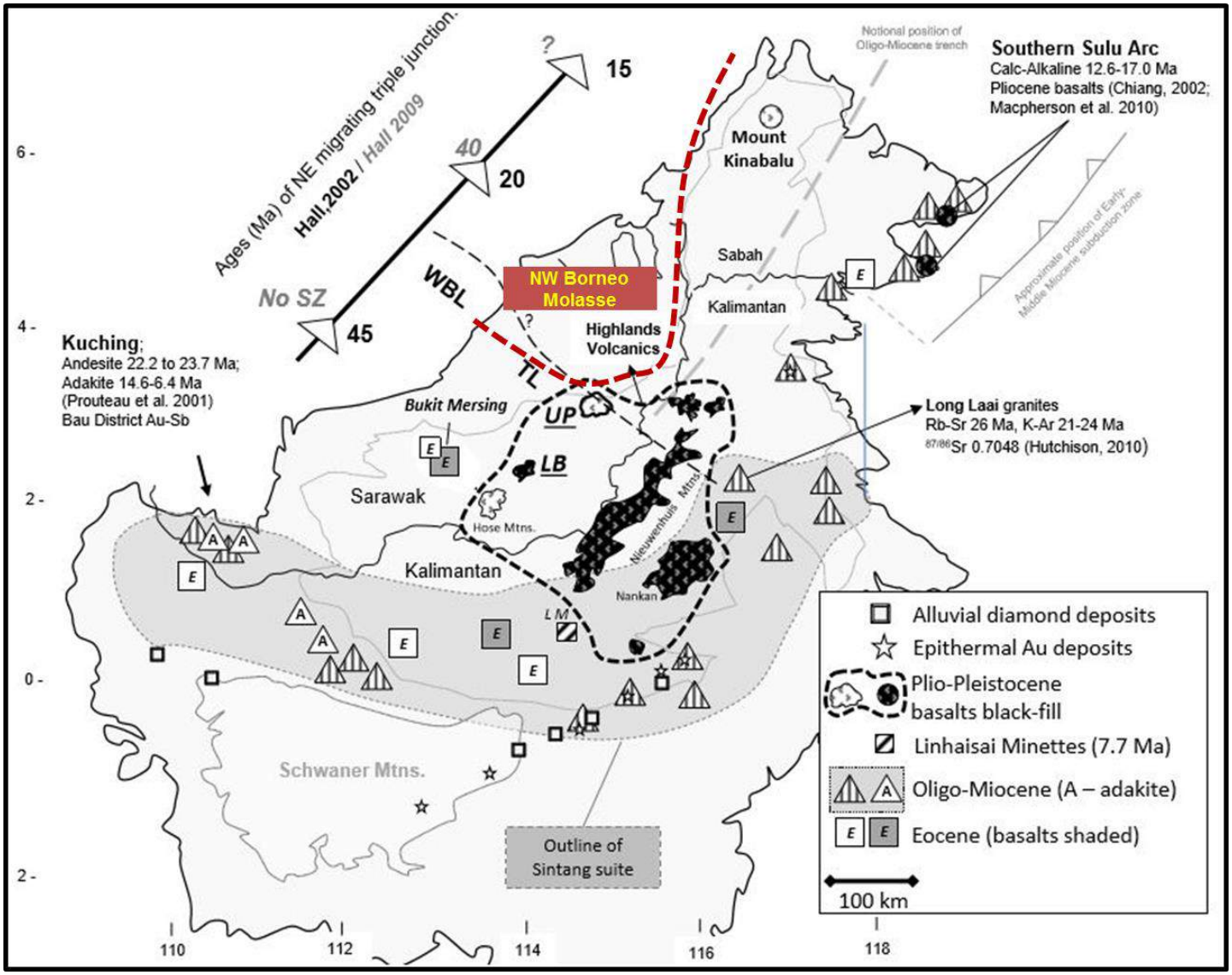


Figure 9. *Map showing distribution and age of Cenozoic igneous rocks in relation to tectonic elements discussed in Cullen et al. (2013). Open triangles show the different ages of position of subduction tip line in the different tectonic reconstructions of Hall (2002, 2009), with the distribution of NW Borneo molasse as indicated. Modified after Cullen et al., 2013. The Sundaland Plate boundary is suspected to be located south from the (in red) boundary of the molasse near to the Sarawak/ Kalimantan border.*

The Sabah Inboard area has been studied extensively by various authors with Levell (1987) first documenting the nature and significance of the regional unconformities, such as the Deep Regional Unconformity (DRU) and SRU, which were later dated and correlated by Shell across the NW Borneo Margin incorporating sequence stratigraphic principles (Figure 16). NW Borneo Foredeep extends in a northeast direction from the West Baram Line towards Sabah and Palawan. On the landward side, the foredeep is welded against the Crocker Block, a strongly folded terrane of Upper Cretaceous to Lower Tertiary age formed by metamorphosed deepwater sediments. The western and deepwater part of the foredeep is filled mainly by Mid-Miocene to Pliocene sediments. GPS measurements indicate that NW Borneo Margin is a tectonically active setting with ~4 cm yr^{-1} NW-SE convergence with related compressional stress affecting the area (Rangin et al., 1999).

AFTA data produced by Swauger et al. (2000) from samples collected from a 10-day field collection expedition across Sabah in 1994 indicate strong uplift of the rocks of the Western Cordillera (Crocker and Trusmadi Formations), suggesting the rocks have been buried beneath 4-8 km of overburden and exhumed and cooled in the Upper Miocene. The AFTA data suggest extremely rapid exhumation rates for the rocks of the Western Cordillera of *ca.* 0.5-0.7 mm y^{-1}. Such values are comparable to well-known collisional mountain belts (Hutchison, 2004). Recent publications by Kessler & Jong (2014, 2015a) and Jong et al. (2016) proved inversion and uplift in the molasse basin, and summarized evidence for uplift which continued into the Holocene in some areas such as Miri.

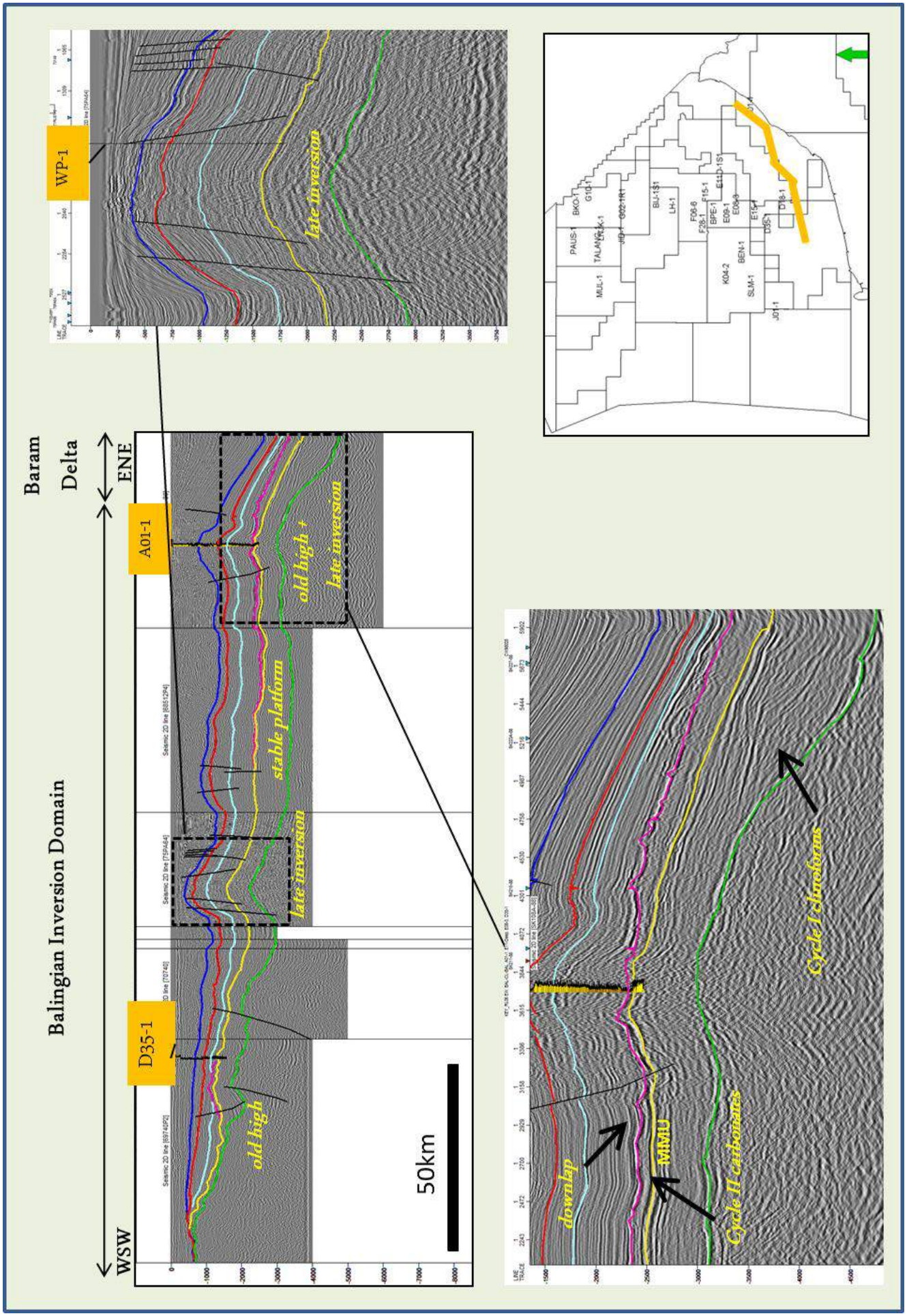


Figure 10. *Balingian Province to Baram Delta with inversion created broad anticlines that continued into the Pliocene with general thickening and deepening to the east. The MMU is approximately at Top Cycle II represented by a yellow horizon.*

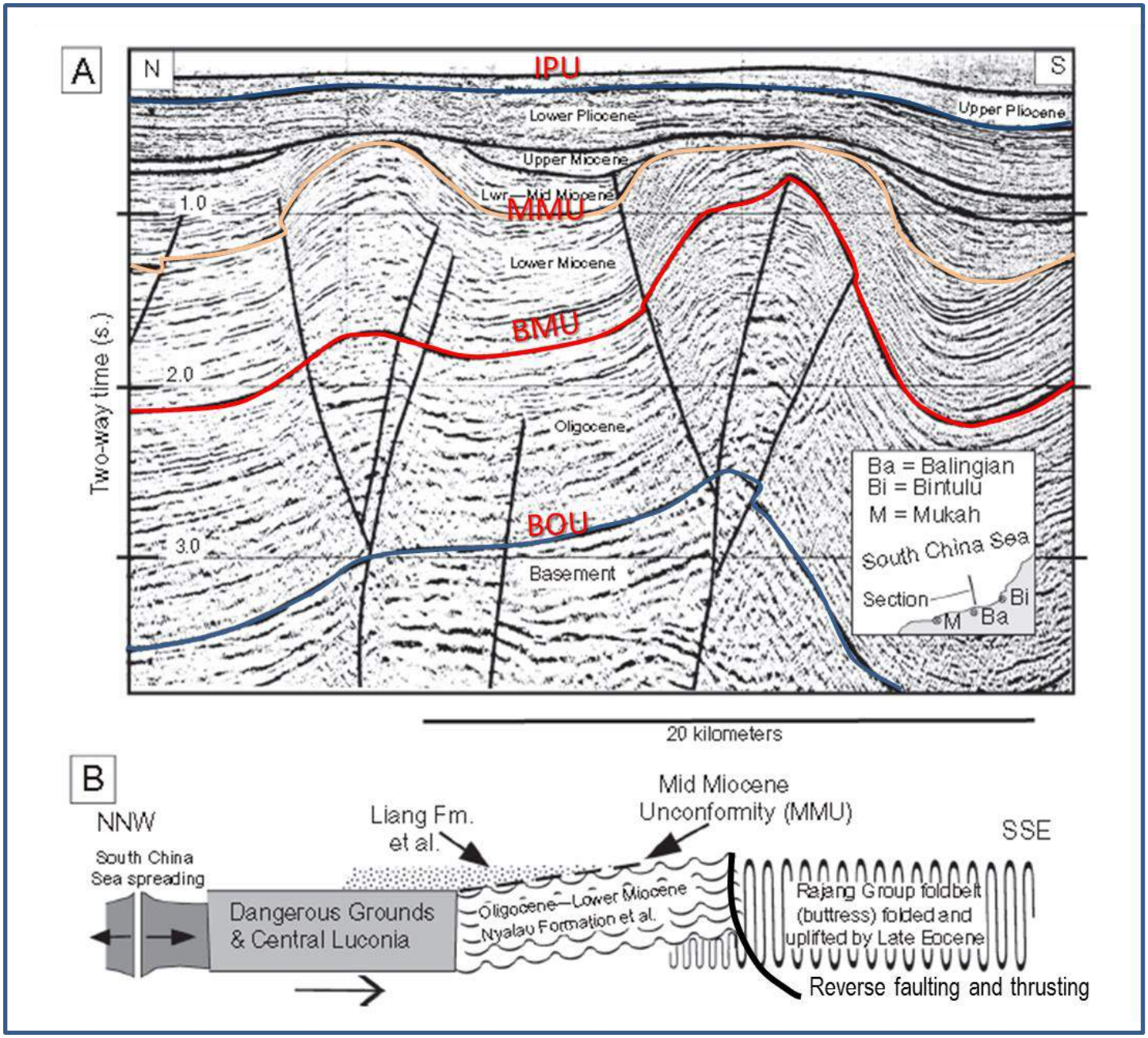


Figure 11. *(A) Seismic section immediately south of Central Luconia, showing the tightly compressed and eroded anticlines as a product of the Mid-Miocene Unconformity (Mat Zin & Tucker, 1999). The thrust-up and eroded anticlines have been commonly mistaken for horsts (Hutchison, 2005). (B) The cartoon suggests the cause of folding within the Balingian, Central Luconia and Miri Zones, and could point to the location of the Sundaland Plate Margin located beneath the Rajang thrust belt. Modified after Hutchison & Vijayan (2010).*

The Philippines/Palawan Margin

The Philippine archipelago is composed of fragments of the Eurasian margin, which have been rifted away from mainland Eurasia (Pubellier et al., 2005; Pubellier & Morley, 2014), and a large volcanic belt, referred to as the Philippine Arc, whose history is linked to that of the Philippine Plate. The juxtaposition of the Philippine Arc against the margin occurred during the Late Neogene but in detail varies from north to south. The tectonic features of the collision include strike-slip faults and thrust tectonics. The post-collision setting involves two subduction zones of opposite polarity which define between them a varied assemblage of continental, older volcanic and oceanic crust fragments upon which the active volcanic arcs are built. The southern Philippines Margin of Palawan Trough is the northward extension of NW Borneo Foredeep.

Figure 17 shows a regional traverse across the southern Philippines/Palawan Margin with development of rift graben and carbonate growth, the latter is tilted southeastward indicating uplift of the Palawan Island. Figure 18 illustrates the elements of Palawan subduction system with interpreted occurrence of MMU.

The fission-track data from the Island of Luzon point to a wide range of uplift events; ranging from Eocene to Holocene cooling ages (Yang et al., 1995).

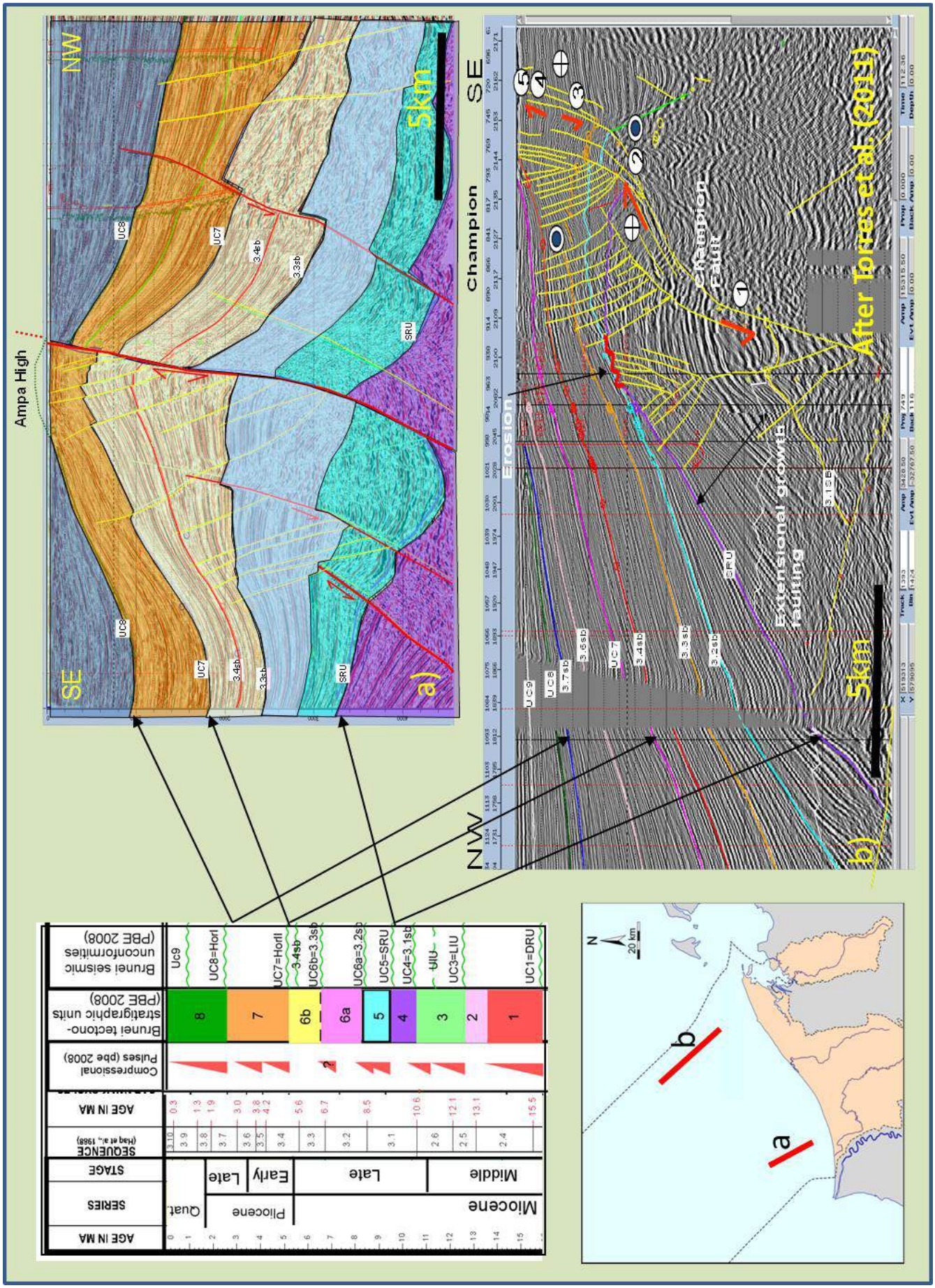


***Figure 12**. Late inversion features on Brunei Shelf, a) Ampa Structure and b) Champion Structure. Both features are heavily compartmentalised. Torres et al. (2011) mapped a number of erosional events (UC1=DRU=MMU to UC9) and commented on the significant impact of tectonic uplift on creation of regional unconformities.*

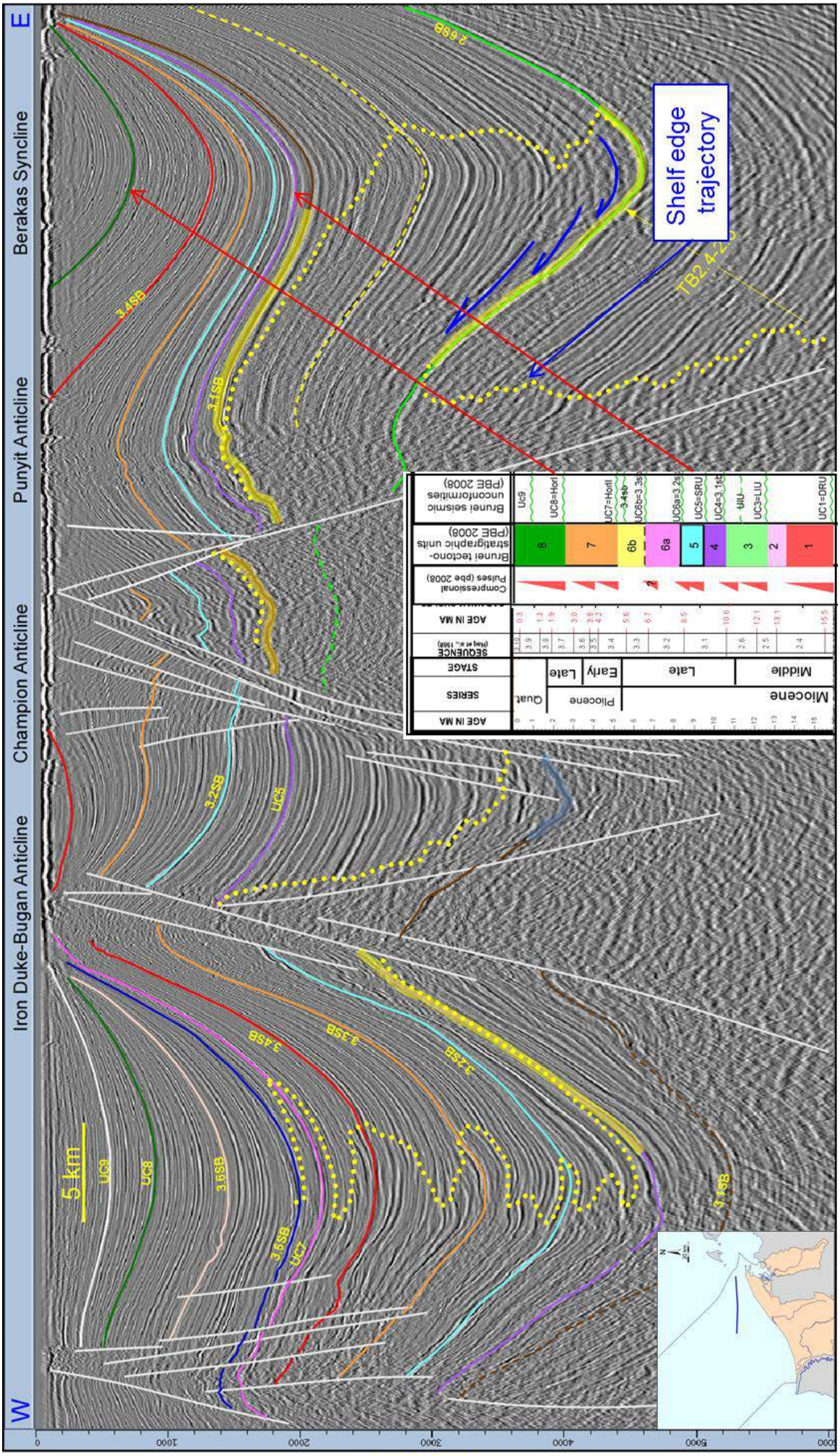


Figure 13. *Regional 2D section trending W-E illustrating the older Champion Delta sequences that can be currently seen in eastern inboard sector of Brunei. The change in the shelf edge trajectory of 2.6SB event is related to an inversion event that locked the Jerudong counter-regional fault, and inverted that depocentre and formed the current Punyit-Champion Anticline (after Torres et al., 2011).*

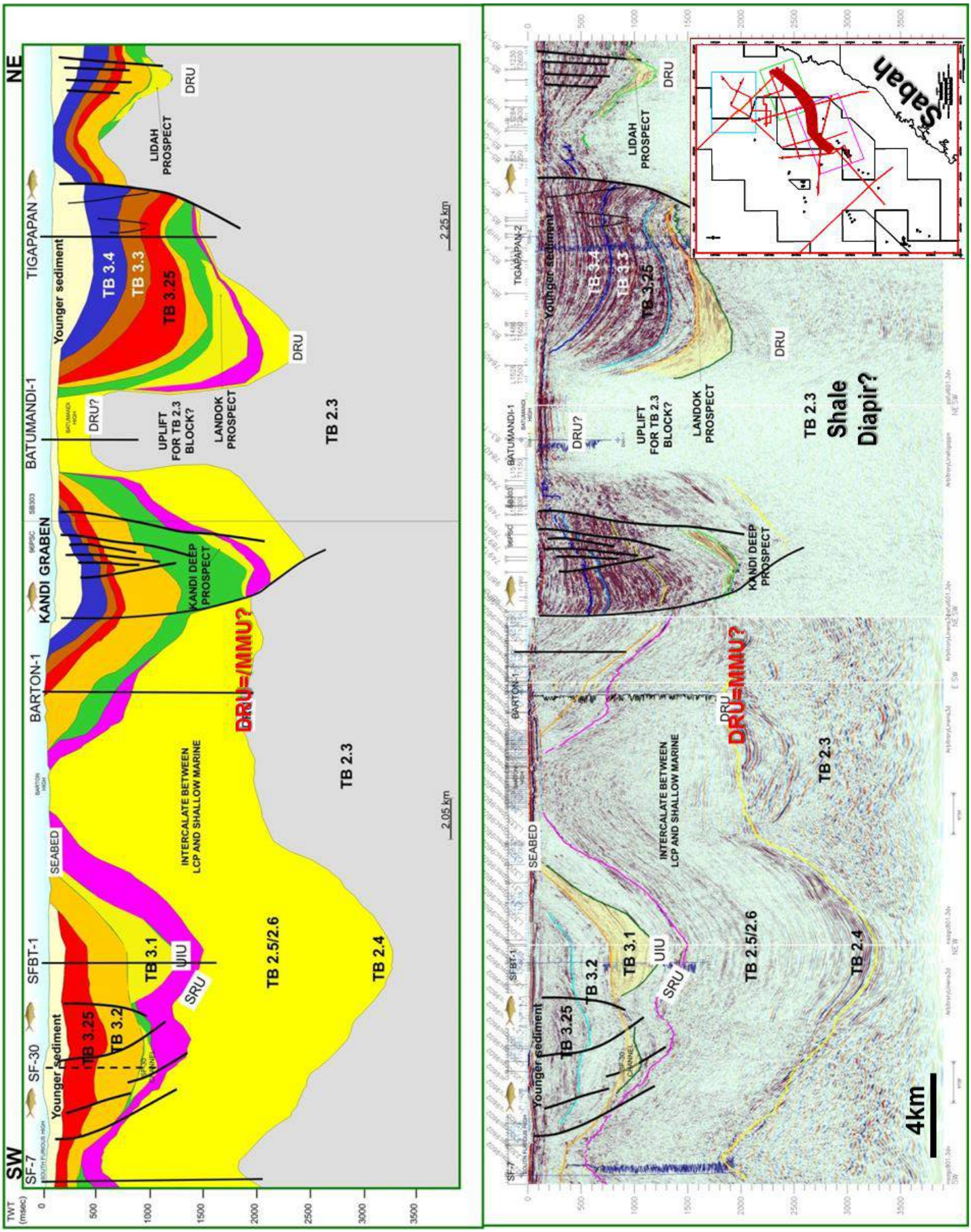


Figure 14. *Regional composite 2D seismic line with mapped TB sequences from Sabah Inboard area showing areas of tremendous uplift, exhumation and amalgamated unconformities with development of mini-basins between ridges. The above shown DRU might correspond to the MMU.*

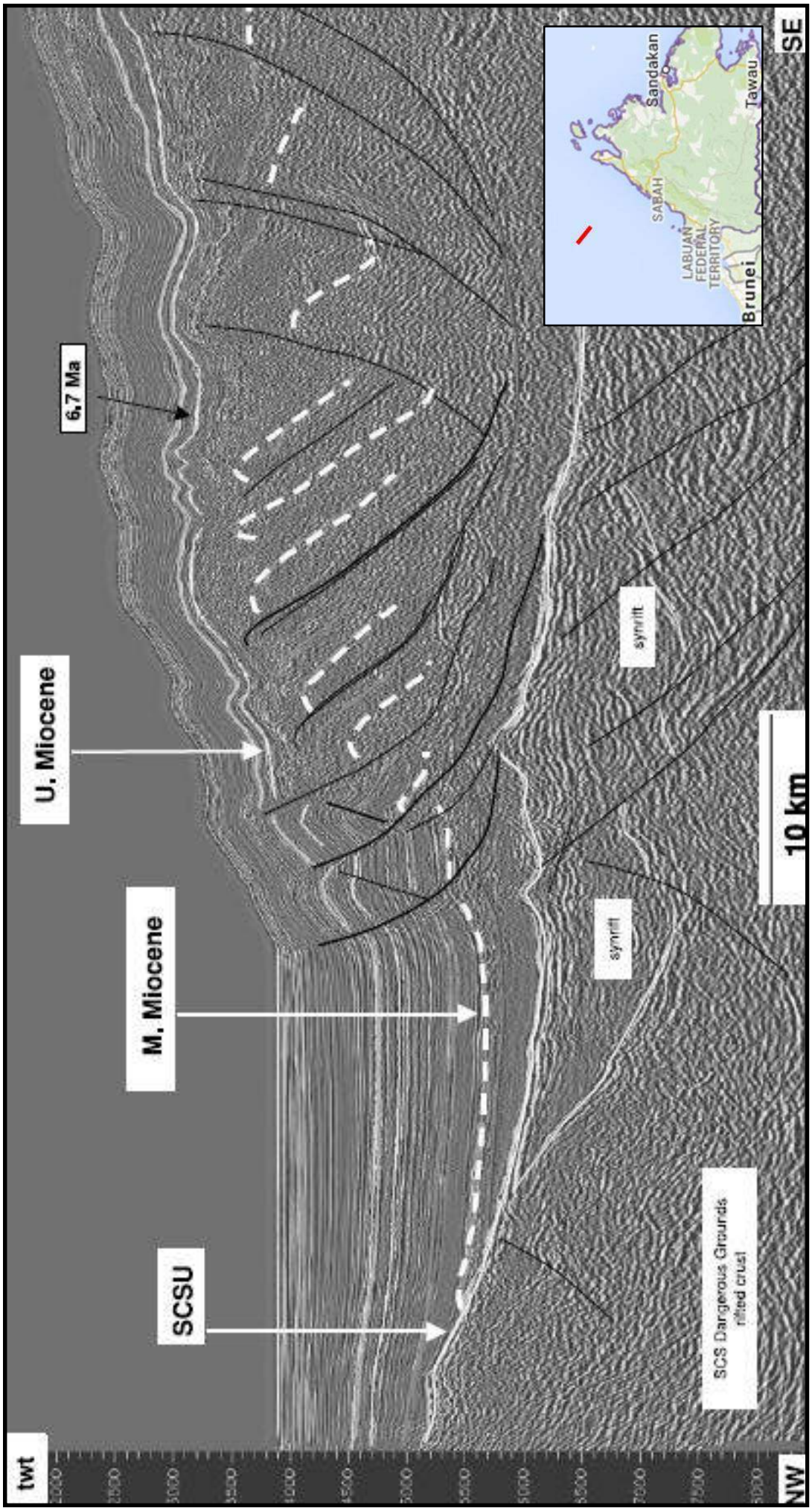


Figure 15. *Regional 2D seismic line for the Miocene allochthon structural domain in deepwater Sabah with SCSU (white line) illustrated (after Cullen, 2010). The SCSU may be synonymous here with the EMU.*

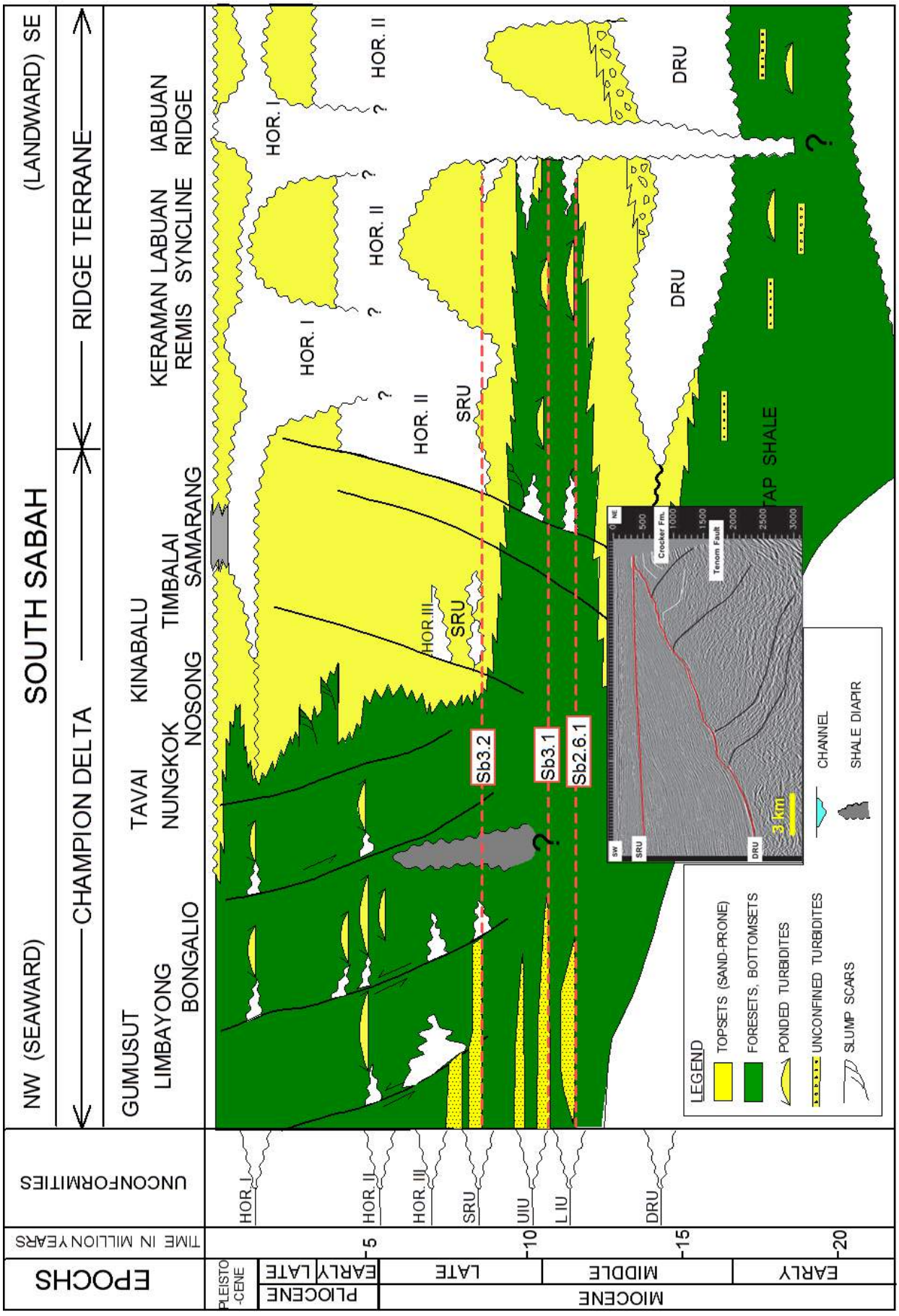


Figure 16. *Shell's lithostratigraphic scheme of Brunei and Sabah Inboard where Levell's (1987) unconformity nomenclature was established. It relies heavily on biostratigraphic age interpretation in old exploration wells, that can be often erroneous. Inset seismic example shows the DRU, an angular, erosional unconformity which separates the Late Eocene to Early Miocene deepwater sediments from the early Middle Miocene shallow marine clastics (Levell, 1987). However, age-dating for DRU remains questionable and the scheme shown here is likely placed too shallow and may correspond to the MMU as calibrated in Sarawak (see Jong et al., 2016).*

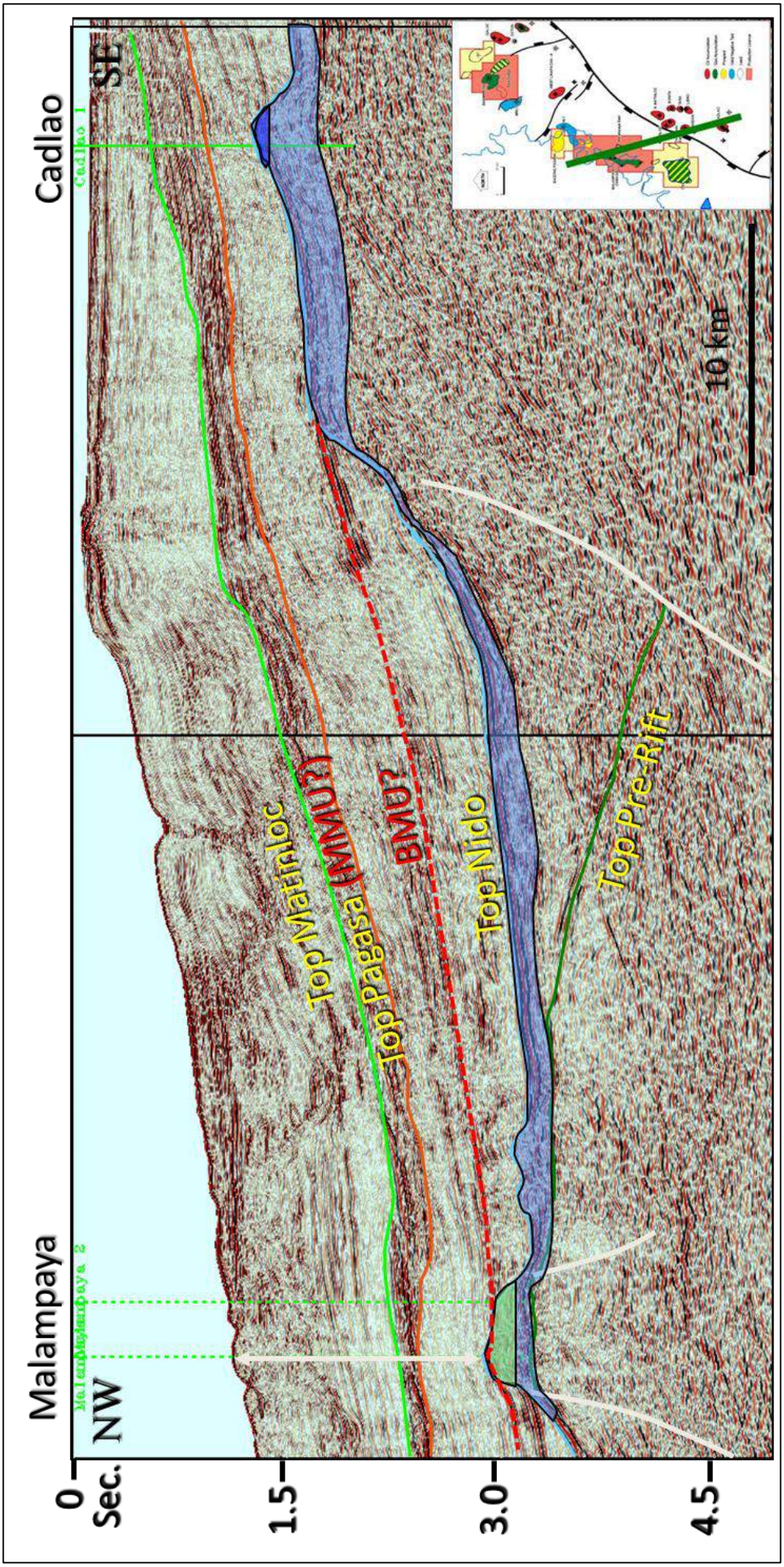


Figure 17. *Regional traverse across the southern Philippines/Palawan Margin with rift graben and carbonate growth (Nido Limestone), tilted southeastward indicating uplift of the Palawan Island. Dash red line is likely equivalent of BMU horizon, whilst Top Pagasa equates to MMU(?) that extend westwards to the Dangerous Grounds. According to Steuer et al. (2014) the Nido carbonates were established in the Early Oligocene. They were deposited after the BOU.*

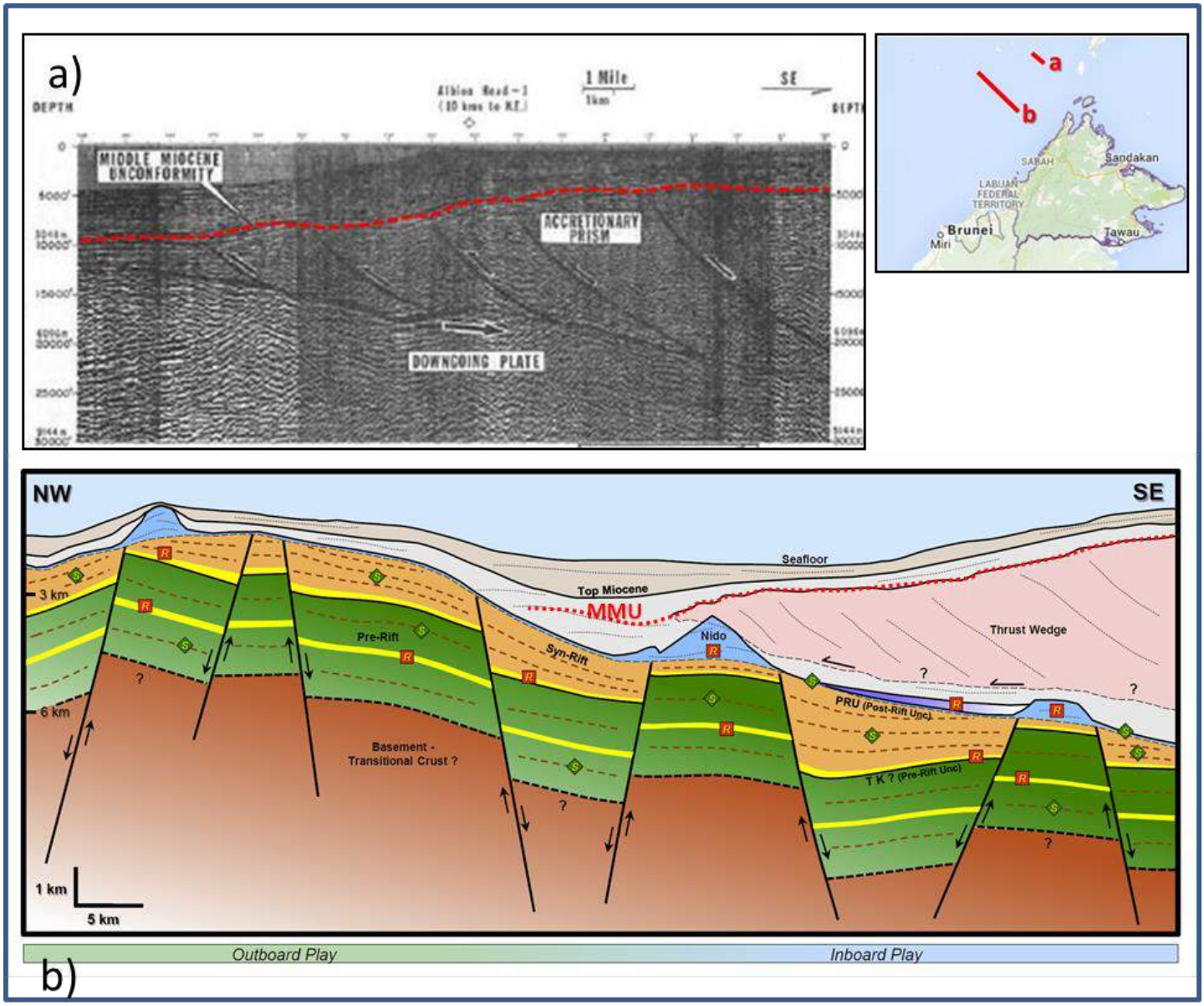


Figure 18. *a) Elements of Palawan subduction system with MMU indicated (modified after Holloway, 1981). b) BHPB's play diagram located along the same trend further south in deepwater Sabah with potential MMU event illustrated. However, recent work by Cullen (2010, 2014) has placed the event within the thrust wedge/ accretionary prism (see Figure 15).*

Based on the study of uplifted Holocene marine terraces in Pangasinan Province, westernmost Luzon Island, by Ramos & Tatsumi (2010); the authors estimated a maximum uplift rate of 1.7 mm yr^{-1}, which is almost the same as the Late Pleistocene uplift rate of 1.3 mm yr^{-1}. Overall, there appears to be uncertainty of this margin in respect of the uplift history, as few fission-track results are reported.

The Central SCS: Dangerous Grounds

This area has seen particular strong crustal stretching, with oceanic crust developed in its centre and flanked by remnants of continental crusts known as the Dangerous Grounds. According to seismic and sea-bottom sampling data published by Hinz & Schluter (1985), the Dangerous Grounds and possibly also parts of the Palawan Trough are underlain by a moderately stretched crust of continental origin. Hutchison (2004, Figure 19), Hutchison et al. (2000), Hutchison & Vijayan (2010) and Cullen (2014, Figure 20) interpreted the suture between the Dangerous Grounds and North Borneo Palawan Block as passing through the central part of Sabah. Mesozoic granitic rocks have been dredged from fault scarps on the Dangerous Grounds (Kudrass et al., 1986; Yan et al., 2010). Zircons from the Late Miocene Mt. Kinabalu Pluton with inherited Late Cretaceous and older cores (Cottam et al., 2013b) are strong evidence that Dangerous Grounds basement extended to the suture proposed by Hutchison et al. (2000). Although the North Borneo Palawan Block has an oceanic character marked by exposures of Lower Cretaceous ophiolites, the nature of the basement supporting the Sabah and South Palawan ophiolites is unclear. Several lines of evidence suggest this basement is of a continental affinity; Jurassic to Triassic age granitoids crop out in small windows beneath the ophiolites (Hutchison, 2005).

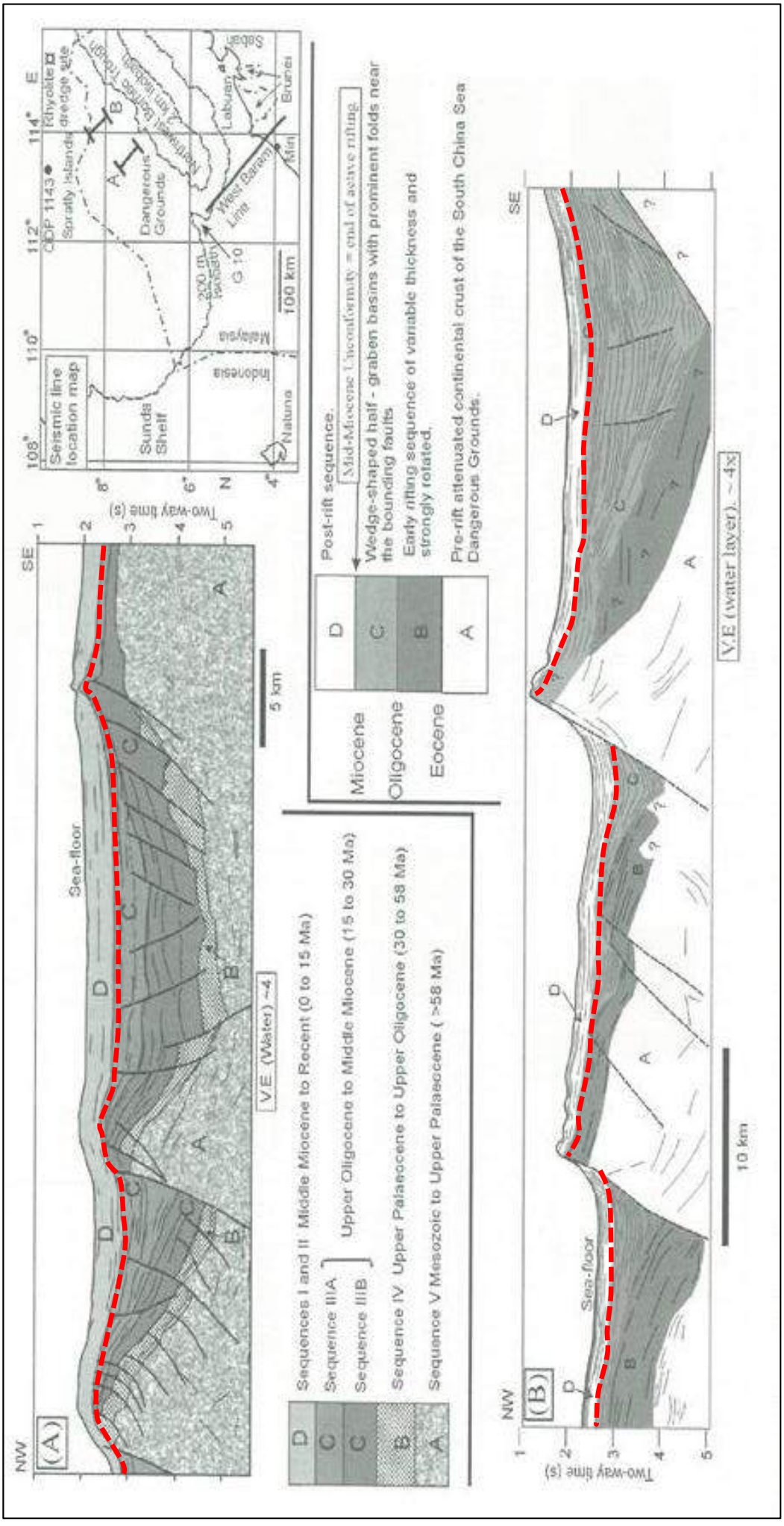


Figure 19. *Interpretation of seismic line in eastern Dangerous Grounds near the Spratly Islands presented by Hutchison (2004). The post-MMU (dash red line) drape is thin and placed it significantly shallower than the SCSU interpretation by Cullen (2010). However, in view of the well results from recent drilling campaigns testing the pre-MMU play, the interpretation by Cullen (2014) seems more viable.*

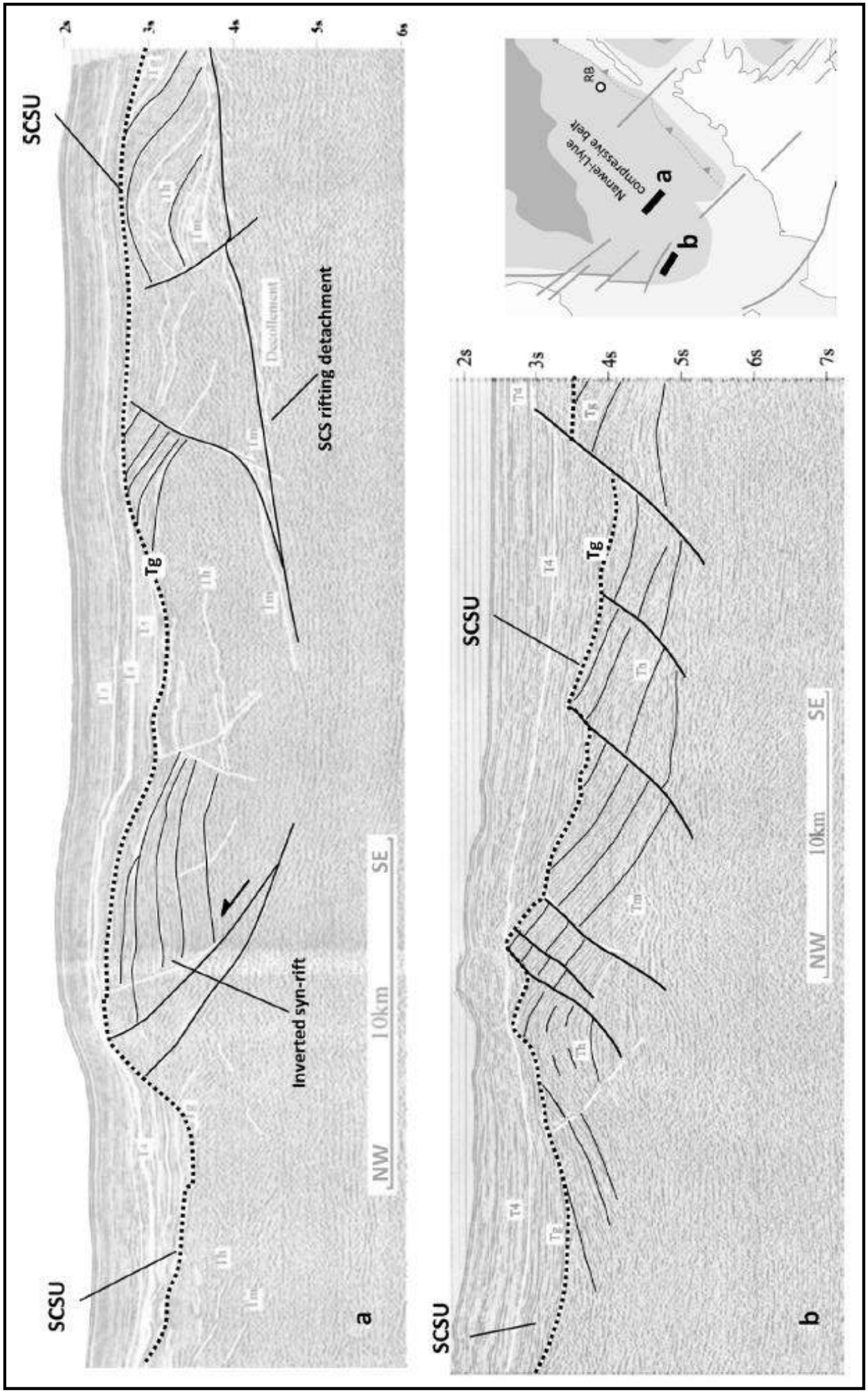


Figure 20. *a and b) Seismic lines from Yan et al. (2004) reinterpreted by Cullen (2014) to show folded rift succession beneath SCSU = MMU(?) (Horizon Tg). c) shows line locations.*

The key regional unconformity established here is the MMU, which coincides with the end of seafloor spreading in the SCS and has been termed differently by various researchers (e.g., Red Unconformity, Hinz & Schlüter, 1985; MMU, Hutchison, 2005; South China Sea Unconformity - SCSU, Cullen, 2010). Whilst the older BMU, which often marks the top of a carbonate platform in the SCS (Hinz & Schlüter, 1985) is present and interpretable within the half graben areas, its regional correlation over structural highs remain a challenging task. However, we are currently not aware of any published AFTA data from this region.

Taiwan Island

Figure 21c shows schematic diagrams summarizing the evolution model of active continental subduction in Taiwan, whilst crustal exhumation is presented in Profiles 1–4 from south to north. Profile 1 that cuts through the Manila Trench shows a typical subduction of the oceanic crust. Profile 2 shows the subduction of the continental margin and failure in the front of the subducting crust. Also the overlying oceanic crust beneath the forearc basin is initially deformed. Profile 3 cutting through southern Taiwan shows exhumation in the Eastern Central Range originally resulting from buoyancy, and the strong deformation of both the exhuming and overlying crusts. Profile 4 cutting through central Taiwan shows the acceleration of exhumation in the Eastern Central Range owing to the combination of both rapid erosion and buoyancy (Lin, 2002). In this case, areas of uplift, denudation and erosion can be distinguished; these three processes are summarized in Figure 22.

Of all the mentioned areas around the SCS, Taiwan has a history of very strong crustal uplift, and there is a wealth of high quality fission-track data published. According to Lin (2002), uplift rates recorded in Taiwan Island are much higher than average. A study of zircon fission-track ages of rocks in the Eastern Central Range by Tsao (1996) suggested that the rate of uplift increased from 7 to 16 mm yr^{-1} over the past 1.5 My. Furthermore, GPS levelling measurements showed rates of uplift of 36–42 mm yr^{-1} in the Eastern Central Range over the past decade. Thus, it seems that uplift of much of the Eastern Central Range is recent and has accelerated over the past several million years. Uplift in Taiwan is ongoing, which is unique, as perhaps with the exception for parts of Borneo, most parts of the SCS is currently undergoing a period of quiescence and inactivity. Liu (1982) and Dadson et al. (2003) indicate that zones within Taiwan are contrasting by time and magnitude of uplift, illustrating a fine example of fast uplift and exhumation processes (Figure 21a).

Due to the lack of available seismic data, offshore areas surrounding Taiwan have not been assessed in this paper; therefore a link between the island's uplift and the unconformity fingerprint of adjacent offshore areas was not made.

SE China and Hainan Island

The Cenozoic Song Hong (Yinggehai Basin, Figure 23) in the SCS contains a large volume of sediment that points to the existence of a large paleo-drainage system that connected eastern Tibet with the SCS (Yan et al., 2011).

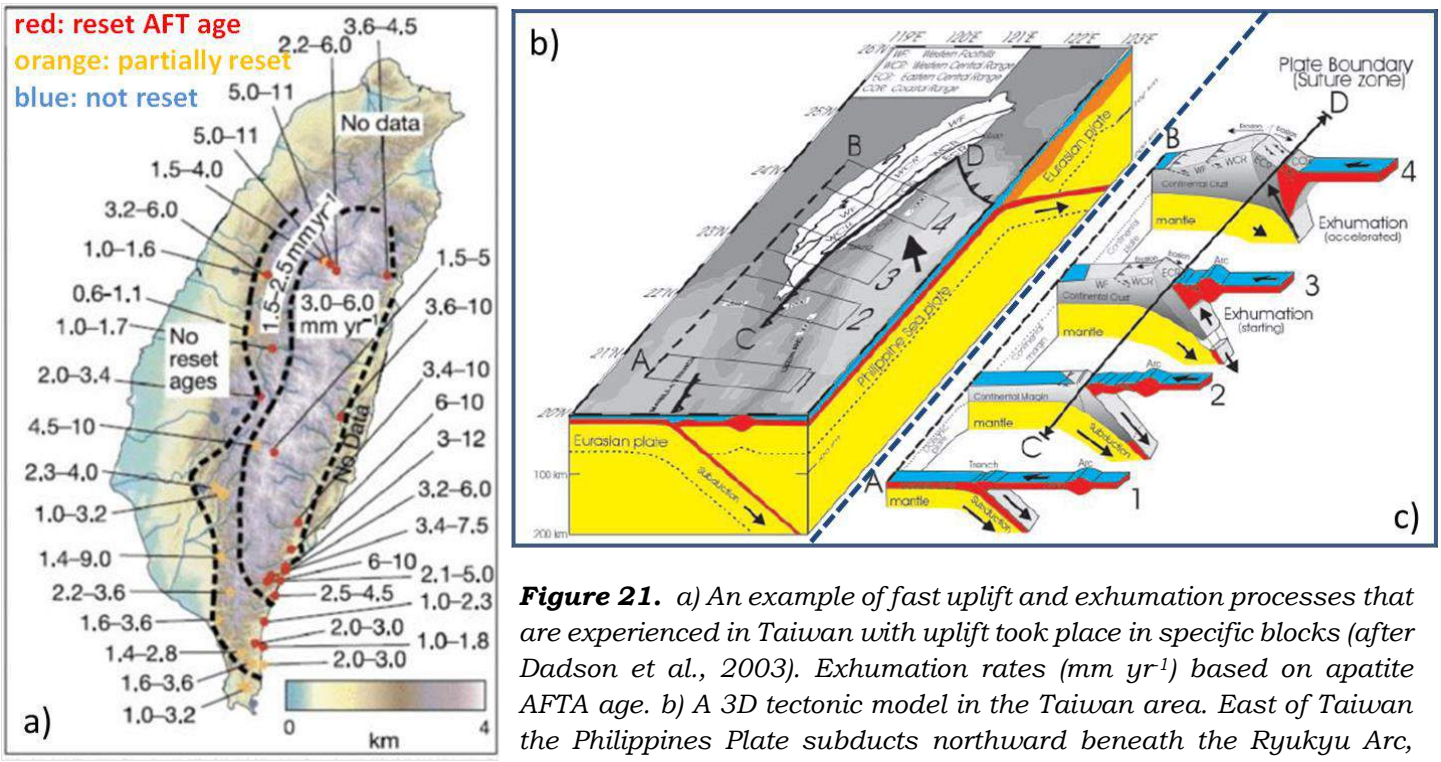


Figure 21. *a) An example of fast uplift and exhumation processes that are experienced in Taiwan with uplift took place in specific blocks (after Dadson et al., 2003). Exhumation rates (mm yr^{-1}) based on apatite AFTA age. b) A 3D tectonic model in the Taiwan area. East of Taiwan the Philippines Plate subducts northward beneath the Ryukyu Arc, Ryukyu Arc, while south of the island Eurasian Plate oceanic lithosphere beneath the SCS subducts to the east beneath the Philippines Plate. c) Schematic diagrams summarizing the evolution model of active continental subduction and crustal exhumation. b) and c) after Lin (2002).*

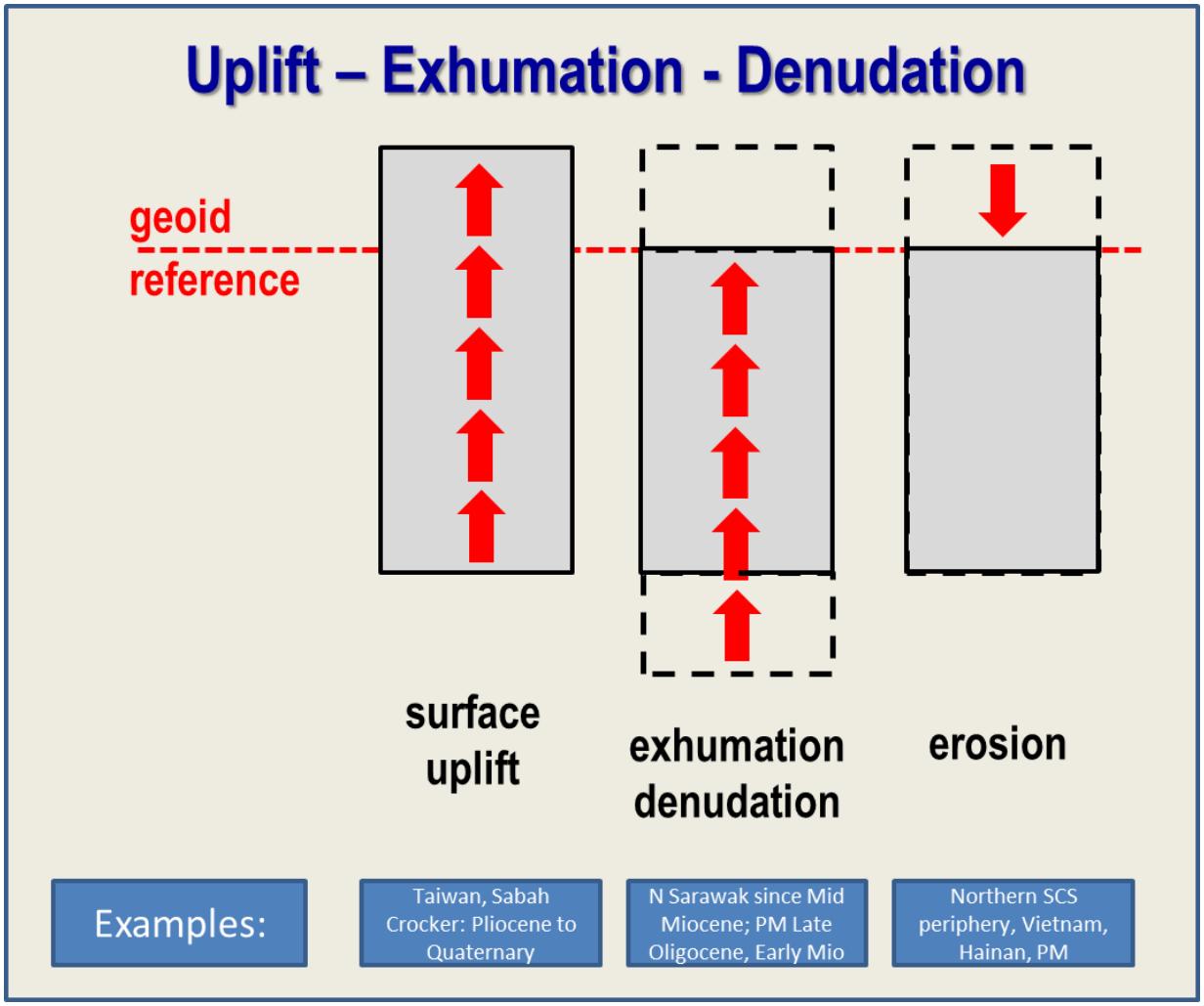


Figure 22. *Model for the context of uplift, exhumation and denudation (modified after England & Molnar, 1990). Active (recent) uplift can be demonstrated in areas of the southern SCS periphery (Kessler & Jong, 2015a) by anomalies of the geoid, and might by triggered by the monsoon.*

The study by Wang et al. (2014) revealed that the detritus was derived from multiple sources. Comparison of the results with the rock types and their ages surrounding the potential source areas indicates that the clastic material was derived from three dominant age sources: (1) Yangtze Craton, (2) Hainan Island and, (3) Indochina Block. The Yangtze Craton was recognized as a major and continuous source area contribution to the basin.

Uplift data show several pulses in distinct areas. The mentioned study compared erosion histories of source regions with sediment volumes deposited during the two main stages in basin evolution spanning active rifting and subsidence (30 – 15.5 Ma) and post-rift sedimentation (15.5 Ma to present-day). Whilst there is a wealth of fission-track data from the coastal hinterlands, authors differ in their respective interpretations when it comes to the question when rifting in this part of the SCS ended: ranging from 21 Ma in Qiongdongnan Basin (Xie et al., 2006) to 23 Ma in Beibuwan Basin, as assigned by Liu et al. (2014).

Detrital zircon U-Pb dating revealed that Hainan was an important and continuous source of sediment, and a bedrock thermo-chronological study quantified its overall contribution to basin sedimentation. The mass of basin sediment, calculated from AFTA across the modern Red River drainage in northern Vietnam, as well as from Hainan Island, accounted for the bulk of sediment deposited since 30 million years ago. In addition, AFTA data and (U–Th–Sm)/He ages presented by Shi et al. (2011) indicate that much of southern Hainan Island experienced a well-defined cooling episode commencing in Late Eocene – Oligocene time. Assuming a constant paleo-geothermal gradient of 2.3 °C/100m (similar to that of the present-day), since Oligocene time when most samples cooled into the base of the AFT partial annealing zone, the total eroded section is estimated at a minimum of ~ 3.5 km, about two-thirds of which was removed during the Oligocene rapid cooling phase. This implies that elevation of southern Hainan Island has decreased since the Oligocene.

During the compilation of data for this area of the SCS, we have not found sufficient data to assess the context of uplift and unconformities.

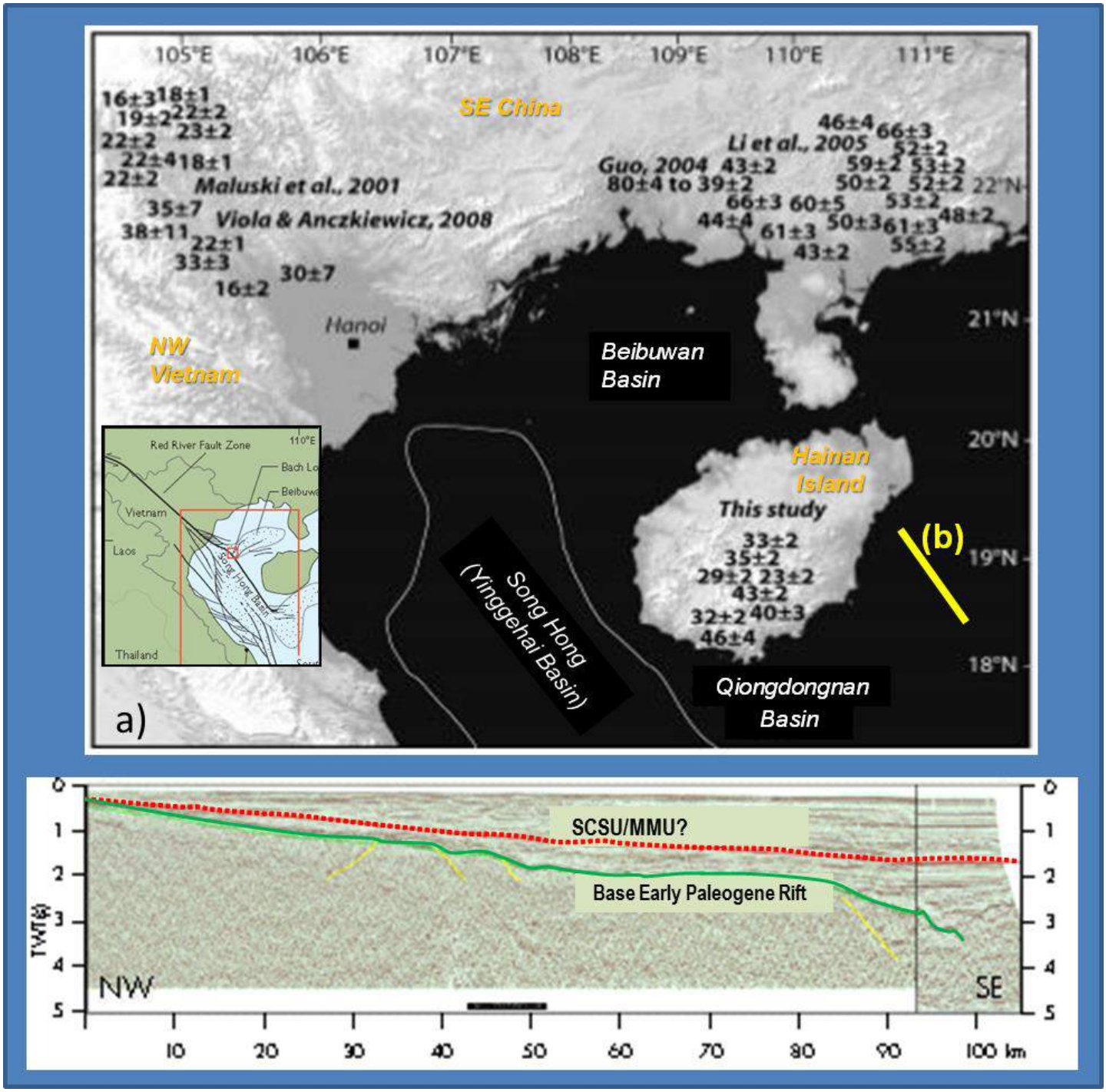


Figure 23. *a) Summary map of published AFTA data from Yang et al. (1995), Guo (2004), Li et al. (2005), Maluski et al. (2001) and Viola & Anczkiewicz (2008). The area of SE China and Hainan Island is dominated by data suggesting a Paleogene uplift, with the exception of a number of Miocene AFTA points inferred to portray uplift along the Red River Fault in NW Vietnam. b) Seismic profile runs from the continental shelf east of Hainan Island into the Qiongdongnan Basin. The interpreted SCSU/ MMU(?) in this profile is relatively shallow and sub-cropping towards the Hainan Island indicating significant uplift experienced in the area since the Eocene.*

The Vietnam Margin: Uplift and Depositional Evolution

The Vietnam continental shelf area lies above a system of Cenozoic sub-basins that lie within a transition zone from the continental crust of the Indochina Block to the sub-oceanic crust of the eastern deepwater basins. The basins developed here are rift basins with multiphase history as summarized by Fyhn et al. (2009b, 2012). The main regular sedimentation along Indochina margin were defined by the rate of subsidence and structure of the basement, location of large river systems of the SE Asia, eustatic sea-level changes and paleo-climate factors. The basins are characterised by high sedimentation rates, abrupt facies changes, abrupt thickening of sedimentary sequences over short ranges, numerous unconformities and scattered volcanic/extrusive activity. A very important source of sediment on the Vietnam Margin is the Song Chay Massif in the north-

easternmost metamorphic complex in Vietnam, to the east of the Red River Shear Zone.

Research by Maluski et al. (2001) shows a large antiformal structure involving orthogneisses and migmatites overlain by muscovite bearing marbles. Across the dome ages range from 236 Ma at the southern edge to 160 Ma in the core, attesting to a strong imprint in the Early Triassic time. A clear difference is seen between these Mesozoic ages and the Eocene to Miocene ages (from 40 to 24 Ma) that were obtained in the nearby Red River Shear Zone. These data show that the Song Chay Massif was already high in the crust when the high temperature deformation of the Red River Shear Zone took place. The final exhumation of the Song Chay orthogneiss constrained by fission-track analysis on samples along the same transect occurred during the Early Miocene and could be interpreted as the consequence of a first normal sense of motion along the fault which bounds the massif to the south. Timing is similar to that of exhumation in the Red River Shear Zone.

The **Song Hong Basin** (Figure 24), the largest Tertiary basin in the continental shelf of Vietnam, is classified as a pull-apart system (e.g., Leloup et al. 2001), with up to 15-20 km of Eocene to Quaternary sediment, evolving in several phases throughout Oligocene to Pliocene times (Fyhn et al., 2012). The onset of the basin's formation is related to the collision of the Indian sub-continent with Asia during the Late Eocene. Left lateral strike-slip and pull-apart along the Song Hong Fault Zone in which two main fault systems formed the eastern and western limits of its main depocentre controlled the shape of the basin. The Eocene-Oligocene marked the major rifting phase.

Analysis of the seismic sections from the Gulf of Tonkin shows several angular unconformities, beginning from pre-Cenozoic basement of Late Eocene (~ 38 - 37 Ma), to Early Oligocene (~ 32 Ma), Late Oligocene (25.2 Ma, approximately BMU), Middle Miocene (~15.5 Ma, see Figure 24c), Late Miocene (~10.5 Ma, approximately SRU) and top of Miocene (~5.5 Ma) (Phung et al., 2015). The strongest tectonic inversion took place in the Late Miocene. This inversion caused significant uplift and resulted in deep truncation of the deformed strata. This is the strongest tectonic event in this region in the Late Cenozoic and can be recognized clearly in the outcrops where Tertiary rocks are exposed. The Early to Middle Miocene was a quiescent marine sedimentation period.

The **Phu Khanh Basin** (Figure 25) is a frontier deepwater basin which lies on the central and southern Vietnamese continental margin. It shows characteristic rift structures, which belong to the transtensional system developed along the mega shear zone at the boundary between the relatively rigid Indochina Block and the more mobile spreading zone of the SCS. During the Mid-Miocene, a regional subsidence took place with a tilting towards the east that affected the entire basin, and a medium rate of subsidence was maintained. Two significant transpressional tectonic events took place during the Mid-Miocene, forming large-sized flower structures in the sedimentary succession and partial inversion of the basement blocks. During the Late Miocene - Quaternary, the tectonic activity was a rifting phase with high rate of subsidence. The deepening of the basin was accompanied by minor events of submarine erosion and non-deposition in the shelf areas. The final subsidence along the inherited fault zones at the shelf margin and a relatively low amplitude uplift of the western part of the inner shelf gave the basin its present-day aspect. Interpretation of the seismic and gravity data supports the existence of two main depocentres filled with multiphase syn-rift Paleogene - Neogene sediments (Choi & McArdle, 2015).

According to recent literature, summarized in Morley (2016), Clift et al. (2008) interpreted that the strong extension and structural inversion largely pre-date the 16 Ma unconformity. The authors called this event MMU, following Hutchison (2004) (Figure 25). C.-F. Li et al. (2014) and L. Li et al. (2014) present a more detailed interpretation that shows faulting stopping at the unconformity (see Figures 25b and c), with the Early Miocene section clearly involved with the faulting. Fyhn et al. (2009a, b) show the main termination of extension along the Vietnam Margin as being around the Lower Miocene – Oligocene boundary (i.e. 23 – 21Ma).

The **Cuu Long Basin** (Lee et al., 2001; Nguyen & Hung, 2003; Swiecicki & Maynard, 2009; Figure 26), a NE-SW trending extensional basin, is formed within the Sundaland Craton initiated in the Late Eocene.

In the first phase of extension, narrow grabens were created. During the Early Oligocene, a broader down-warping produced a shallow sag basin. The axial zone of the basin subsided rapidly again in the Late Oligocene. A regional unconformity at the end of the Oligocene (BMU) marked a period of uplift. During the earliest rifting phase (Paleocene or Eocene), narrow grabens subsided rapidly and were filled with great thickness of the non-marine clastics. During the Middle Miocene, a widespread marine incursion flooded the Cuu Long Basin, depositing the Rotalia mudstones, a thick shale section, which acts as a regional seal. The Upper Miocene and the overlying Pliocene - Quaternary sediments were deposited during transgressive/regressive cycles of the modern Cuu Long Delta. They appear to be controlled by changes in eustatic sea-level, rather than tectonic uplift.

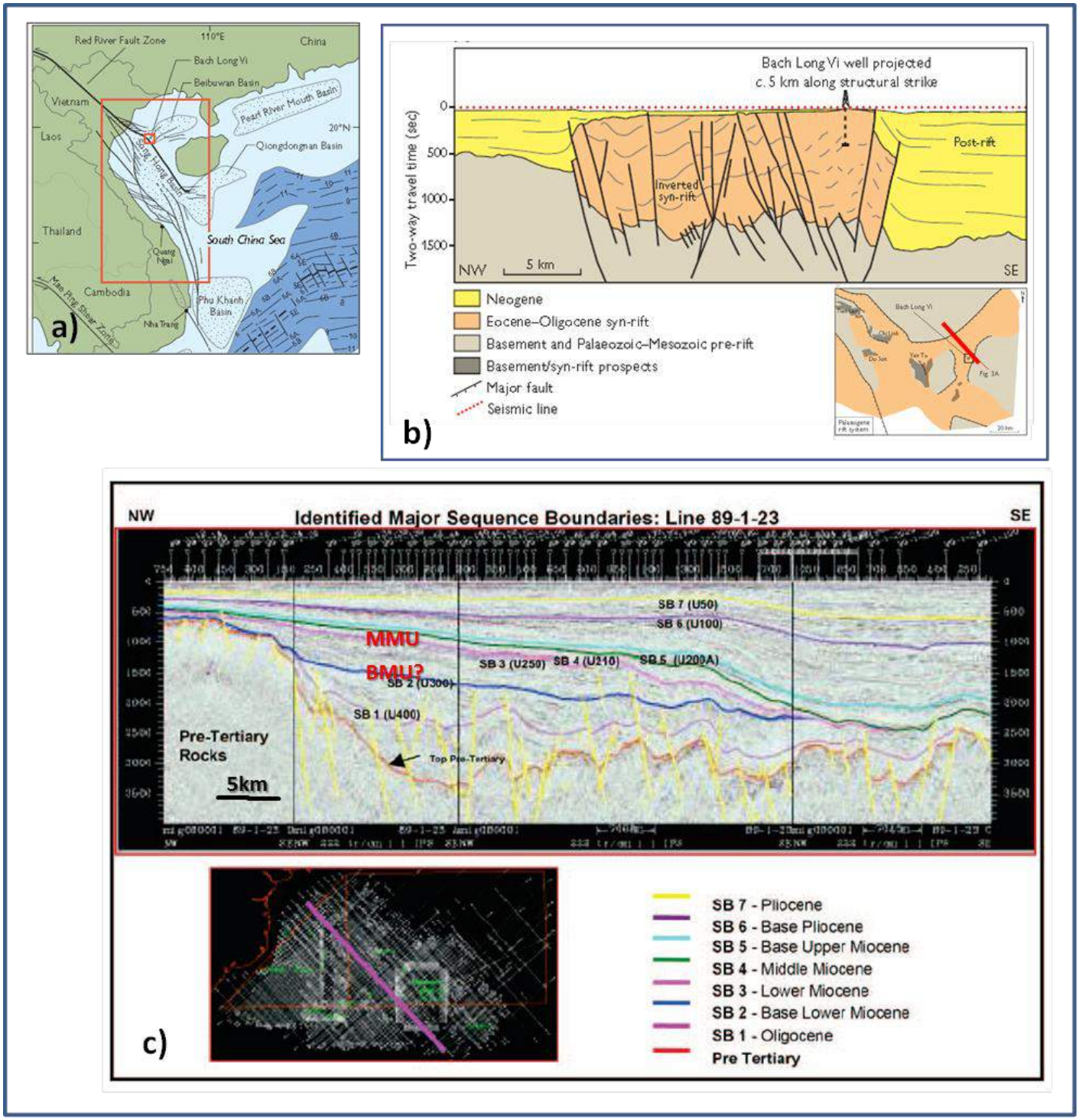


Figure 24. *a) Location Map of Song Hong Basin and NE extension Beibuwan Basin. b) Geotransect across the inverted Palaeogene graben, which is exposed on the island of Bach Long with Bach Long Vi a few kilometres from the profile. The approximate well trajectory is projected onto the section. c). Seismic section of Song Hong depocentre with SB4 equivalent to MMU and SB2 likely the Late Oligocene unconformity/ BMU mapped in the Phu Khanh Basin. a) and b) modified after Fyhn, et al., 2012, and c) after Unir & Mahmud, 2006.*

In a summary provided by Morley (2016), Swiecicki & Maynard (2009) placed the end of the rifting in the Cuu Long Basin at the Early Oligocene - Late Oligocene boundary 5 (i.e. around 28 Ma). The Tra Tan Formation is of Late Oligocene age, the lower part of the formation marks a period of post-rift subsidence, whilst inversion occurred during deposition of the upper part of the formation (Cuong & Warren, 2009; Swiecicki & Maynard, 2009). The entire Neogene section of the Cuu Long Basin belongs to the post-rift stage (Lee et al., 2001; Swiecicki & Maynard, 2009).

Development of the **Nam Con Son Basin** (Figure 27) situated at the intersection of two major tectonic systems related to the Indochina extrusion and SCS seafloor spreading, was initiated during the Paleogene (Lee et al., 2001; Fyhn et al., 2009b). During the Eocene - Oligocene, extension related to the early opening of the SCS resulted in the development of NE-SW-trending half grabens; the fill of these half grabens are continental.

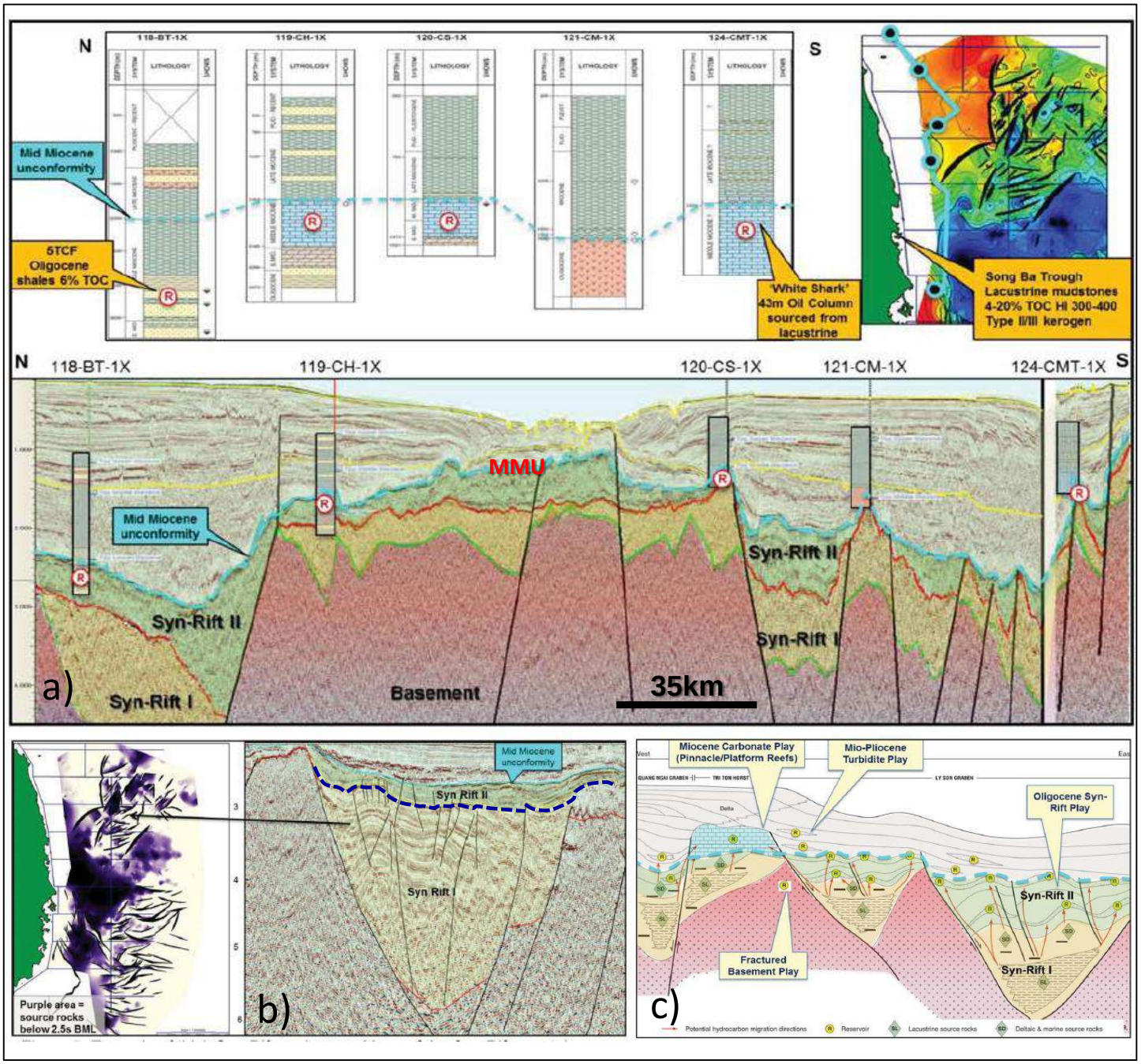


Figure 25. *a) Geo-seismic section going through several wells and highlighting the major stratigraphic units with mapped MMU (light blue horizon) illustrated across the Phu Khanh Basin, dashed dark-blue line = Late Oligocene Unconformity/ BMU. b) Syn-rift depocentre. c). Schematic summary of the play types of the Phu Khanh Basin. Modified after Choi & McArdle, 2015.*

Sag sequences became progressively non-marine upward and became more marine west to east, due to overall transgression and backstepping of deltas during the earliest Miocene. Rifting and by inference seafloor spreading continued until the end of Mid-Miocene time although at significantly reduced rates during the final 5 - 10 Ma.

Termination of seafloor spreading is marked by a distinct latest MMU in the Nam Con Son and the southern Phu Khanh Basins (Fyhn et al., 2009a). In the Late Miocene the basin was again tectonically restructured by a mild inversion, followed by thermal subsidence, resulting in large carbonate reefal buildups and infilled by sandy turbidites on the basin floor. The process was interrupted in the Early Pliocene due to a major transgression. The tentative positions of regional unconformities are shown in Figure 27.

Overall, to the best of our knowledge, there are no AFTA points from the hinterland published.

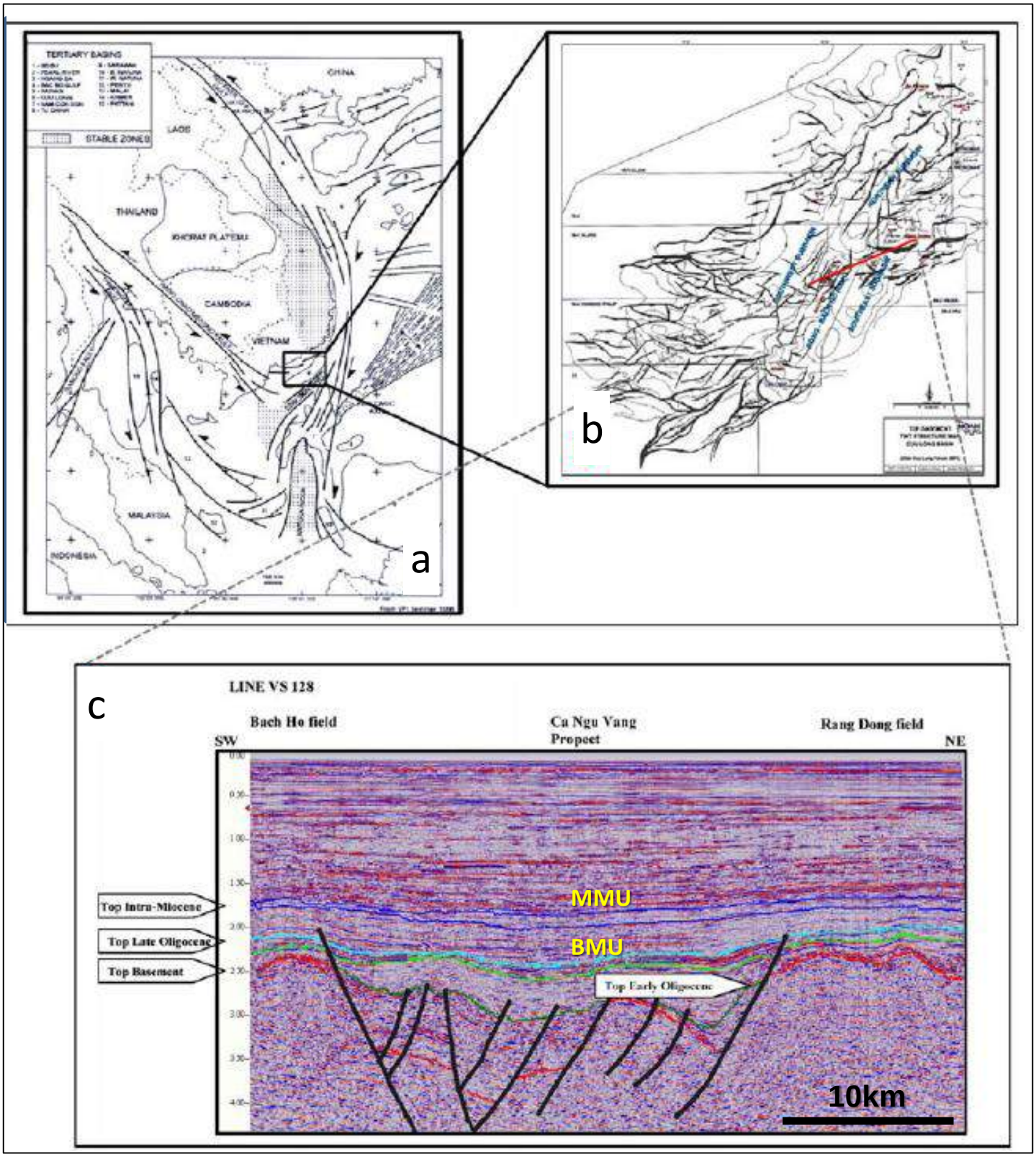


Figure 26. *a) Tectonic map of Vietnam and environs, including Tertiary basins. b) Tectonic map of Cuu Long Basin. c). Seismic line across two fields and prospect in Cuu Long Basin, Horizon Top Intra-Miocene is approximately MMU. Modified after Nguyen & Hung, 2004.*

REGIONAL STRATIGRAPHY

Detailed stratigraphic summaries of the discussed SCS sub-basins are documented in the key references presented in the previous section (e.g., Hutchison 2004; Fyhn, 2009a, b, 2012; Cullen, 2014; Morley, 2016). However, these stratigraphic schemes are mostly confined to an individual basin or are encompassing nearby basinal areas, such as the Malay-Penyu-West Natuna Basins (Shoup et al., 2012) with common tectonic and structural affinity. Nonetheless, a useful and collective approach in describing the petroleum systems in rift basins of SE Asian basins was introduced by Doust & Sumner (2007).

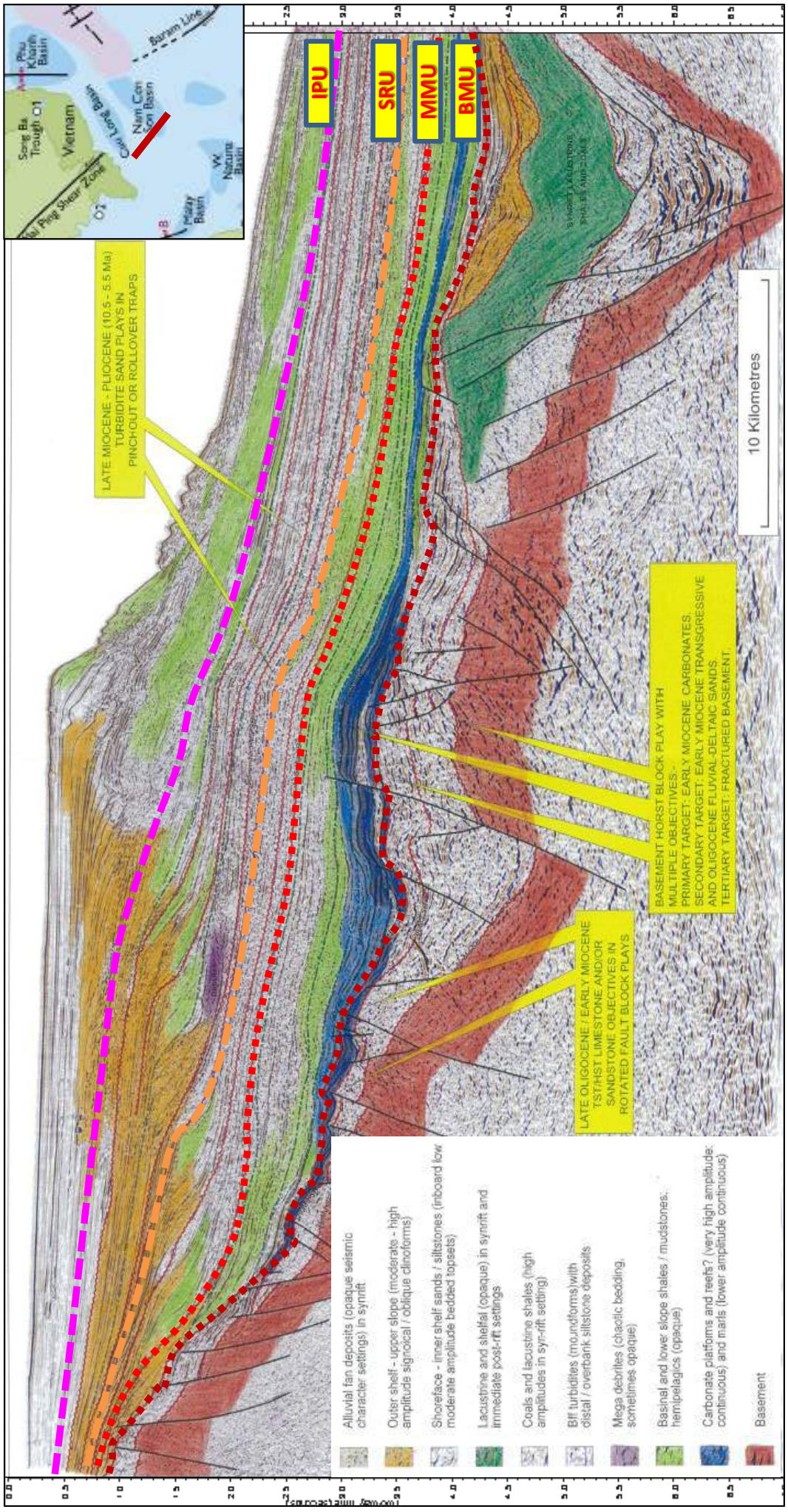


Figure 27. *Other than areas of the Gulf of Thailand, the post-MMU Nam Con Song margin appears quiet and less affected by transparent faulting and inversion with tentative positions of regional unconformities as shown above. Section courtesy of Dr. Peter Barber.*

The concept being many of the SCS sub-basins originate in some way in a rifting episode and subsequently pass through a syn-rift to post-rift evolution. Worldwide this observation has been well-documented by many authors (e.g., Kingston et al., 1983). Although often complex, the sedimentary response and tectonic development of the various stages can be correlated frequently with phases in tectonostratigraphic development. Similarly, although the depositional environments and tectonic situation of the rift fill may change considerably over short distances, basic sedimentary sequence patterns and structural styles can usually be recognized and it is possible to make regional-scale comparisons of structural development and petroleum systems between basins with similar geological histories (Doust 2003). According to Doust & Sumner (2007), in the typical rift to post-rift basins of the Tertiary of SE Asia, four phases of tectonostratigraphic basin development can be recognized: Early syn-rift, Late syn-rift, Early post-rift, and Late post-rift; each with their own characteristic structural history and sedimentation pattern.

Figure 28, adapted from Doust & Sumner (2007), shows the various phases of tectono-stratigraphic basin evolution and illustrates their relation to tectonic events for the basins/margins described in this paper. A few comments to highlight:

- Firstly, we have annotated the Late Miocene compression/inversion signatures on the Vietnam Margin, which was suggested to be periods of quiescence by the authors;
- According to the authors, the Indian Plate collision with Asia was initiated at around 55 Ma and continued to around 43 Ma. In Cullen's (2010) study, the (delayed by extrusion?) impact was felt on the southern SCS margin during a period from 40 to 36 Ma, a time window allocated to the Sarawak Orogeny. An alternative source of plate stress and compression might be associated with the opening of a spreading centre in the Celebes Sea, which occurred from 49 Ma to 44 Ma according to Longley's model (2014);
- Cullen (2010) inferred the Sundaland/Australia collision in a time window of 26 to 24 Ma, the Chattian to Aquitanian. This time period equates to the age of the BMU;
- Noted also the boundary between the Early Oligocene syn-rift 'Lacustrine' in green and the late syn-rift 'Transgressive Deltaic' unit is somewhat tentative and not properly dated (Ian Longley, pers. comm.), and has been revised from Doust & Sumner (2007), given the Late Oligocene deltas are predominantly fluvial with transition to very shallow marine (tidal) deposits. Therefore, the boundary between syn-rift and late syn-rift is diachronous at least in basins such as the Malay and the Penyu Basins, and along the Vietnam Margin (Morley, 2016);
- Fully marine deposits only appear in the Early Miocene, perhaps with the exception of SW Palawan. This particular margin, the facies, as well as stratigraphy, stands out differently and should be further reviewed in the context with data from the other SCS sub-basins;
- It is noted that an alternative interpretation of general stratigraphic columns, timing of structural events, and unconformities in several SCS sub-basins has also been summarized and illustrated in Figure 3 of Morley's 2016 publication.

DISCUSSION

Uplift Signatures of Regional Sub-Basins on the Periphery of SCS

When reviewing the ages of uplift, we noticed that these are not equally distributed over the intervals of interest, which is the Tertiary plus the Quaternary (Figures 29 & 30). There are clearly time periods, when mountains were rising around the SCS, whilst during other periods no uplift is recorded. Very few areas indicate uplift older than the Oligocene (Figures 29 & 30); where a strong peak of activity is seen during the Upper Oligocene (Rupelian and Chattian), in particular between 36 and 32 Ma and encompasses several areas (around the timing of Sarawak Orogeny). Another peak of uplift is seen at the boundary between the Oligocene and the Miocene, at the onset of the Aquitanian, *ca.* 22 Ma. Several uplift data are recorded during the Burdigalian at *ca.* 16- 17 Ma. Given the relative paucity of the data it is difficult to say, whether or not the Lower Miocene saw one extended period of uplift (from 25 to 16 Ma), or two distinct spikes as mentioned above. A final period of regional uplift, starting in the Late Tertiary at the boundary between the Miocene (Messinian) and the Pliocene is also recognized (Kessler & Jong, 2015a, Jong et al., 2016). When looking at the spatial distribution of the uplift data (Figure 30), we notice that a few areas including SE China/Beibuwan hinterland, Hainan Island; Sarawak/Kalimantan, Schwaner Mountains that have recorded uplift ages older than 40 Ma. In other areas, Late Oligocene to Lower Miocene uplift appears to be more common. In three tectonically active areas (Taiwan, NW Java, NW Sarawak/Brunei/Sabah) the uplift may have continued into the Quaternary.

The Opening of South China Sea

The picture of the tectonic evolution of the SCS would be incomplete without addressing the opening/formation of oceanic crust of the SCS and on adjacent plates. One of the earliest rifts was originated in the Celebes Sea, where oceanic crust was formed during the Eocene at *ca.* 49 - 40 Ma (Ian Longley, pers. comm.). This rift should have created compression in NW-SE direction, in the context of the Sarawak Orogeny. A few million years later, rifting started at the center of the SCS. It led to the development of a triangular-shaped rift between the Paracel Islands and the Dangerous Grounds (see Hutchison, 2005 p. 6; Figures 1 & 29), with the western tip located east of the Mio-Pliocene Bunguran Trough.

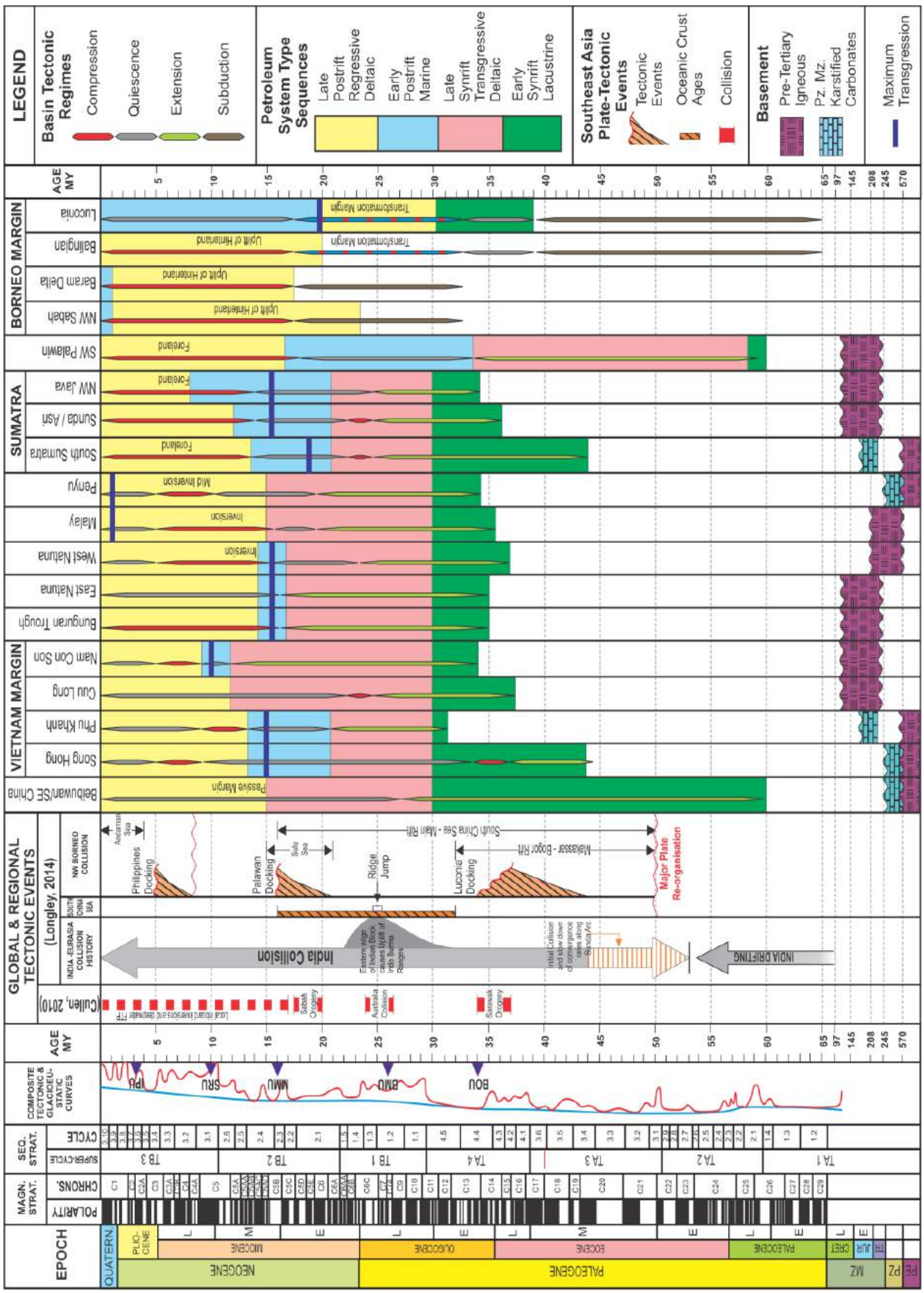


Figure 28. *Summary of basin evolution, basin cycles and geodynamic events of the SCS sedimentary basins discussed in this paper (modified after Doust & Sumner, 2007). The occurrences of the later compressional events are more common on eastern and southern margins of the SCS. See text for further discussions. It should be noted that an alternative interpretation of general stratigraphic columns, timing of structural events and unconformities for different sub-basins in the SCS is captured in Figure 3 of Morley's 2016 publication.*

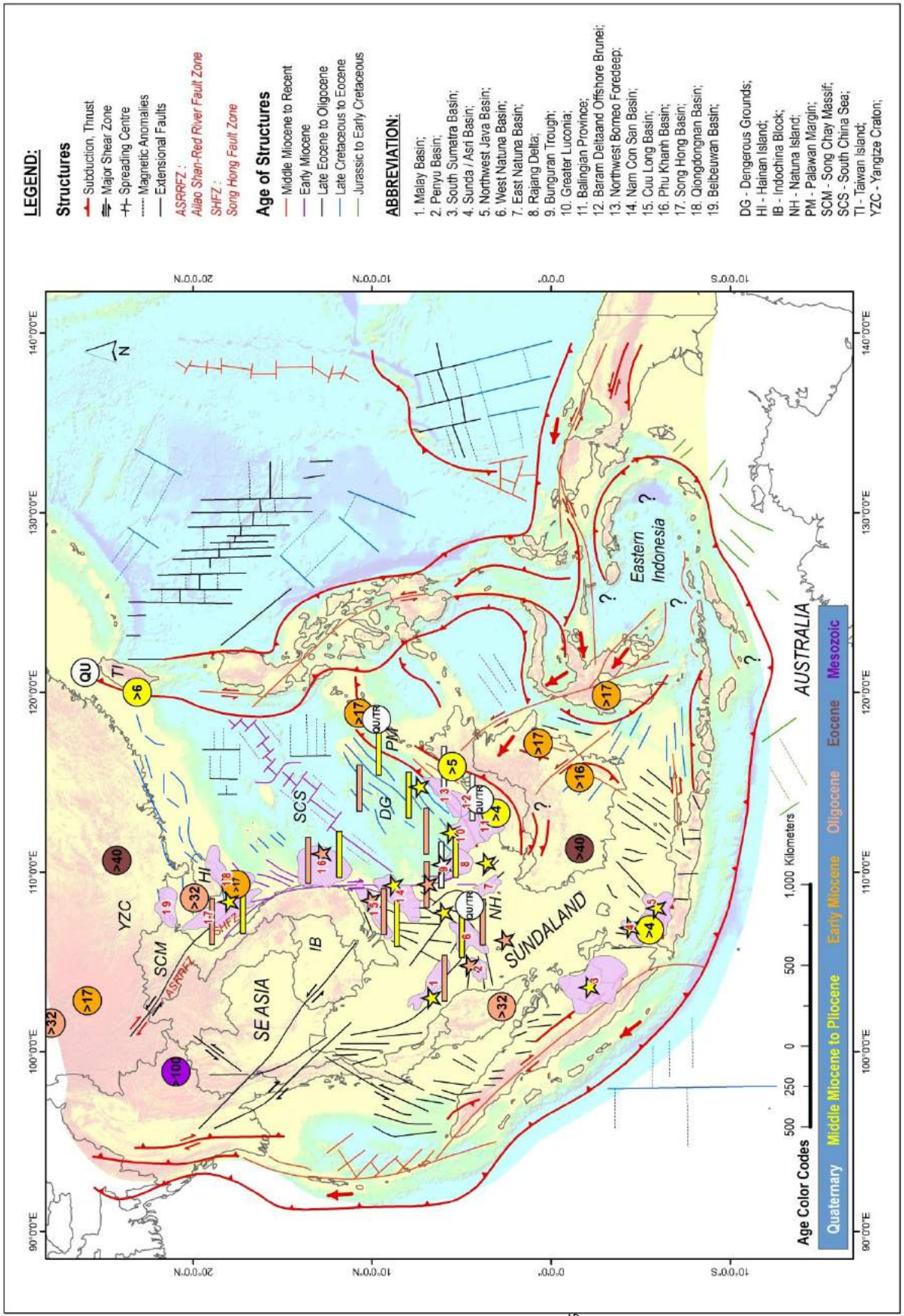


Figure 29. *Schematic block diagram with a regional reconstruction of Late Miocene/Pliocene showing the major tectonic features of SE Asia. As overlays are shown uplift ages (round symbols) with age and color code, QU/TR=Quaternary Uplift & Terraces. The colored bars show the tentative age of seismically mapped unconformities. Stars show inversion with color-coding for age; structure and age of structures after Doust & Sumner (2007). Note published uplift data outside of the focus area from mainland China, eastern Borneo and West Sulawesi are included for reference only but not discussed in this paper.*

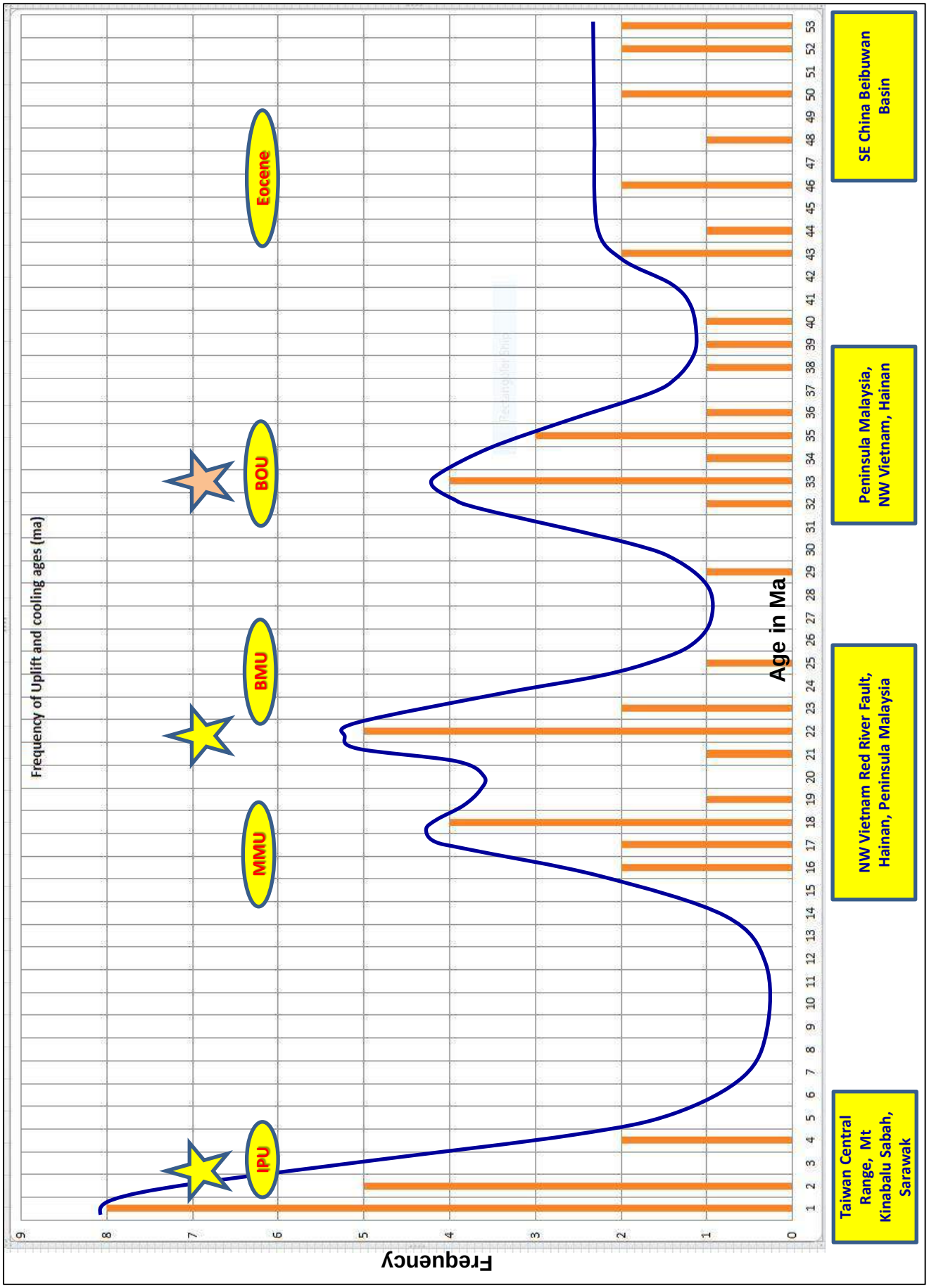


***Figure 30**. Histogram with uplift measurements indicating peaks at 0-2 Ma, 16-18 Ma, 22-23 Ma, 33-34 Ma and >43 Ma, combined with unconformities (ellipses), periods of inversion (stars). Data authorship for the AFTA uplift data is referenced in text.*

Extension started before *ca.* 34 Ma (anomaly 11) in the Middle to Late Oligocene, and ended *ca.* 17 Ma (anomaly 5D). Longley (2014) suggested the window of SCS spreading from 32 Ma to 16 Ma. However, if looked in detail, the data regarding the onset and termination of spreading appear less coherent. This is shown in a good summary by Morley (2016). The author quotes the following ages:

- 33 - 32 Ma. Onset of seafloor spreading in the eastern SCS (Barkhausen et al., 2014);
- 32 Ma. Age of Break-up Unconformity, southern shoulder of the ocean crust, north of Palawan. Steuer et al. (2013) show evidence for the Break-up Unconformity occurring around 32 Ma, below the Nido Limestone;
- 28 Ma. Unconformity, dated in deep sea wells, marks end of rifting in the eastern SCS, with sediments just above dated at 24 Ma;
- 23 Ma. Onset at 23 Ma in the western SCS (same author);
- 20.5 Ma. Spreading ends at southwest ridge tip (Barckhausen et al., 2014), or 15 –16Ma (Briais et al., 1993; C.-F. Li et al., 2014; L. Li et al., 2014).

As a result of the wide opening on the eastern portion, and little opening in the western portion, the southern part of the Sundaland Plate was shifted SE, which might have caused a clockwise rotation of the greater Borneo Block, as well as compressional stress in NW-SE direction. A few million years later, rifting started again in the Sulu Sea, enacting compressive stress again in NW-SE direction. How far this latest rifting event could have affected the SCS other than the eastern Borneo/Sundaland margin however, remains a matter of speculation.

Inversion Tectonism

The widespread occurrence of inversion observed in the sub-basins of SCS points to the fact, that compression affected not only the plate margins, but also the inner parts of the Sundaland Plate. There are at least 2-3 phases of inversion observed:

- At the border between Oligocene and Miocene, hence pre-BMU;
- One Intra-Miocene event, arguably pre-MMU;
- One Late Miocene event, arguably pre-SRU;
- More rarely during Pliocene to Pleistocene times (Bunguran Trough; Jong et al., 2014, 2015).

We can discriminate between inversion located near to the suspected southern Sundaland Plate margin, and also areas of inversion in the centre of the SCS. We see inversion in the Balingian (Figure 10), Central Luconia (Figure 11), and the NW Borneo Foredeep such as in Brunei Ampa (Figure 12), Brunei Champion Delta (Figure 13), and Sabah (Figure14). The inner parts of the SCS also saw (Oligocene and Miocene) inversion in the greater Natuna area (Figures 5a & 31).

The study by Jong et al. (2014) has demonstrated that compressive stress acting in SCS is likely to be felt, not only in the epicentre, but in other structural provinces of the SCS, hence the resonance and synchronous nature of some inversion features at the periphery of SCS with a common tectonic signature. For instance, Figure 31 illustrates the common Late Miocene inversion tectonism that affected the West Natuna and Malay Basins, which was also commonly observed on the NW Borneo Margin. On the other hand, older inversion tectonic could be more pronounced, particularly closer to the centre of the SCS.

Unconformity and Uplift Events (Figures 28, 30 & 32)

From the accounts of the timing of deformation from published data for various sub-basins in the SCS, there appear to be significant discrepancies in both the duration of the initial and subsequent extensional phases, and correlation of stratigraphy particularly for the Vietnam Margin, as outlined by Morley (2016). All these studies are probably based on industry dating of wells, and correlations that may vary from well to well, and company to company datasets resulting in a variation of assigned ages for the key events observed.

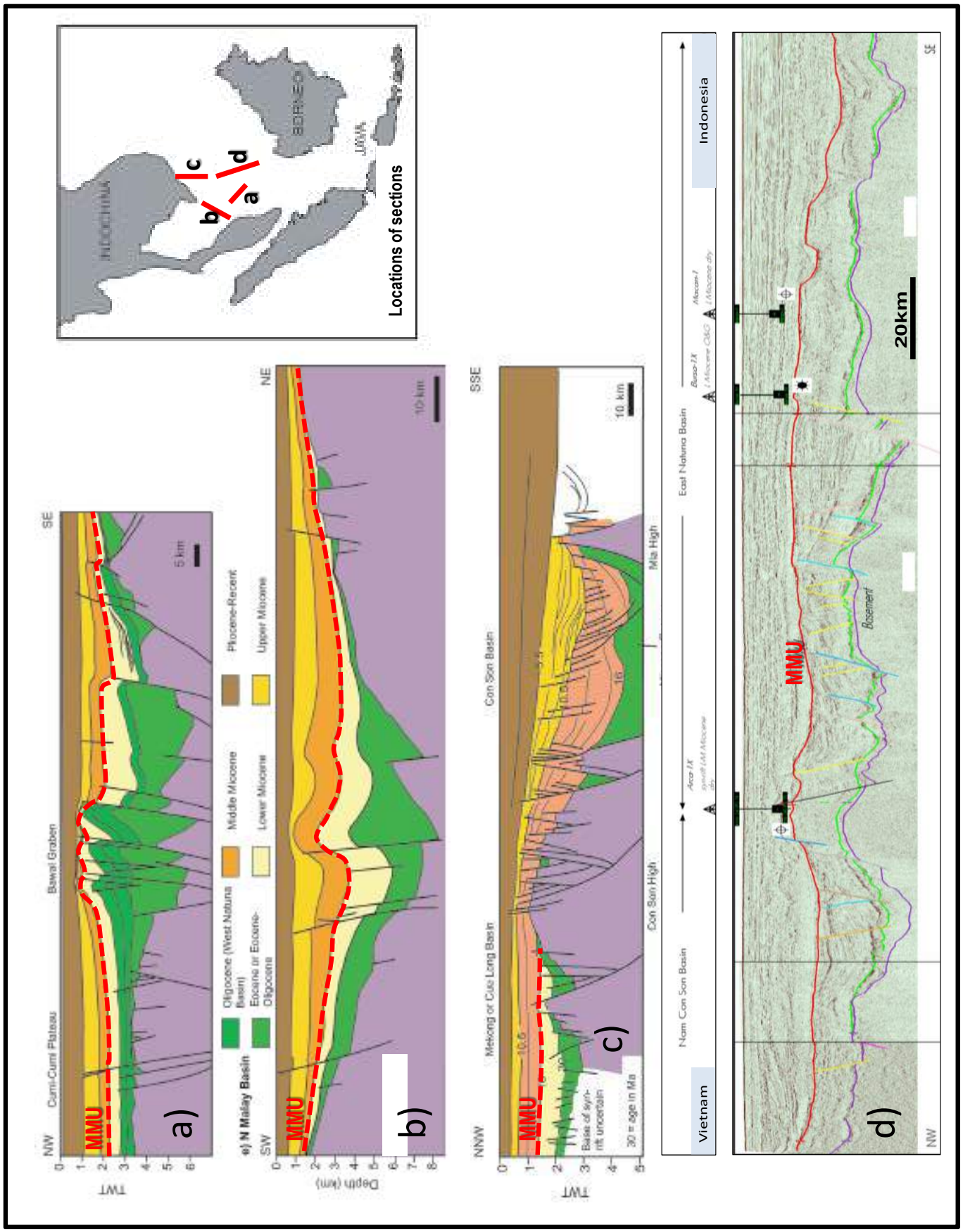


Figure 31. *Inversion features in the SCS, a) West Natuna Basin, Sunda Shelf. Many half-grabens, but by far not all, have seen strong inversion in the area. b) Malay Basin, similar to the West Natuna Basin, most recent inversion tectonism took place in the Late Miocene. c) Cross section from Cuu Long Basin to Nam Con Son Basin and, d) Seismic section from Nam Con Son Basin to East Natuna Basin, where both sections are dominated by the pre-MMU inversion with several oil and gas fields discovered. a), b) and c) after Hall & Morley (2014) and references provided therein.*

Table 1 below lists the main documented unconformities in the Borneo SCS.

Table 1. *Regional unconformities discussed in this paper and their relationship to other studies (incorporating summary from Franke et al., 2008)*

Time	Mentioned Unconformities	Properties and identifications
Pleistocene	Horizon I (Levell, 1987); Pleistocene Terraces (Wilford, 1961; Ramos & Tatsumi, 2010; Kessler & Jong, 2014, 2015).	Uplift associated with tensional faulting over the crests of many structures (mild onlap). Uplift of coastal terraces in Sumatra, NW Borneo, Palawan.
Early/Late Pliocene boundary 3.6Ma	Horizon II (Levell, 1987); Unconformity A (Hinz et al., 1989); Horizon A (Franke et al., 2008); Early Pliocene Unconformity (EPU; Morley, 2016); **Intra-Pliocene Unconformity (IPU) in this study.**	A consequence of collision in Taiwan with the docking of the Philippines Plate in the Early Pliocene (Longley, 2014).Truncation or mild onlap associated with the formation of open anticlines and synclines with a general NW–SE orientation (compressional tectonic), something forming the base of NW Sarawak terraces.
Late Miocene 10Ma	Shallow regional unconformity (SRU); unconformity B of Schlüter et al. (1996); Horizon B (Franke et al., 2008). Late Miocene Unconformity (LMU; Morley, 2016); **SRU in this study.**	A consequence of Sulawesi collisions that move the allochthon in Sabah over a stationary SCS (Longley, 2014).This erosional surface remained on the shallow shelf above sea-level until Pliocene times (Rice-Oxely, 1991) (onlap, erosional).
	Upper intermediate unconformity (UIU) (Levell, 1987)	Reduced rates of relative sea-level rise in the early Late Miocene (onlap, erosional). Prominent in areas of Sabah only, and related to mobile clay tectonism.
	Lower intermediate unconformity (LIU) (Levell, 1987)	A marine onlap unconformity. Increase in the rate of relative sea-level rise. Prominent in parts of Sabah only, and related to mobile clay tectonism (late Middle Miocene).
Early Middle Miocene? 16Ma	Red Unconformity (Hinz & Schlüter, 1985, Morley 2016); Unconformity C/6 (Hinz et al., 1989; Schlüter et al., 1996); MMU (Hutchison, 1996, 2005); Horizon C (Franke et al., 2008); SCS Unconformity (Cullen, 2010, 2014); **Mid-Miocene Unconformity (MMU, ca. 15-17Ma) in this study.**	Underlies the wedge of deformed thrust rocks. Cessation od SCS spreading?, maximum trangressions onto craton. Often overlaid by thick section of hemi-pelagics in most parts of SCS. Show diachonousity in Central/North Luconia area.
	Deep Regional Unconformity (DRU) (e.g. Levell, 1987)	Angular and somewhere erosional unconformity which separated the deep marine shales and turbidity sands of the Late Eocene to Early Miocene from the clastic shallow sediments of post-early Middle Miocene (onlap). Mainly seismic defined without reliable age control in Sabah.
Oligocene to late Early Miocene 17–33Ma	Horizon D (Kudrass et al., 1986; Hinz et al., 1989; Schlüter et al., 1996); Horizon D (Franke et al. (2008); Early Miocene Unconformity (Madon et al., 2013); Base Miocene Unconformity (Morley, 2016); **(BMU, ca. 26 Ma) in this study.**	'Ridge jump' in SCS (Longley, 2014). End of Inversion/folding in the Penyu Basin; Base of Miocene clastic deposits in most sub-basins. Top of a unit of carbonates known from the Dangerous Grounds. Generally thermal cooling, regressive carbonate platform facies in shallow water.
Early/Middle Oligocene 32Ma	Unconformity E (Schlüter et al., 1996); Horizon E (Franke et al., 2008).	Base of the carbonates
Base Oligocene 34Ma	**Base Oligocene Unconformity (BOU) in this study**	Indo-Australian Plate collision/Sarawak Orogeny (Cullen, 2010) vs. Luconia docking (Longley, 2014), rift climax in proto-South China Sea.
Mesozoic/Tertiary basement	Unconformity F (Schlüter et al., 1996); Horizon F (Franke et al., 2008).	Unconformity between Mesozoic and Tertiary rocks; poor seismic definition and cannot be mapped reliably in basinal areas.

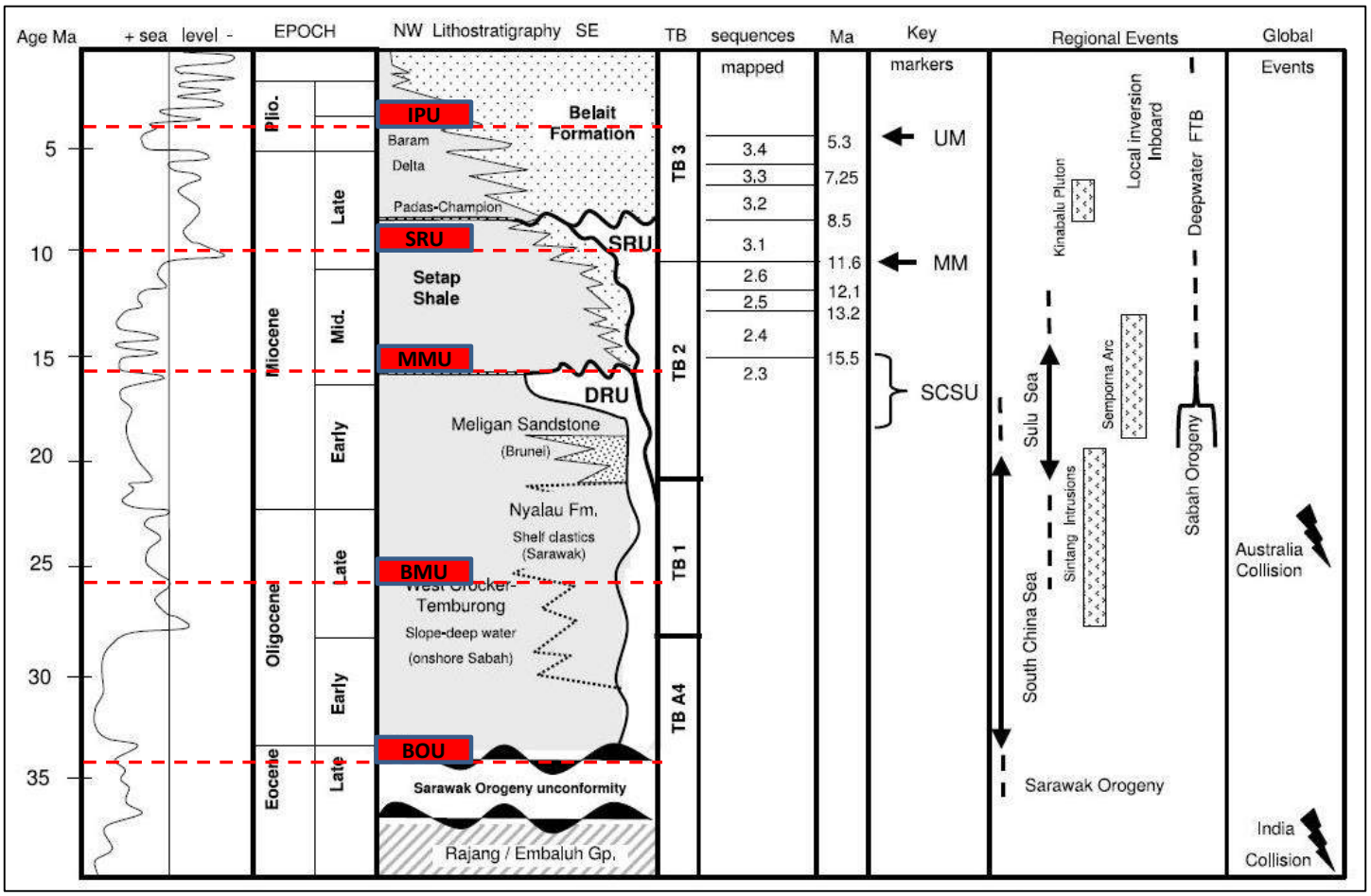


Figure 32. *Simplified stratigraphic column and events chart for the Baram-Balabac Basin modified after Cullen (2010). BOU, Base Oligocene Unconformity; BMU, Base Miocene Unconformity; MMU, Mid-Miocene Unconformity; SRU, Shallow Regional Unconformity; IPU, Intra-Pliocene Unconformity; UM, top Upper Miocene; MM, top Middle Miocene; SCSU, South China Sea Unconformity. The occurrence of BMU, based on the outcomes of this paper is ca. 26 Ma, coinciding with global event of Australia collision, with MMU ca. 16 Ma, SRU ca. 10 Ma and Intra-Pliocene Unconformity ca. 3.6 Ma.*

We refer to the following key publications: Hinz & Schlüter (1985), Levell (1987), Hinz et al. (1989), Schlüter et al. (1996), Hutchison (1996, 2005), Franke et al. (2008), Cullen (2010, 2014) and Morley (2016). In shallow water offshore Sabah, Levell (1987) first summarized the key regional unconformities, which resulted in a number of key erosional events being established: the DRU, Lower Intermediate Unconformity (LIU), Upper Intermediate Unconformity (UIU), SRU, Horizon III, Horizon II and Horizon I (Figure 16, Table 1). Franke et al. (2008) extended these events to the deepwater Sabah area and identified corresponding events as 'Horizons A-F', whilst more recently Cullen (2010, 2014) established the term 'SCSU'. This unconformity could be synonymous to the DRU in Sabah offshore, albeit unfortunately, the DRU is a purely seismically defined concept, with poor age control. This said, the SCSU (and the equivalent DRU) can be tracked from Luconia onto the Dangerous Grounds to Palawan and offshore Vietnam (Cullen, 2010, 2014). In the Dangerous Grounds area, Hutchison (2004) and Hutchison & Vijayan (2010) use the term MMU, whereas Madon et al. (2013) in deepwater Sarawak basins imply a similar event as the Early Miocene Unconformity (EMU). Because the DRU was claimed to be strongly diachronous (Levell, 1987), at the regional scale the term SCSU was thus proposed encompassing a 'zone' that was variably described by various authors as DRU, ERU and MMU. In deepwater Sarawak, the SCSU/EMU ranges in expression from strongly angular with up to 2.6 km of section locally removed and a time gap of 10 Ma to a para-conformable foreland basin onlap above a condensed section (Madon et al., 2013).

Detailed descriptions and ages of the unconformities along the Vietnam Margin have been recently published by Morley (2016), where the term Red Unconformity of Hinz & Schlüter (1985) was used, which we believe could be coeval to the MMU. Although we recognize a good time correlation between pulses of uplift and major basin-wide unconformities, the causal relationship between the two are not quite as clear. Furthermore, we must reckon the effects of the opening of the SCS, and climatic factors. The major unconformities observed in this study are summarized below (Table 1, Figures 28 & 30):

The Base Oligocene Unconformity (BOU, *ca.* 34 Ma)

According to Longley's model of SCS evolution (2014), The BOU is a consequence of docking of a very prominent Luconia Block. In comparison, Madon (1999) suggests Luconia drifted and collided with West Borneo Basement in the Early Oligocene (37 – 32 Ma) to form the Sarawak foreland basins. This said, there remain questions if the above inferred plate tectonic models can be substantiated by the few available data points. The BOU marks the transition from a cluster of isolated grabens with older (Eocene) clastics to a period of more widespread sedimentation. However, there existed many large basement highs (such as the Tenggol Arch and the Johor Platform in the Penyu Basin area), which separated the Oligocene basins. Our compiled data point to a period of Oligocene uplift, and coeval significant inversion/erosion, but there are currently not enough data to draw solid conclusions. Remnants of Eocene sediments are reported from the Penyu Basin, where a gap of some 1200 m (based on VRM) was recorded between an eroded Eocene remnant and the overlying Late Oligocene deposits (Donny et al., 2015). At the Engkabang-Karap Anticline onshore Sarawak, a study by Jong et al. (2016) based on biofacies interpretation of the Engkabang well data, suggests a BOU associated with up to 2 My of missing section at the Engkabang-1 and Engkabang West-1 well locations.

The Base Miocene Unconformity (BMU, *ca.* 26 Ma)

The BMU is the oldest widely distributed SCS unconformity. As the crust of the SCS stretched and subsided further, a Miocene sediment blanket is almost present everywhere in the SCS. The hiatus between the eroded Oligocene section and the Early Miocene varies. Moreover, a recent study conducted by Jong et al. (2016) from the Engkabang wells suggest the occurrence of the BMU and only a partially missing Oligocene section of up to 2 My. In areas where sedimentation continued relatively unabated with little interference by transpressive tectonism and/or inversion, such as seen in Figure 3 in the centre of the Malay Basin, and the Vietnam Margin sub-basins, the presence of the unconformity is more difficult to establish. A causal sequence of events related to the tectonic evolution of the SCS might have occurred as follows:

- Opening of the SCS, leading to a rotation of the continental shoulders flanking the widening oceanic crust as well as thinned areas of further subsiding continental crust; possibly a 'Ridge Jump' may have occurred in the SCS (Figure 30), when the inferred subduction rate at the NW Borneo Foredeep suddenly increased (Figure 28; Ian Longley, pers. comm.);
- Compressive stress was building up within the old shoulders, leading to uplift of isolated blocks, whilst a regional tilt occurred in the sub-basins;
- Enhanced erosion affected the newly emerging high zones (BMU) resulting in new (Early Miocene) depocentres located discordantly above the Late Oligocene package.

The Mid-Miocene Unconformity (MMU, *ca.* 15-17 Ma)

The regionally prominent, narrow syn-rift to post-rift transition zone that lies somewhere between the Middle Miocene - Late Miocene could be of a complex nature. The interval appears mostly conformable, yet accompanied by local erosion and angularity that marks the cessation of extension (Morley, 2016). This unconformity or event is related to the end of SCS spreading when the Dangerous Grounds was docked onto NW Borneo subduction (Longley, 2014), and has been called a number of names, including the Red Unconformity (Hinz & Schlüter, 1985) and the MMU (Hutchison, 2004). However, we believe it is premature to subscribe to either of the proposed plate-tectonic models, as long as the often conflicting unconformity ages are not fully reconciled. In recognition of its diachronous nature this widespread unconformity is called the SCSU by Cullen (2010). Madon et al. (2013) claim the youngest strata immediately below the unconformity are dated at 16 Ma (Mulu-1 in North Luconia), representing the minimum age of the tectonic event that produced the unconformity. *Globigerina* sands that cap the unconformity in the Talang-1 well indicate an age around 18.5 – 19 Ma. Hutchison & Vijayan (2010) refer to a strontium isotope age of 18.5 – 19 Ma, with a 2.0 - 2.5 my hiatus that helps pin down the age of the unconformity. Hence Madon et al. (2013) prefer to use the term Early Miocene Unconformity since MMU is 'incorrect with respect to timing'.

The MMU is strongly expressed on the Sarawak/Sabah section of the southern Sundaland margin only. It is noted that Cullen's (2010, 2014) SCSU may be synonymous with the MMU in some areas, and perhaps with the BMU in others, given seismic data are extremely difficult to correlate in areas such as offshore Sabah, and bio-stratigraphic interpretations often remain ambiguous. Onshore central Sarawak, the MMU is characterized by an angular unconformity and at eastern Tatau Horst it separates the strongly folded Bawang Member turbidites and overlying Rangsi Conglomerate (Hutchison, 2005). In NW Sarawak, it is also seen separating the gray Upper Setap Shale from the Lambir Formation (Kessler & Jong, 2015c). Offshore, the unconformity occurs throughout the Dangerous Grounds, North Luconia and the Vietnam Margin, a fact established by regional seismic mapping (Figures 5c, 6, 7, 10, 11, 15, 17,18, 19, 23-27). Fieldwork in Borneo showed that the MMU forms a boundary between neritic marine and shelfal deposits (Kessler & Jong, 2015c), as parts of the Borneo hinterlands where exhumed (Kessler & Jong, 2015a). Other areas of the SCS show less evidence of this unconformity. Iyer et al. (2012) established a context between the unconformity and uplift in Central/North Luconia, and a diachronism

of the MMU towards the northeast was recognized. A missing section based on existing well data varies from 2 – 8.5 Ma (from south to north) but more well penetrations are essential to constrain the MMU time gap. Although uplift data of *ca.* 15 - 17 Ma are not uncommon, the context between uplift and this very important unconformity requires further data and analysis.

The Late Miocene Shallow Regional Unconformity (SRU, *ca.* 10 Ma)

The unconformity was previously interpreted to be the result of sea-level changes (Rice-Oxley, 1991), which is now believed to be the impact of trans-Borneo tectonics where the Sulawesi collisions in the southeast eventually moved the 'allochthon' in Sabah to the northwest over a stationary SCS (Longley, 2014). The compression led to folding of the post-orogenic basin edge equally affecting the Luconia/Tinjar Block and the adjacent Baram Delta Block. Field work in Sarawak equally inferred that the unconformity is angular in a few locations (Kessler & Jong, 2015c), and therefore points to tectonic activity at least in this part of Borneo. As described by Balaguru & Lukie (2012), the Labuan and Jerudong/Morris Anticlines and Belait Syncline were formed during the Late Miocene as fault-bend and fault propagation folds. The pro-delta shale was progressively buried by the prograding delta front and likely became overpressured and mobilized above reactivated basement structures during the Pliocene, further complicating the deformation style. Pliocene - Pleistocene inversion on NNE- and north-trending structures with continued growth on NE-trending structures is most likely controlled by the regional NW-trending sinistral shear zones. Flower structures and thrust cored anticlines were developed above the reactivated structures. Given that the post-unconformity Pliocene sediments were deposited in a shallower facies (= coastal with coals), compared to the Late Miocene beneath (= shelfal) might point to an uplift in the order of 20 - 100 m. Likely, the unconformity points to a relatively short-lived period of compression on the Sundaland margin. Post-SRU, locally repeated episodes of uplift and tilting have resulted in the amalgamation of various unconformities into a single composite surface with an apparently large amount of young denudation when, in fact, erosion took place over multiple intervals (Cullen, 2010).

The Intra-Pliocene Unconformity (IPU, *ca.* 3.6 Ma)

The unconformity appears to postdate the compression of the Sundaland Plate margin by the neighboring plates. The event is likely a consequence of a collision in Taiwan interplayed with the docking of the Philippines Plate in the Early Pliocene, with NW Borneo aligned together with the Palawan/Philippines Margin (Longley, 2014). Uplift occurred likely all along the plate margin, and led to enhanced erosion of sediments. The IPU marks the boundary between the strong uplift/erosion period, and a more quiet tectonic time interval that followed. It is noted, however, that uplift continued in the Quaternary in areas of NW Borneo and Taiwan. Possibly this could be interpreted as a consequence of the monsoonal effect, leading to enhanced erosion, largely, if not entirely, driven by climatic factors (e.g., Hall & Nichols, 2002).

Observation and Comparison with PETRONAS (2007) Study

We noted that in 2007, a monumental study entitled 'Chronostratigraphic Chart of the Cenozoic and Mesozoic Basins' was published in a book format (PETRONAS, 2007). The Chronostratigraphic Chart compares the stratigraphy of seven major basins in Malaysia using the concept of global eustatic sea-level changes to link-up wells calibrated by biostratigraphy. All data compiled including lithostratigraphy, biostratigraphy and bio-chronozones were recalibrated to the Gradstein time scale (Gradstein et al., 2004), albeit no regional seismic lines calibrated to key well investigated were included. In contrast our study combines seismic, fieldwork, sedimentary cycles, published AFTA as well as other uplift data and attempts to outline and compare the timing of uplift with key tectonic processes that produced the regional unconformities encompassing the entire SCS in Malaysian waters and beyond. Consequently and understandably, the interpretation of sequences and ages of the documented unconformities differ considerably.

Important nomenclature and age differences observed are summarised as follows (Figure 33):

- The PETRONAS study does not indicate a BOU, but refers to a Sarawak Orogeny at around 37 - 40 Ma.
- In the mentioned study, the BMU in Sabah is shown at around 22 Ma, with a coeval hiatus at Malay/Penyu Basins and Sarawak (Balingian, West Baram), it was not correlated to the BMU in Sabah but referred to other older events with a dashed question mark line drawn.
- The positioning of the MMU varied as described earlier, but overall is similar in both studies. PETRONAS study suggests an age of 13.65 Ma based on Gradstein time scale and 15.5 Ma based on Haq time scale (Haq et al., 1988) (Base TB2.4). The DRU was assigned an age of 13.53 Ma and 13.80 Ma (Top TB2.4), based on Gradstein and Haq time scales, respectively.
- The SRU in PETRONAS study is located at Top TB3.1, around 9.22 Ma based on Gradstein time scale, whilst ours is positioned at around 10 Ma.

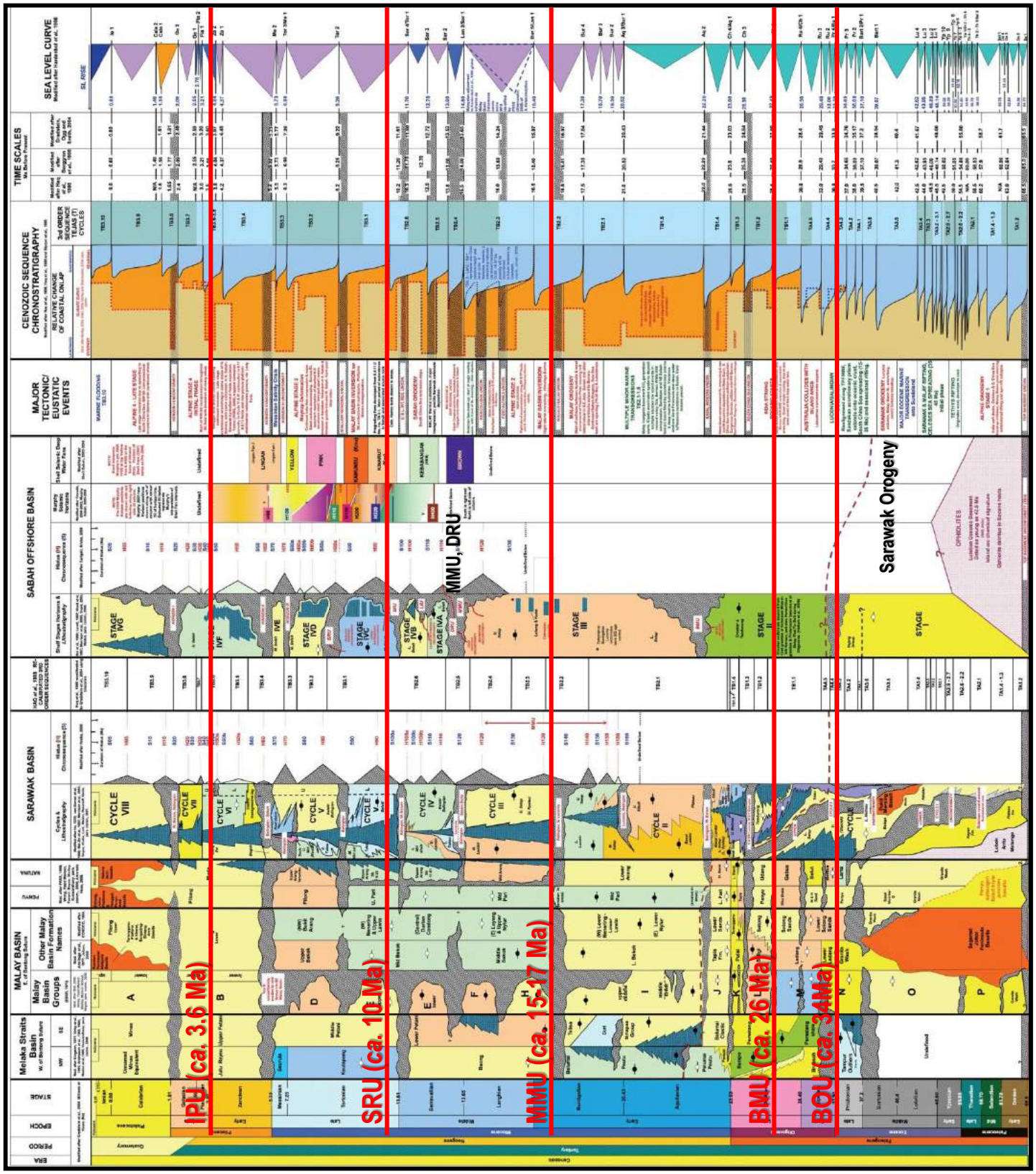


Figure 33. *An adaptation of PETRONAS 'Chronostratigraphic Chart of the Cenozoic and Mesozoic Basins' with regional unconformity established in this study overlain (after PETRONAS, 2007).*

- Our IPU is not related to any of PETRONAS study events. In our approach we see the IPU as a consequence of a plate collision with the docking of Taiwan to the Philippine Plate.

In our earlier publication (Kessler & Jong, 2015a), we have identified that since the Middle Miocene, the Borneo Baram-Balabac shelf margin has recorded a number of significant uplift events and sand pulses that saw a major expansion of the shelf. The question, as to which of these pulses can be linked to sea-level fluctuations, remains open; though it appears that the Borneo uplift has 'outrun' rising sea-level at least since the Late Pleistocene. Only time will tell which approach is more correct and practical. Nonetheless, continual updates will be required as new data and interpretations become available to further enhance the outcomes of both studies.

CONCLUSIONS AND RECOMMENDATIONS

We found that recent uplift is a feature that only occurs at the fringes of the Sundaland Plate; Sumatra/Java, Borneo, the Philippines and Taiwan, and recognize an age correlation between regional unconformities, formation of oceanic crust and uplift of the peripheral mountain ranges. Uplift of the northern SCS areas is largely confined to the Paleogene, whilst the southern SCS has seen pulses of uplift mainly during the Neogene. Episodic inversion tectonism affected areas of the northern and central SCS during the Oligocene and Early Miocene, and appears to be powered by strike-slip tectonics along lineaments. The earliest basin-wide regional unconformity is of Late Oligocene age, here called BMU and acts as an angular unconformity in parts of Sabah, Sarawak, and the Malay/Penyu Basins. The seismic-defined and relatively well-calibrated event of MMU could be correlated with the end of proto-SCS spreading, and hinterland uplift that affected areas of the Sundaland Plate boundary such as Sarawak. The Late Miocene SRU points to a short compressive pulse that affected areas of Sabah and Sarawak. The IPU can be seen in particular in the south and eastern parts of the SCS and correlates with uplift of areas on the Sundaland Plate margin such as NW Borneo and Taiwan. Uplift continued in segments of the southern Sundaland margin, and was likely driven by climatic factors.

More fission-track analysis is recommended for the Natuna High, an area of focused structural activities, which would enable a better analysis of the tectonic movements (transpression, compression, inversion, rotation) that affected this particular part of the SCS. In addition, data from the Vietnam Margin remain sought after, some of which might be in publications that we are not aware of but would be valuable to further enhance the outcomes of this study. A review of age dating is also recommended for the MMU event, the position of which by various authors/researchers appears to be disputed in stratigraphic columns. Although partially addressed by various authors/researchers for specific areas (e.g., Jong et al., 2016), the relationship of the uplift of the periphery mountain ranges and regional erosional unconformities, and their impact on the source-to-sink, provenance-to-sedimentary fill story of the SCS remains to be fully unraveled.

We hope the paper can lay the foundations and stimulate discussions for a new generation of papers, which are not merely basin focused but with a priority on integration of the available data in a regional context. The recent paper by Morley (2016) points to a similar view by attempting to correlate the distributions of unconformities and Cenozoic rifting events in the SCS, which reflects both the modes of rift development, and the effects of driving mechanisms. We believe, however, that the necessary full integration of unconformity and uplift data has not occurred yet, which means that the various current SCS plate tectonic models are both immature and appear over-complex. In the last meeting with our highly esteemed colleague and teacher, the late Prof. C.S Hutchison, we concluded that simple models, when compared to complex ones, are far more likely to reflect nature correctly. We thus welcome feedback and contributions from the readers to help resolve some persistent problems on age assignment for the established unconformities across the SCS. Regional seismic correlation of key dated events and missing uplift data in the study area from the industry players will be most appreciated to fill the knowledge gaps to improve our geological understanding of the SCS evolution (Table 2).

For further study, it will be intriguing to incorporate the uplift data and erosional events associated with SE Asian geology on the frontier margins of Sumatra, Java, eastern Borneo and West Sulawesi (as highlighted in Figure 29); Gulf of Thailand and mainland Indo-China that maybe related to SCS tectonics. In summary, crustal stretching, uplift and the resulting unconformities can be compared to different instruments of an orchestra, and there is little merit in looking at each contributing factor in isolation.

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Table 2. *Summary matrix of uplift and unconformity data.*

SCS Sub-Basin	Uplift Data			Unconformity				
	AFTA, range in Ma	VRM	Terraces	BOU	BMU	MMU	SRU	IPU
Malay and Penyu	36-32, 25	Yes	?	Yes	Yes	?	Yes	?
Sunda/Asri	> 4	?	?	?	?	Likely	Likely	?
Natuna Basins/Natuna High	No (Holocene Terraces in Natuna Island)	Yes?	Yes	Yes	Yes	Yes	Yes	Yes
Bunguran Trough/North Luconia	No	Yes	No	?	?	Yes	Yes	Yes
NW Borneo Margin	>4, > 5	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Philippines/Palawan Margin	> 17	Yes	Yes	?	Yes	Yes	Likely	Likely
Dangerous Grounds	No	No	No	?	Yes	Yes	?	?
Taiwan Island	> 6, Recent	?	Yes	No	No	No	No	No
SE China/Hainan Island	> 40, > 32, > 17	?	No	No	No	Yes	No	No
Song Hong Basin	No	Yes?	No	?	Yes	Yes	Yes	Yes?
Phu Khanh Basin	No	Yes?	No	?	Yes	Yes	?	?
Cuu Long Basin	No	Yes?	No	?	Yes	Yes	?	?
Nam Con Son Basin	No	Yes?	No	?	Yes	Yes	Yes	Yes

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