

The history of fluvial to coastal plain sand deposition and the Cycles of Sarawak

PETER LUNT^{1,2,*}, MOHAMMAD NAZRUL³, KHAIROOL ANWAR LAKSAMANA³

¹ Stratos Energy Advisors PLT, C4-5 Riana Green East, Wangsa Maju, 53300 Kuala Lumpur, Malaysia

² Southeast Clastic and Carbonate Research Laboratory, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia

³ Petroleum Sarawak Berhad (Petros), Wisma Bapa Malaysia, Petra Jaya, 93502 Kuching, Sarawak, Malaysia

*Corresponding author email address: plunt@mac.com

Abstract: A new description of sedimentation onshore Sarawak is given, using the Cycles scheme of empirically observed sequences of deposition. The review clarifies a confused history of terminology and offers a tectono-stratigraphic framework (for the Oligo-Miocene boundary period) that can be used to classify and describe sedimentary geology in a genetic stratigraphy that ties to regional geology. This framework requires a well-constrained biostratigraphy, particularly for the Cycle I to II boundary that can be correlated with the regional Base Miocene Unconformity (BMU). Previous reports have not included this correlation, which is important as it places the geological history of Sarawak in a much wider reconstruction. The nature of the Cycle I to II boundary is an abrupt transgression which, in the area around the Tatau Province in the west, covers an angular unconformity. The second boundary documented here (top Cycle II) is expressed as a rapid rotation in the direction of sediment supply, through almost ninety degrees, associated with a transgression (subsidence) in the west and coeval uplift in the hinterland of Borneo. The coherent movement of entire sedimentary systems at each Cycle boundary has implications through Walther's Law that can be tested, for example in continuous and well-sampled well sections just offshore. This approach brings rigour to apparently contradictory prior accounts of the onshore Sarawak Formations and Cycles. As a result, outcropping lithofacies, which are found in each of the three Cycle-related phases, can now be placed in three different palaeogeographic settings reflecting this tectono-stratigraphic development. The most common lithofacies have been given the names Nyalau Formation, Kakus Member and Biban Sandstone Member, and these can now be subdivided with a simple tabulated nomenclature to reflect the episodic stratigraphy (e.g. Nyalau I, II and III etc.).

Keywords: Stratigraphy, tectonics, basin development, Sarawak

INTRODUCTION

The paralic siliciclastic sediments found onshore Sarawak, extending offshore around the Tatau and western Balingian Provinces (Figure 1), are both important oil and gas reservoirs as well as hydrocarbon source rocks. They have been the focus of exploration for many decades but the wider geological framework is not well documented. This is largely because such a framework must incorporate the regional tectono-stratigraphic movements, which controlled sedimentation and facies development through time, but this regional integration has proven difficult to resolve from just local studies. This is difficult because changes to sediment accommodation space are not evenly expressed, as would be expected if eustatic sea-level changes controlled deposition. Instead there are geographically variable changes to accommodation space, as well as major changes in the direction of sediment supply. A regional examination must include the onshore area, but offshore and onshore areas have been reviewed by different groups with very different tools and budgets; these are, oil companies offshore, with

wells and seismic; and the Geological Survey and academics onshore, based on field samples). It is also difficult to date and therefore correlate such very shallow or non-marine sediments. The correlation of non-marine palynological zones with marine microfossils requires specialist knowledge that has often been documented in unpublished reports (e.g. Hageman *et al.*, 1987), and poorly summarised in the more widely available sources such as Hutchison (2005, his Figure 38), until the papers of van Gorsel *et al.* (2014) and Lunt & Madon (2017a).

This report describes the onshore Nyalau Formation and related lithofacies in a new stratigraphic framework, with new data on both the Cycle I-II and II-III boundaries onshore Sarawak. This new data is part of an important development of the regional geological framework

DEFINITION OF CYCLES I TO III

The Cycles of Sarawak and their complex history were reviewed by Lunt & Madon (2017a). The initial expectation in the 1960s and 70s was that there would

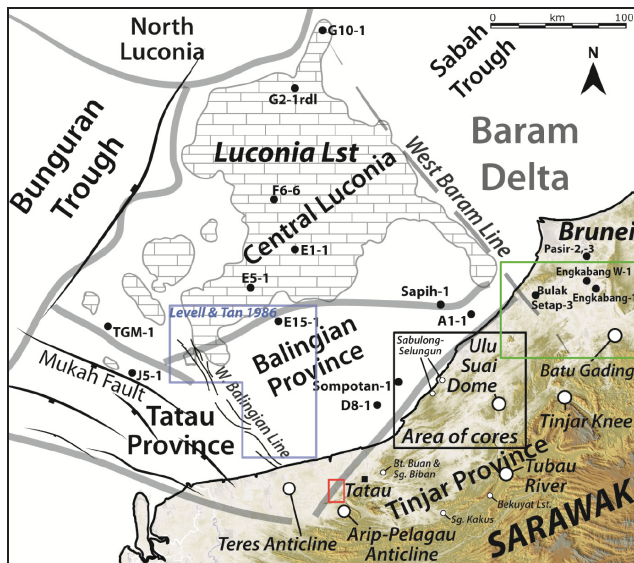


Figure 1: Location map for the central Sarawak and Brunei area. The inset black rectangle is the area of Figure 5, around the cores of Rahdon (1974). The small red rectangle is the area of Figure 3. The green rectangle is the location of Figure 10. The blue polygon is the Cycle I / II study area of Levell & Tan (1986; also Barrett & Tan, 1987), which has historically been the main study area of the Cycle I to II transition.

be exogenic changes in sea-level / accommodation space, of even magnitude across the entire region, including the transgressive floods that defined the base of each Cycle. The Cycle boundaries would therefore be correlatable events, and these marine floods would also contain the best marine biostratigraphy for age dating. Each flood was overcome by sediment supply to form a regressive and progressively less marine highstand. Originally there was an attempt to apply the Cycles in early Sabah wells (e.g. Emerald-1, 1961 and others), reflecting this belief in a widespread exogenic or epeirogenic sea-level change. However, it soon became apparent that the Cycles were a stratigraphic description with strong tectonic controls and thereby geographic variation (Ho Kiam Fui, 1978; Doust, 1981). Note that in this report the terms exogenic and endogenic are used for processes controlled by events originating *outside* (Greek *exō*) or *within* (Greek *endon*) the local basin, respectively. Epeirogenic is an old geological term for regional uplift or subsidence, from the Greek *epeiros* for ‘mainland’.

From the early work Cycle I was particularly poorly defined because, in the oil-bearing Tatau Province and western Balingian Province, only a fluvio-deltaic lithofacies is found deposited over “pre-Cycle I basement” (reached in the wells J5-1 and TGM-1; Figure 1). An older section comprising deep marine marls and clays of the Sap Marls, Buan and Tatau Formations are found onshore south and east of the town of Tatau and around the Arip-Pelagau Anticline (Wolfenden, 1960) but these units have not been drilled offshore. Early worker such as Ho Kiam Fui (1978)

and Doust (1981) included these older marine formations in Cycle I, but they neither offered any definition for the mid Cycle I transition from open marine marls to fluvial clastics, nor a clear definition for the upper Cycle I to Cycle II boundary.

Unpublished Shell reports by Levell & Tan (1986) and Barrett & Tan (1987) were the first to fix the Cycle I to II boundary at the top of pollen Zone “Pcs.145” (now called Zone P200). This boundary was identified as a low angle unconformity followed by a transgression that was originally dated as just within the uppermost part of the thick Zone Pcs.145, and hence the event was named the intra-145 unconformity. However, as more analyses were done, it was realised by Levell & Tan (1986) that the unconformity and the palynology datum were effectively coeval. Correlating this event to marine time scales was difficult, but Hageman *et al.* (1987) estimated this was within basal Miocene Zone N4 (Blow, 1969, updated Bolli & Saunders, 1985) and near base NN2 (about 23 Ma on modern time scales; also see Broolsma, 1981). This dating was achieved through long distance seismic correlation to wells drilling marine facies, as well as very limited palynology on these few marine sections.

Even by the late 1980s not many wells northeast of the Tatau Province (in which direction facies gradually became more marine) had drilled through the Cycle I-II boundary. The G2-1rdl and G10-1 wells (both 1972) reached siliciclastics with Pcs.145 pollen, but below thick limestones that did not yield any pollen. Other early and stratigraphically deep, wells such as E15-1 reached Cycle I but not in marine facies, so integration of the palynology data with marine fauna was not possible. In addition many other pre-1987 deep tests such as E1-1, E1-4, E5-1 and F6-6 did not even reach Cycle I / Zone Pcs.145. As a result of this limited number of data point, neither a firm age for the Cycle I to II boundary was available in its “type” area of SW Sarawak, nor was there a reliable correlation to the Subis and equivalent limestones in the northeast.

As noted by Lunt & Madon (2017a), the stratigraphic report by Sulaiman (1977) claimed to have found the Pcs.145 floral assemblage in the Subis and equivalent limestones dated as Letter Stage Te5 (basal Miocene). The statement in his report is unambiguous (“the age of the limestones [in the Suai-5 and A1-1 wells] is Te5, *Globigerina binaiensis* Zone and the sporomorphs suggests Pcs.145 subzone”), but the original data is not given, and the summary log notes the Te5 limestones only to be “probably Pcs.145 subzone”

As shown in the results given below from the Bintulu-Suai cores, and also highlighted in the appendixes on methodology given in biostratigraphy reports, pollen is very rarely preserved in carbonates or cemented marly lithofacies. However, this unreliable statement from Sulaiman seems to be the reason why many authors in the 1980s (Doust, 1981; Broolsma, 1981) placed the Subis and equivalent limestones in Cycle I, even though the widespread transgression that

the limestone represents would have qualified this to be the base of a Sarawak Cycle. In many places this was the first marine transgression over thick (one or two thousand metres) non-marine fluvial to coastal plain deposition.

After resolving the correlation of the palynology with the Letter Stages (see below) Cycle II is established as the succession after the regional Base Miocene Unconformity (BMU), dated at the top of Pcs.145 / base Te5 (Figure 2). At this time across Sundaland there was an abrupt subsidence, of varying magnitude depending on location. In the Tatau Province of SW Sarawak, and also a large part of north Borneo, it was also the time of the end of latest Oligocene deformation in several places. In north Borneo the compressive deformation was characterised by widespread reworking of older Cenozoic rock fragments and microfossils, which terminated at the Base Miocene Unconformity (cf. Lunt, 2022b). Even in carbonate facies such as the shallow marine Melinau Limestone and Batu Gading Limestone as well as sediment starved deep marine Selidong and Keramat planktonic marls, the latest Oligocene includes reworking of Eocene microfossils (Bowen & Wright, 1957; Liechti 1960; Adams & Haak, 1962; Wannier, 2009). This is thought to indicate that local uplift was a common feature of the latest Oligocene compression.

The Cycle I to II boundary is also the divide between the Temburong Formation and Setap Shale, identified as a low angle unconformity between more and less deformed claystones (Brondijk, 1962). This is dated by the presence of Letter Stage Te4 Pangli and other calciturbidites in the upper Temburong Formation and Te5 calciturbidites in the base of the Setap Shales (Pulun Limestone; cf. Liechti, 1960). As shown on Figure 2, the Te4 to Te5 boundary

is a relatively precise age determination, based on a well established evolutionary series of distinct morphotypes (*Neorotalia* to *Miogypsinoides* to *Miogypsina*).

The slightly younger Cycle II to III boundary has also proven difficult to date due to the lack of marine fossils in the type area. In contrast to the regional BMU event, the Cycle II to III boundary event is geographically restricted to western Sarawak. However, like the Cycle I to II boundary, this event also consisted of local uplift and erosion followed by rapid subsidence and transgression. These two events (local uplift then transgression) seem to have been very closely spaced in time, and the nature of the Mukah Fault trend activity suggests this may have been due to transpression of a new wrenching stress, first causing local uplift, followed very soon afterwards by brittle failure of the crust leading to more widespread subsidence. The unconformity has been dated by palynology as within the upper part of the old “Po3.79” pollen zone (now Zone P410), and was called the “Intra-79 Unconformity”. This pollen zone is defined as being between the oldest (evolutionary) and rare records of the mangrove pollen *Florschuetzia levipoli*, and then the base of common occurrences of *F. levipoli* that was used to define the base of Pcs.38 (now Zone P420). At the time of Hageman *et al.* (1987) the former event was respectively dated as near the base of marine zones NN3 and N6 (c. 19 Ma on modern time scales), and the later event close to the base of nannofossil zone NN4 or within foraminifera Zone N7 (roughly 17½ Ma on modern time scales). Subsequent work has changed our understanding of the range of this pollen and its correlation to better dated marine biostratigraphy. Based on nannofossil data in the Nan Con Son and Natuna basins Morley (1991), van

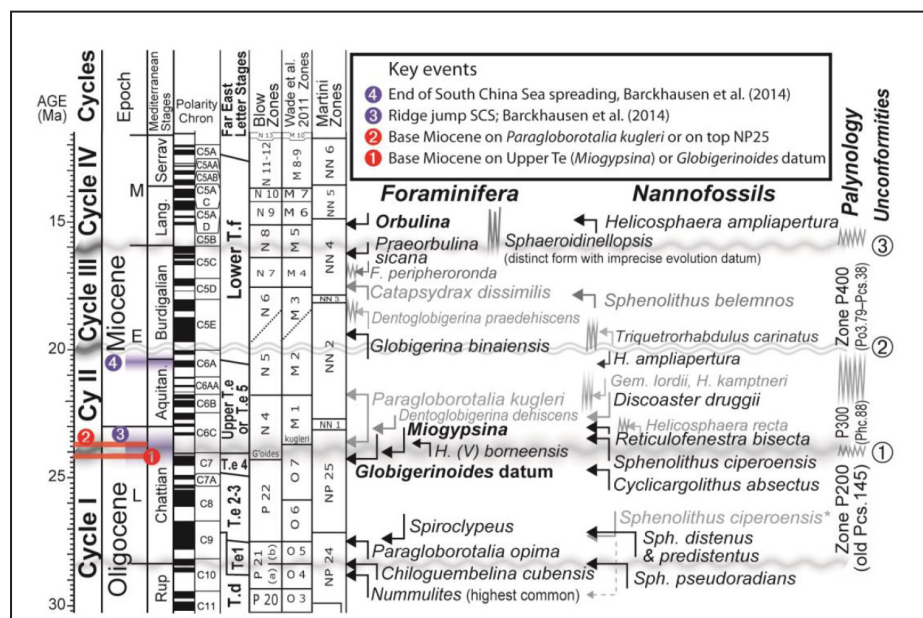


Figure 2: Stratigraphic summary and time scale, including the unconformities and Cycle boundaries. Time scale is based on GTS2020 (Gradstein *et al.*, 2020).

Gorsel *et al.* (2014) and Morley *et al.* (2021) now place the imprecise evolution of rare records of *F. levipoli* within early nannofossil Zone NN2, approximately 21.9 Ma. An abrupt up-section increase in abundance is not obvious in modern data, but instead there was a gradual increase within the mid to later Early Miocene. Consequently the age of the tectonism and then subsidence at base Cycle III is poorly dated in the area where it is most strongly expressed. However, if it is assumed that the end of the Cycle II limestone in the G2-1 well, followed by the onset of deep marine clay deposition is the same transgressive event, then this is dated as just before the extinction of *Globigerina binaiensis* in the clays (so slightly older than 19.4 Ma), with the underlying Cycle II, Upper Te limestone having strontium dating of 19.0 to 19.1 (CSIRO, 2009; two analyses based on GTS04 time scale, analytical error bars not given). Based on this, it is reasonable to place the Cycle II to III boundary at about 20 Ma (Figure 2).

The end of Cycle III is the major subsidence and breakup type unconformity at c. 16 Ma called the Middle Miocene Unconformity or Doust MMU (Lunt, 2019; to distinguish it from other unconformities using the acronym MMU). This was the main subsidence event of the Bunguran Trough (Lunt & Madon, 2017a; Lunt, 2022a).

DEFINITION OF THE TYPE FORMATIONS

Primary divisions of the siliciclastics

Formations are lithofacies that are mapped from observation of characters in outcrop or samples. They are lithofacies-based units, but there must be a guiding stratigraphic framework to prevent *reductio ad absurdum* of mapping “mostly limestone” or “mostly clays”. The first part of an enhanced definition is to include a wider facies identity from sedimentology and palaeontology, which links formations to Walther’s Law. The facies properties are then expected to be fixed within a framework related to geography and time. As noted above for the thick, deep marine clays of north Sarawak, the old “Setap Shales” unit was subdivided by recognition of the regional Base Miocene Unconformity, below which the older unit, which then became known as the Temburong Formation (Brondijk, 1962), was more strongly deformed. This deformation denotes a time of significant change, and while clays either side of the BMU may have little facies contrast (as deep marine clays generally have little facies diversity) it is directly implied that in other locations there will be more obvious facies contrast associated with such a significant tectono-stratigraphic change. However, this means that in many places very similar clays need both age dating and a validated framework in order to be assigned either to the Temburong or Setap Formations. Assignment of a formation name is an attempt to record an objective observation, but a more complex, validated stratigraphic framework cannot be avoided as part of a meaningful source of stratigraphic classification. This is the subject of this review, as each

Cycle boundary unconformity in Sarawak has a different palaeogeography, and this is a fundamental part of the geological framework.

The sandy delta-plain deposits of Cycle I in Sarawak are historically divided into the Biban Sandstone Member, the main Nyalau Formation and the Kakus Member. Wolfenden (1960) abandoned use of the term Biban Sandstone Member as he thought it was indistinguishable from the Nyalau Formation. Liechti (1960) seemed to accept this idea, but he still included a Biban Sandstone Member on his maps, and reproduced the definition of older workers. This historical division was based on the locally calcareous nature of sands and clays in the Biban Sandstone Member and, perhaps as a result of these cements, the Member formed high relief morphological features. The Biban Sandstone Member is mapped mostly in the southwest, in the Bukit Buan, Bukit Lesong and Bukit Kana area east and southeast of the town of Tatau. A Petros field trip to this area found no significant increase in calcareous content, or obvious lithological difference to the Nyalau Formation. In this area near to the town of Tatau and the Biban River it is early to mid Oligocene in age (with rare *Nummulites fichteli* fossils), however 115 km northeast in the Ulu Suai Dome, the same facies is dated as Early Miocene, *Globigerina binaiensis* Zone, and Liechti (1960) notes other locations in this northerly area where it occurs with the Te5 and younger foraminifera *Miogyopsina*.

The Nyalau Formation was assigned a type area by Liechti (1960) in the Sabulong-Selungun area, between Bintulu and the location of the old Suai wells (Figure 5). This area has numerous field samples and was cored by Shell Sarawak (Rahdon, 1974), and is known to be a sandy lower coastal plain deposit with rare marine floods of latest Oligocene age (Te2-4/ Pcs.145 zone). Other sites mapped as Nyalau Formation to the southeast, such as around the Ulu Suai Dome, are known to be well within the Early Miocene.

The Nyalau Formation changes gradually into the Kakus Member that has a different succession of sandstones and laminated clays with lignite seams, no marine foraminifera, and only occasional brackish water forms. The Kakus Member is named after the Sungai Kakus, WSW of the Bekuyat Limestone, where the Kakus facies is above a thin unit of Tubau Formation clays with *Paragloborotalia kugleri* Zone fossils, indicating it is a basal Miocene age unit in its type location. Other sites mapped as Kakus Member onshore are known to have different ages, and the younger Cycle I and II sections offshore in the western Tatau province have equivalent non-marine facies (Barrett & Tan, 1987).

The Rangsi, Begrih and Tunggal conglomerates

Three conglomerate beds in the region have previously been considered to be a single unit. The Rangsi (or Ransi) Conglomerate is located on the northeast side of the Tatau Horst and has been interpreted as being stratigraphically between the Bawang Member (upper part of the pre Rajang

Unconformity Rajang Group, Belaga Formation) and the overlying Tatau/Buan Formations that contain Late Eocene and Early Oligocene microfossils. However, as noted by Wolfenden at its only outcrop location, while the lower contact with the Bawang Member is seen, there is no evidence that it actually underlies the Tatau Formation. Wolfenden and Liechti both considered the Rangsi Conglomerate as synonymous with the Tunggul Conglomerate, and the old mapping reports abbreviate both these units as “TRC” for Tunggul-Rangsi Conglomerate. This unit outcrops as a distinct ridge around the north and northwest side of the Tatau Horst, including the Tunggul Tutong Hill (Figure 3).

To the south, on the flanks of the Arip-Pelagau Anticline, there is an unnamed conglomerate above the Arip Volcanics and below the Tatau Formation (Liechti, 1960, p.113, Table 9) about 250 m thick and “composed of quartzitic sandstone boulders, vein quartz and chert pebbles, with some igneous fragments”. Recent fieldwork by the present authors not re-

locate this site, and it would be worth examining to see if it is compositionally distinct from the Tunggul Conglomerate that is dominated by rhyolite clasts.

Liechti and Wolfenden both speculate that their TRC unit correlates with the Begrih Conglomerate about 33 km to the west. Liechti (1960) stated “If the Tunggul-Rangsi Conglomerate forms an extension of the Begrih Conglomerate (which appears most probable) the presence of the formation in a wider subsurface area east of the Balingian river would appear probable” and “The Tunggul-Rangsi Conglomerate itself is probably a member of the Begrih Conglomerate, but this remains conjectural”.

Both the Begrih Conglomerate and the TRC are up to 200 metres thick (Liechti, 1960; Wolfenden, 1960). Both contain clasts derived from the Rajang Group (Hennig-Breitfeld *et al.*, 2019). The Tunggul Conglomerate however is rich in rhyolitic igneous clasts (vitreous tuffs), a lithotype that the present authors could find no trace of in the Begrih Conglomerate. In this latter unit the pale clasts are exclusively of vein quartz, as seen developed in the Belaga Formation beds to the south.

The age of the Begrih Conglomerate, at the base of the Begrih Formation, is about mid Early Miocene on palynology (above the evolution of *Florscheutzia levipoli* and also with latest Early Miocene *Praeorbulina* species in rare marine floods; Murtaza *et al.*, 2018) in the upper Begrih Formation. It is considered to be at the base of Cycle III.

The hard Tunggul Conglomerate bed in the north and northwest of the Tatau Horst clearly overlies both the Tatau Formation at the western end of the horst, as well as a part of the Nyalau Formation (see Figure 3). This is shown in the mapping of Wolfenden (1960) and Liechti (1960). Zin (2000) noted that the Rangsi Conglomerate “has been regarded by many workers as a classical example of the geological contact between the Tatau and Belaga formations”. However, Zin (2000, his Figure 5) showed seismic across the Tunggul Hill area (Tunggul Conglomerate) and field data to suggest an alternative age for all conglomerates around the Tatau Horst, to be at the base of his Sequence T4S (Cycle V and possibly IV), which he considered Late Miocene as a result of being mis-led by false ages on the Balingian Formation (see Murtaza *et al.*, 2018; who published radiometric dating of tuffs from just above the Begrih Formation). Hennig-Breitfeld *et al.* (2019), with fieldwork only in the eastern road cuttings at Rangsi, mistakenly continued to regard all conglomerates around the Tatau Horst as being below the Tatau Formation.

This present paper concludes that the Begrih Conglomerate was a unit at the base of Cycle III, unconnected to the Tatau area conglomerates. The Tunggul Conglomerate is probably younger and was deposited at a time following uplift, folding and erosion of the Arip-Pelagau Anticline, which would have exposed a local source for the clasts of rhyolitic tuff. This is probably the base Cycle IV tectonism (Doust MMU) based on the seismic correlation of Zin (2000).

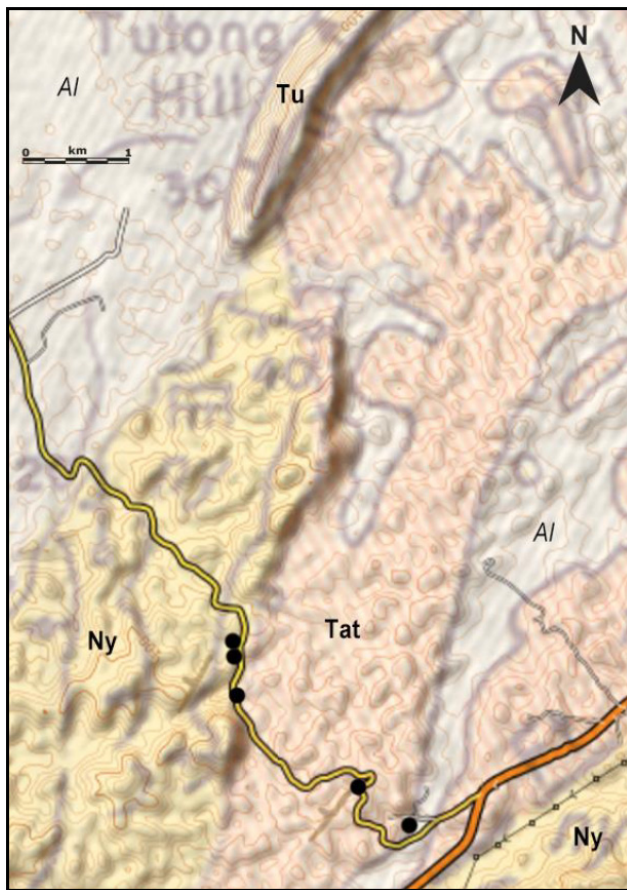


Figure 3: The geology map of Wolfenden (1960) overlain on open-source topographic maps (see Figure 1 for location). The ridge of the Tunggul Conglomerate in the north (Tu; Tunggul Tutong Hill) is clear, and it overlies both the Tatau Formation (Tat) and Nyalau Formation (Ny). The black dots are new samples collected by the authors confirming the formations and that the contact of Nyalau with Tatau Formations is a well-defined break-of slope with the trend shown by the contours.

BINTULU TO SUAI CORING

A key area onshore is where the transgression that defines the base of Cycle II can be integrated with biostratigraphy data. The majority of Cycle I to Cycle II studies have been carried out in the offshore area and to the west (such as Levell & Tan, 1986; area marked on Figure 1), where there are multiple oil fields and a low angle unconformity on seismic, but where the facies are non-marine, and hard to date.

Between the town of Bintulu and the Suai River, 75 km to the NW, is the type location of the Nyalau Formation (Sabulong and Selungun Anticlines; Liechti, 1960). This area has multiple outcrop samples as well as fifteen core-holes that were drilled by Sarawak Shell to study lithological properties below the effects of weathering (Rahdon, 1974). There were seven deeper holes from 400' to 558' feet deep annotated "RD" (reconnaissance drilling) cored in 1972 or 1973, and eight shallower holes drilled in 1973 using a lightweight Winkie-type drill, annotated "WRD", reaching 143 to 180 feet (Figures 4 and 5). Samples from these core holes were examined by Shell for sedimentology, micropalaeontology, palynology, as well as petrography, porosity and permeability. The thermal maturity properties of spore colour and vitrinite reflectance were measured but were reported on a proprietary Shell degree of organic maturity (DOM) scale, which has only an approximate correlation to published maturity scales. All samples in this area have thermal maturity in the early oil window, roughly 0.6 to 0.7% Ro in terms of vitrinite reflectance. This degree of burial and induration (between 2 and 2.5 km of burial depending on assumed geothermal gradient) also affected the younger, more calcareous samples that are cemented, which restricts the ability to process out some of the smaller planktonic foraminifera (see below).

The importance of this area is that there are marine interbeds within the type Nyalau Formation that have been studied in tandem with non-marine palynology. Figure 4 summarises these cores, plotted in geographic order from the SW (Type Nyalau area) to the NE (Setap Shale or Tangap Formation marls around Subis). A map of surface geology and the core locations is shown on Figure 5, also showing the GPS based Locations 7 and 9 of Madon *et al.* (2022) and less accurately described sample locations from Breitfeld *et al.* (2020). The stratigraphic significance of this area is that there are both core and outcrop samples in the type Nyalau Formation indicating an age of Lower Te, or more precisely Te2-4, with *Spiroclypeus* (sensu lato), *Heterostegina* (*Vlerkina*) and *Miogypsinoidea*, along with pollen floras indicative of the Zone Pcs.145 (now called Zone P200; see Lunt & Luan, 2025, for details on the ages assigned). Samples to the northeast show an increasing influence of clays (mapped by Liechti, 1960, as the Setap Shale) and at the same time there is a transition to samples with upper Te (Te5) larger foraminifera, which is the evolutionary appearance of *Miogypsina* in a stratigraphic record already

containing the ancestor *Miogypsinoidea*. The transition to a more clay-rich deposition is also seen in the core samples as both an appearance of more calcareous argillaceous beds (limestones and marly clays), and also for these marls to contain the planktonic foraminifera *Globigerinoides*. The down-section disappearance of *Globigerinoides* (=evolution datum) alone does not identify the base of Zone N4 (a proxy for the base of the Miocene), as its absence could have been environmentally influenced by the paucity of planktonic foraminifera in the clays of Nyalau Formation. However, it confirms that the oldest inner to middle neritic, clay-rich facies as being from within the Miocene. At the same level at this marine transgression is the climate related (end of seasonal, onset of everwet conditions) palynology event that defines the top of pollen Zone Pcs.145. This contact was noted by Rahdon (1974) to have been drilled in the RD73-4 core-hole.

A visit to the area by Petros in 2023 could confirm the dominance of heterolithic, non-marine sediments (sites SK-1 to 3 and SK-6,-7 in Figure 5). Site SK-4 was of marine clays and SK-5 contained a rich Upper Te (Te5) foraminiferal assemblage.

Note that Rahdon's report used the designation of the *Globigerina binaiensis* Zone for the oldest Miocene planktonic foraminiferal fauna. This implies that the prior and basalmost Miocene *Paragloborotalia kugleri* Zone might be missing. However, the data listing in Rahdon (1974) reveals that the calcareous rocks above the marine transgression are well cemented and this adversely affected the fauna recovered. The larger foraminifera were examined in thin section and observations were not significantly affected, but recovery of small planktonic foraminifera, such as *Paragloborotalia kugleri* ("*Globorotalia* 19" in Shell's old nomenclature), which are not a significant proportion of the total planktonic fauna, will possibly not be observed because these smaller bioclasts are hard to extract from cemented rock. The Petros sample SK-5 was from a larger foraminifera rich calcareous clay and it confirmed this bias against the observation of *P. kugleri*, even though its larger foraminifera based age of Letter Upper Te is mostly age equivalent to the *Paragloborotalia kugleri* Zone. Consequently both in Rahdon's report and other geological survey work in the area it has to be considered that assignment of samples to the *Globigerina binaiensis* Zone probably includes ages in the older "*Globorotalia kugleri*" Zone. In contrast, *Globigerinoides* is a distinct morphological form (and present in Petros sample SK-5), so that while the separate species of *Globigerinoides* are noted as hard to distinguish by Rahdon (1974), the distinct form of the genus, and an age above the "*Globigerinoides* datum", is a reliable observation.

A perspective of the total thickness studied by the Bintulu-Suai cores is the 24 km long correlation from the Selungan-1 to Suai wells (Figure 6). This is less than half of the 75 km SW to NE distance covered by the core samples,

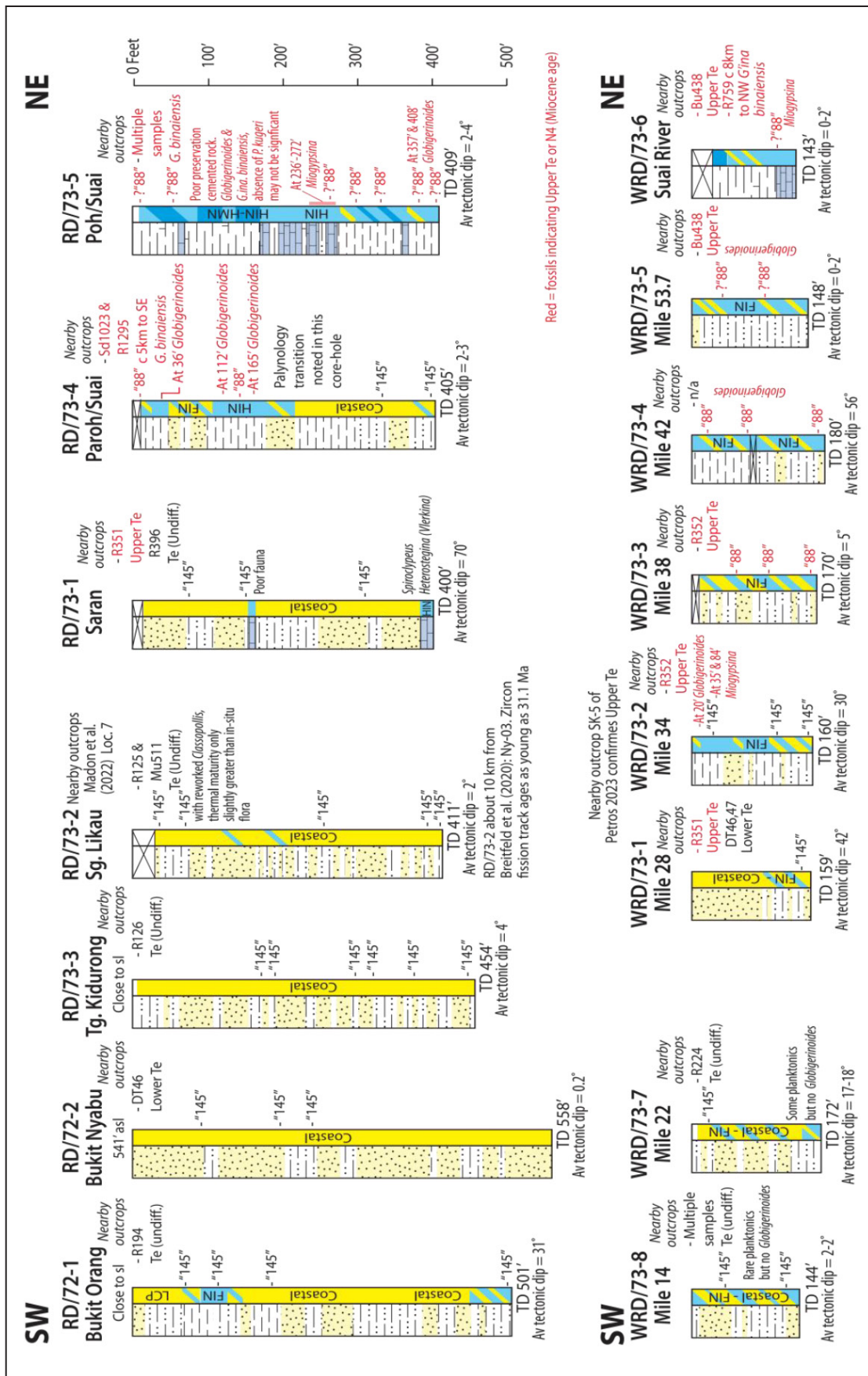


Figure 4: Rahdon (1974) coring results. Cores aligned from SW (left) to NE (right), locations shown on Figure 5.

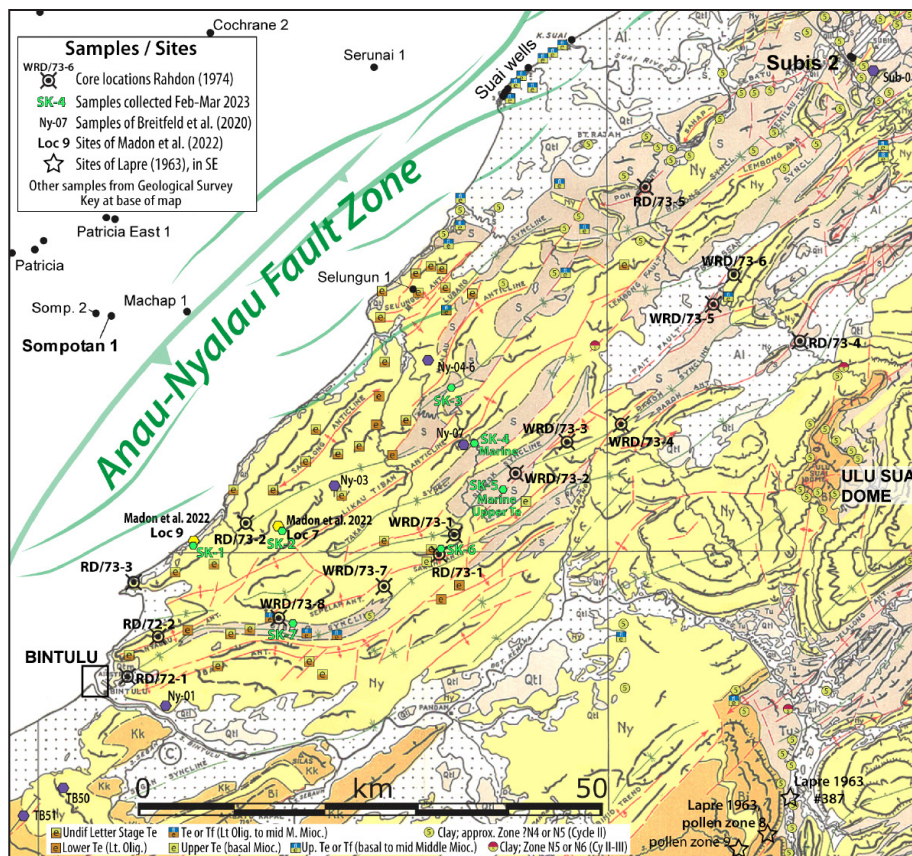


Figure 5: Location map of cores and samples on the geology map from Liechti (1960). Location of this map shown on Figure 1. Sites RD are the deeper “reconnaissance drilling” and WRD are Winkie-type shallow bore holes using more portable equipment. Petros 2023 field sample sites are annotated “SK”. Sompotan-1 offshore is the key well showing the transgression to be a large stratigraphic event and not a horizontal trend to more marine beds in the NE.

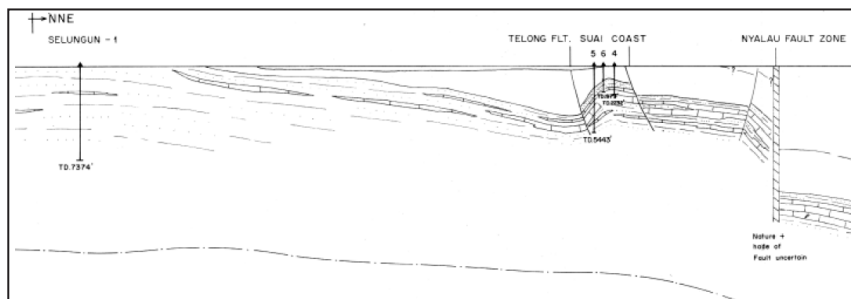


Figure 6: Simple correlation of the Selungun and Suai wells (from the 1968 A1-1 well proposal), showing the approximate proportions of Cycle thickness over a third of the Bintulu-Suai coring study area, with the prevailing dip to the NE.

but this well-based cross section shows the general, gentle dip to the NE. This indicates that about 2 km of stratigraphic section was sampled by the outcrops and shallow cores.

It can be demonstrated that the change to marine fauna in this cored area is a transgression exposed on an eastern dipping traverse, and it is not just a horizontal trend into more marine facies in the northeast. This is shown by the analyses of the Sompotan-1 well about 20 km offshore from the study area. In this well (Figure 7) the Cycle I section is almost

always barren of marine microfossils (rare traces of estuarine arenaceous foraminifera and very rare larger foraminifera are present) and this section has Oligocene palynomorphs such as *Meyeripollis naharkotensis* to its top. The original analysts (Robertson Research) noted that there was an abrupt change up-section to samples with consistent marine (inner neritic) microfossils in every sample, including Letter Stage Te5 age markers. The palaeogeographic expression of the transgression is illustrated in Figure 8 by the limestone

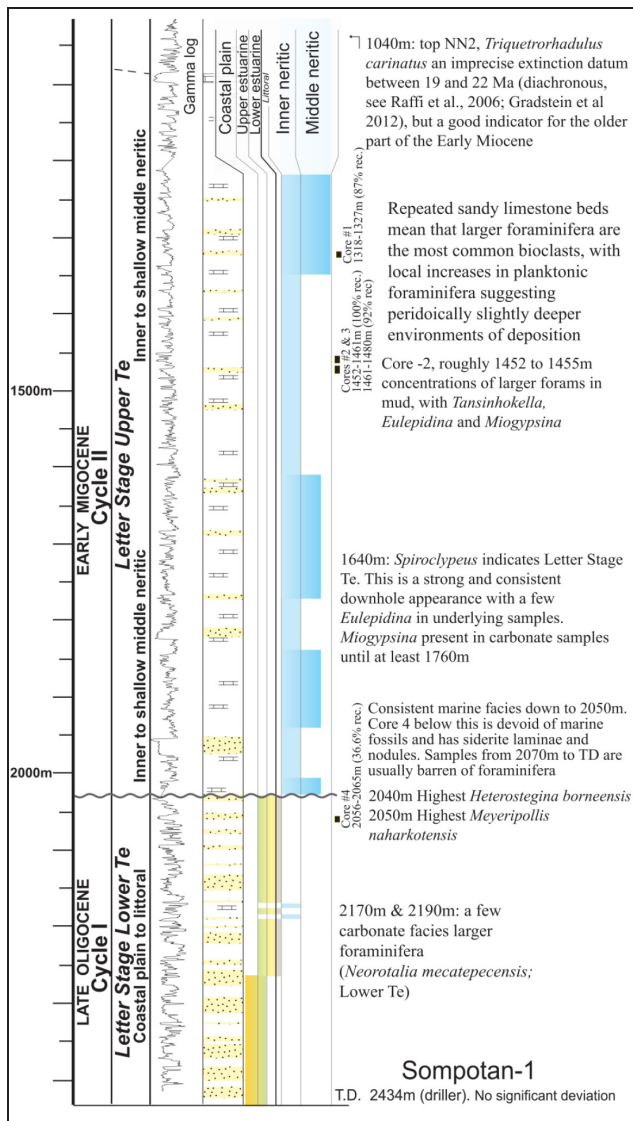


Figure 7: Summary of the offshore Sompotan-1 well (location shown on Figure 1). The environment of deposition summary column is traced off the Robertson Research biostratigraphy report and it shows a single, abrupt transgressive event, well-dated on larger foraminifera as close to the Lower to Upper Te boundary at top Cycle I (evolution *Miogypsina*, approximate extinction of *Heterostegina* and *Neorotalia mecatepecensis*; analyses by Ong Guan Bee of Robertson Research who used strict species concepts for the last two markers). The Oligocene palynomorph *Meyeripollis naharkotensis* was found as high as 2050m but the climate related palynology event marking the top of P200 (old Pcs.145) was not logged in this well.

that appeared after the end of Cycle I, as shown on the mid Cycle II map (top right). The Sompotan-1 well could have become the type location of the Cycle I to II boundary except it was drilled by Agip, who did not apply the then proprietary Shell palynology scheme that identifies the top Pcs.145 (top P200) pollen zone. It is the identification of the angular seismic event offshore and further west, at the top of Zone P200, that is crucial to correlate marine and

non-marine facies to sequence stratigraphy and the bounding unconformities.

Walther's Law requires that if an abrupt, step-like transgression is seen in Sompotan-1 and a similar step-like transgression is also seen in the Subis area (onset of the Subis limestone, see Liechti, 1960, his Enclosure 1) then a similar step-like shift in facies must be expected in the type Nyalau area about half way between these two other sites. Furthermore a step-like change in facies must reflect an abrupt (hardly diachronous) shift in sedimentary systems.

INTEGRATION OF LITHOFACIES WITH CYCLES

The development of lithofacies (the basis of formations) and the Cycles is best shown as a series of palaeogeography maps (Figure 6). The reason why such a series of maps is required is to demonstrate the geographically uneven variation in palaeogeography through time. Many workers on onshore outcrops have assumed a single, gradually regressive succession, and hence deduce that the facies-related formations will have a roughly "layer-cake" stratigraphic distribution (e.g. Figures 6 and 7 of Liechti, 1960; Figure 3 of Breitfeld *et al.*, 2020), however the actual age and geographic distribution of facies and environment significant foraminifera indicates that this is not the case.

These early workers placed the non-marine Kakus Member at the top of a single regression, Liechti could not rule out a Tfl age for the youngest part of this regression, and Breitfeld *et al.* (2020) assumed this to mean an age for the uppermost Kakus Member to be near the Te5 to Tfl boundary (their Figure 3). This was then calibrated by them to an obsolete correlation of Letter Stages to standard time scales (see Lunt & Luan, 2025), and consequently they incorrectly inferred an age for the maximum regression and the Kakus Member to be in the later part of the Early Miocene, stated to be about 17.5 to 18 Ma. All of this reasoning towards a concluding statement of age expressed with an implied precision of half a million years, was based on a series of unsupported assumptions, so can be disregarded.

Facies mapped as Kakus Member, such as the coal-bearing outcrops just south of Bintulu, are clearly Late Oligocene, Lower Te in age, based on Rahdon's coring and geological survey samples (Figure 5). A different, large outcrop (c. 50 by 10 km) also assigned to the Kakus Member is located about 20 km SE of the edge of the map in Figure 1, as an outlier around Batu Bora, overlapping onto eroded Rajang Group, and is also dated as Lower Te, or Late Oligocene, based on a number of thin, larger foraminifera-bearing beds (Jordi & Bowen, 1956; Liechti, 1960). A third location is the type Kakus in the Sungai Kakus river that is dated as basal Miocene *Paragloborotalia kugleri* zone (21.8 to 23.7 Ma). Finally, the Kakus Member studied by Lapre (1963; SE of Figure 5) contained pollen but no marine microfossils and is well above the type Tubau Formation (local name for the Setap

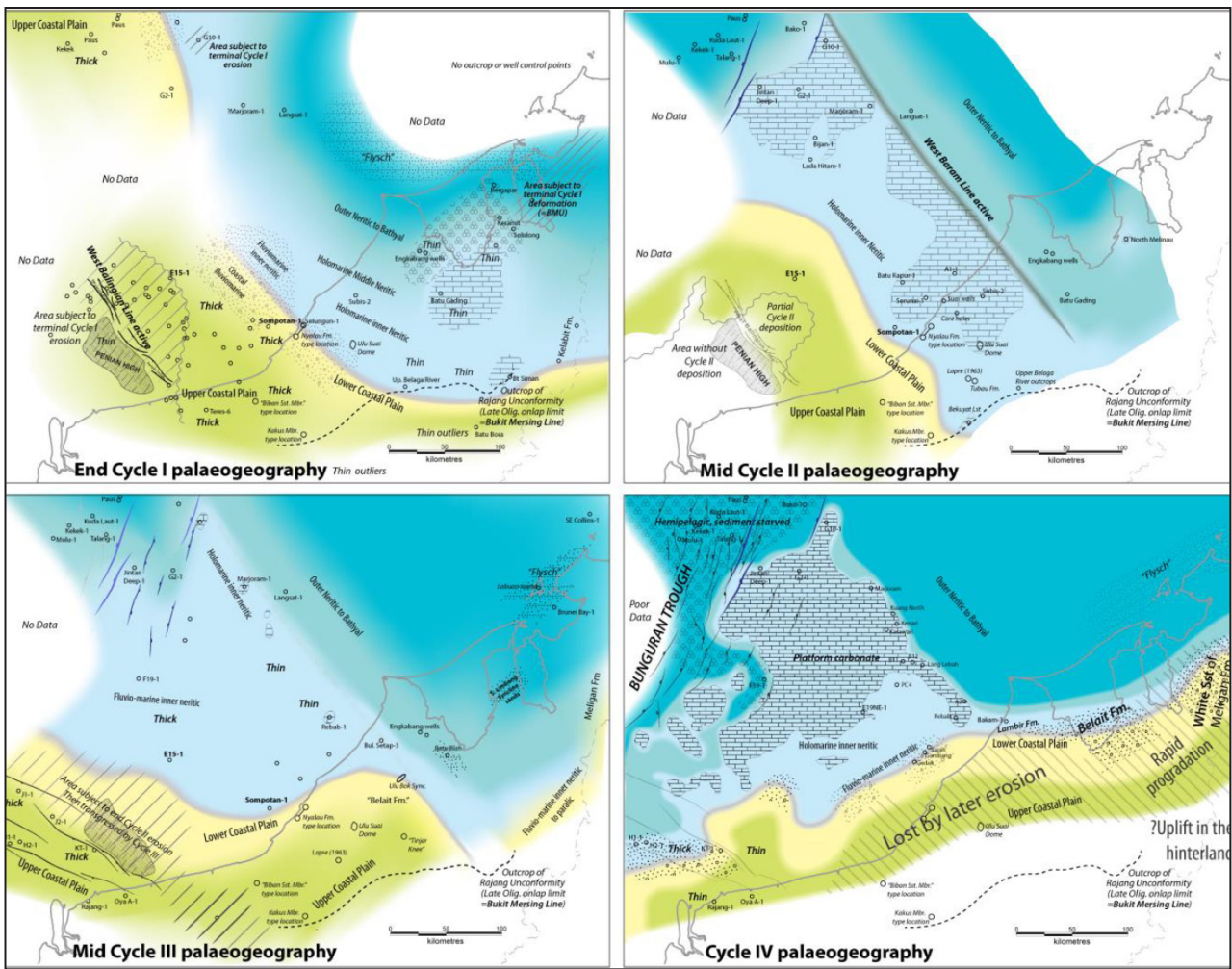


Figure 8: Palaeogeographic sketch maps of Sarawak Cycles I to IV. Cycle IV shown for completeness and because there is still uncertainty about the age of, or stages within, the regression (uplift) in the area NE of the West Baram Line to the Meligan outcrops. The data currently suggests the palaeo-coastline during Cycle III lay just east of the map limits until an acceleration in uplift of central Borneo at the base of Cycle IV, but this is the best case interpretation of fieldwork done in the 1950s and 60s. Note that the coastal plain sands SW of the West Baram Line in Cycle III (as far NE as the Ulu Bok Syncline) are disconnected from the Belait-Meligan Formation sands of Cycle IV, and therefore the term Belait Formation for sands around Ulu Bok to Ulu Suai is probably inappropriate. These are better classified as Nyalau III Formation.

Shale) of Cycle II age, so here the Kakus Member may well be part of Cycle III (see below).

The coastal plain to occasionally shallow fluvio-marine Biban Sandstone Member, used by some authors to cover the lower part of the Nyalau Formation (see above), is Early Oligocene in its type location, but it is dated as Early Miocene *Globigerina binaiensis* Zone in the Ulu Suai Dome. Clearly there is not a single regressive and diachronous stacking of lithofacies types.

It is well known that there are tectono-stratigraphic events, identified on seismic and in well analyses offshore (Ho Kiam Fui, 1978; Zin & Tucker, 1999; Lunt & Madon, 2017a). We also know the ages of these events (the Cycle boundaries) and it is proposed here that they can be projected onshore to separate the different facies sets in the Nyalau group into a predictable stratigraphic framework. This is

inevitable, as there is no reason to suspect the Cycles tectono-stratigraphy to only apply to modern offshore areas. These events split the apparently erratic facies palaeogeography described in the previous paragraphs into three units, each with a coherent palaeogeography, and each bounding event having a slightly different magnitude of change and a different palaeogeographic expression of change. That is, the Cycle I to II boundary is the broad transgression towards the WSW over an unconformity in wells offshore (Levell & Tan, 1986; Barrett & Tan, 1987; top two panels of Figure 8) that correlates to the marine transgression over the Bintulu-Suai outcrop area (Figures 4, 5 and also 6), as well as correlating with the regional subsidence of the Base Miocene Unconformity (see Lunt & Luan, 2025). The Cycle II to III boundary is strongly focused in the northwest where there was subsidence, while in the southeast of Sarawak there

was a coeval increase in sedimentation and indications of simultaneous uplift in central Borneo (bottom left panel of Figure 8), increasing in Cycle IV to the palaeogeography shown in the bottom right of Figure 8.

The Cycle I-II transition

The Cycle I to II boundary was a transgressive event after short-lived latest Cycle I tectonism in the west (local inversion of the West Balingian Line grabens and a lesser amount of uplift of the adjacent areas, see Figure 3 of Lunt & Madon, 2017a). Seismic data offshore shows only a very thin section of latest Cycle I with syn-deformational thinning during the time of this short-lived tectonism, which terminated with the base Cycle II transgression. To the north there was also some faulting and tilting during latest Cycle I prior to the abrupt base Cycle II transgression (van Vliet & Krebs, 2009). This pattern of short-lived transgression and minor, local uplift, followed by widespread subsidence is seen at each of the Cycle I to II, II to III and III to IV boundary events. The transgressive Subis and equivalent limestones that followed this local uplift and erosion at the end of Cycle I maintained a NW to SE palaeogeographic strike in the area nearshore Sarawak (Figure 8), and at this time there was the first evidence of the West Baram Line as a linear and steep shelf edge, fringed on the SW by Subis-age equivalent biohermal limestones. Wells further to the SW have diminishing thicknesses of marine carbonate with only minor, thin limestones in Sompotan-1. There was much higher magnitude subsidence at the Cycle I to II boundary in North Luconia, also well dated to be at the base of Zone N4, base Upper Te, where thick fluvio-deltaic beds were abruptly overlain by bathyal clays (Lunt, 2019).

The overall palaeogeography of the transition is shown in Figure 8 with extension in the northwest and west possibly as an early precursor to the Bunguran Trough, and possible dextral wrenching on the West Baram Line. There is debate as to the nature of the West Baram Line (e.g. Cullen, 2014), but onshore the lineament trend of the pre-Rajang beds was re-folded in a dextral wrenching manner, around the label “Sarawak” in Figure 1). This includes the Late Oligocene Batu Bora outcrops (dip and strike measurements in Jordi & Bowen, 1956). It is assumed that there was a very short period of strain reactivating the West Balingian Line and a few faults around north Luconia (G10 area), but the main movement was wrenching of the West Baram Line and extension across the North Luconia (and maybe west Central Luconia area below seismic resolution), as well as general subsidence of the entire region. This would correspond to movement in west Sabah that saw short-lived compression terminated by widespread subsidence at exactly the same time (Lunt, 2022b).

The Cycle II-III transition

It is the Cycle II-III transition that seems to be associated with the rotation in siliciclastic sedimentary supply, which

is not surprising considering the simultaneous, rapid and massive subsidence of a large part of the old delta-plain area in the west. This western subsidence is related to the formation of the proto-Bunguran Trough at about 20 Ma and is strongly seen in well and seismic data, as it involved both the extension of faults in northwestern Central Luconia (Jintan Deep to G2-1rdl) as well as the opening of multiple half grabens in the SW (the Half-Graben Subprovince, a newly formed subdivision of the older Tatau Province). This western subsidence is well illustrated on seismic in Zin & Tucker (1999) where it is the base of their tectono-stratigraphic unit T3S (=Cycle III).

About 20 km south of the Ulu Suai Dome, Lapre (1963) visited a field site between the Tubau River, where the type Tubau Formation claystones occur (a local name for the Setap Shale), and stratigraphically above this are outcrops of Kakus Member sands that were thought to be above an unconformity based on photogeology. Lapre’s mapping could not confirm an unconformity, but he found lower claystones of the “*Globigerina* 28 Zone” (markers not mentioned). This is about Zone N4 to early N5 in modern schemes, with this zone shown as directly equivalent to the *Globigerina binaiensis* zone on integrated Shell and Geological Survey schemes (Rahdon, 1971). The fauna of this zone contained a distinct bathyal assemblage, with *Cyclammina cancellata*, *Uvigerina*, *Sphaeroidina bulloides*, *Glomospira*, although the planktonic to benthic (P:B) ratio was given as only 30%. The Kakus Member non-marine sands a few kilometres away, and a few hundred metres above, contained no marine fauna and therefore probably represent a rapid filling of a Cycle II deep marine location with the new Cycle III clastics derived from the southeast.

In north Sarawak, from the Ulu Suai Dome to the West Baram Line there are Biban Sandstone Member beds deposited during the *Globigerina binaiensis* zone (bearing in mind these ages from indurated samples might also cover the difficult-to-observe *Gt. kugleri* Zone; see earlier note). These pass up into beds with diminishing marine influence, first called Nyalau Formation near the Ulu Suai Dome, but further NE, around the Tinjar Knee called “Belait Sandstone”. This change in name was apparently applied because the Nyalau Sandstone was not recognised as being this young, and also the outcropping locations are here closer to the type Belait Formation on the border with Brunei. This is the danger of circular reasoning from including geography or age as part of a formation diagnosis, without a stratigraphic framework (also discussed in a later section). In this more northern area the Geological Survey found a few marine beds assigned to the *Globigerina binaiensis* to *Catapsydrax dissimilis* Zone in coastal sandy beds. Such a combined zone represents most of the middle Early Miocene, with poor precision but good reliability. The Belait Formation in Brunei is a coastal plain facies (with rare marine floods), while the Lambir Formation outcropping to the NW is the same age, or slightly younger than the beds of the Tinjar Knee, but given their

own formation status by being slightly more marine, with more frequent development of thin limestones. On the same northwesterly trend is the Bulak Setap-3 well which drilled an entire Early Miocene clay-rich section almost devoid of any sands. It is well dated by both planktonic foraminifera and larger foraminifera (the latter within the clay facies, examined and dated biometrically by Ho Kiam Fui, 1973). These three sites, from the so-called “Belait Formation” of the Tinjar Knee to shallow marine Bulak Setap-3, and nearby the Cycle III Bekenu Limestone (Epting, 1979; Kocsis *et al.*, 2022), all shows a clear palaeogeographic trend deepening to the NW across northern Sarawak in mid Early Miocene times. We know from the A1-1 well offshore that within zone NN4 (middle through latest Early Miocene, ?basal Middle Miocene) there was a regressive succession from inner neritic to coastal and sandy facies, as the sediment prograding from the SE filled this area. In a strike direction, perpendicular to this, near-shore wells from D8-1 in the SW to Sapih-1 in the NE offshore area show no variation in Cycle III environments of deposition, being consistently inner to middle neritic clays and minor sands.

The Cycle III palaeogeographic deepening trend is therefore roughly from S to N, as shown in Figure 8 and also in Hutchison (2005, his Figure 36). It seems that north of the West Baram Line a deep trough was created by Cycle II movement, and as it was a larger space to fill the depositional facies are displaced to the east (Figure 8 lower left). In the far northeast of Sarawak, the Meligan Formation includes both Cycle II and III but lacks modern work (Wilson, 1964; taxonomy and time scale reviewed in Lunt & Madon, 2017b), however it appears to show? Cycle III to Cycle IV regression due to sediment fill from the SE (Figure 8 lower right), but the upper, coal-bearing White Sandstone Member is undated. The history of the Meligan Formation is an example of the type of unconstrained formation terminology that requires a stratigraphic framework to bring order, as well as integration with tectono-stratigraphy and geology. When the Meligan area was first mapped by Bowen & Wright (1957) they called it the “Nyalau Facies”, with what would be re-named the White Sandstone Member called “Kakus”. This was based on simple lithofacies observations, but even the 1957 larger foraminifera-based biostratigraphy indicated this area was Early Miocene, and significantly younger than the type Nyalau Formation near Bintulu, so hence Wilson (1964) erected a new name. However the question of how this facies history fits with the dynamic Cycles tectono-stratigraphy of Sarawak, or the related “Stages” scheme of Sabah, has not been attempted until this present paper. The regional Base Miocene Unconformity (Cycle I to II or Stage II to III boundary in Sabah) is a key part of this integrated reconstruction.

The Cycle III-IV transition

The Cycle III to IV boundary is a large scale and complex event summarised elsewhere (Lunt, 2022a), and

it is the event described by Doust (1981) and hence named the Doust MMU (Lunt, 2019) to distinguish it from other events in the region called Mid Miocene Unconformity, but of different ages and character. Here it is shown in Figure 8 (lower right) only to emphasise that there appears to have been another acceleration in sediment supply from central Borneo at this time. This was an acceleration of the prior trend begun at the base of Cycle III. An unpublished report by Mulock-Houwer (1968) used facies and biostratigraphic data to suggest an unconformity and increase in sand supply in the Lambir Hills region (Figure 10). There has been no follow-up work after this, and the few wells in the region are not very good study sections. Either they start almost at the top of Cycle III (Engkabang-1, Engkabang West-1, Bulak Setap-3), or are very old wells with little reliable biostratigraphy through Cycle IV and younger beds, questionably reaching Cycle III at TD (e.g. Pasir-1, Pasir-2, 1954-55, and Bakam-3, 1955). Modern work in the Lambir Hills and on the Meligan Formation is needed to distinguish Cycle II-III and III to IV in far NE Sarawak.

Summary of nomenclature

The dynamic evolution of palaeogeography presents a problem for the naming of formations because specific facies would have continued through both the I to II and II to III transitions, only moving in location, and in their direction of deposition. As noted several times above, from the published subdivision of the Setap Shale and Temburong Formation (Brondijk, 1962) and the separation of the Meligan Formation from the “Nyalau/Kakus”, as well as the local distribution of lithofacies around the study area, a framework is needed to describe and subdivide similar facies into natural tectono-stratigraphic sequences, each with a distinct palaeogeography. Consequently, it is argued that a shift from a simple lithofacies classification, to names based on a tested integration of observed lithofacies and the overall stratigraphic framework, is a better approach in tectonically active areas. However, this means that documentation must include discussion of the stratigraphic framework, including aspects of precision and trueness of observations, especially for age, environment of deposition data, and the palaeogeography of the bounding unconformities. The product of this approach is a testable, tectono-stratigraphic framework, which in this case can be extended to eventually integrate with the geological framework of the Temburong, Kelabit to Meligan Formations in the north.

For the current topic of the Nyalau group of facies we do not propose a new set of names, which will just add to the confusion and clutter of excess terminology. A system is proposed in Figure 9 that assigns lithofacies units to Cycles, so the type Kakus Member will be Kakus (II) when in Cycle II, but if its is found to be mis-dated there it is only a small change to Kakus (I), and not a redundant pronoun. Using this scheme there will be Nyalau (I), Nyalau (II) and Nyalau (III), and so on.

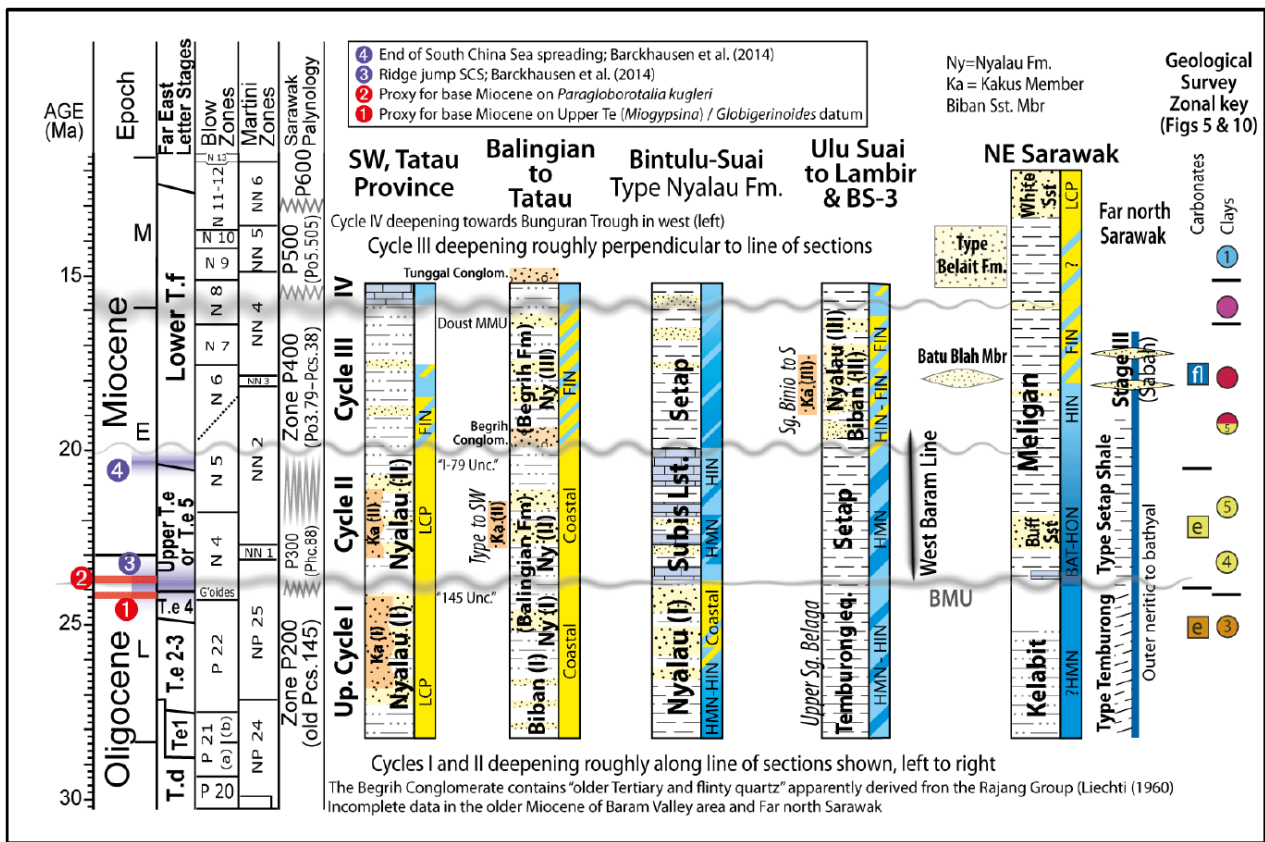


Figure 9: Stratigraphic summary across Sarawak for the Nyalau Formation and related deltaic facies. The Begrih Conglomerate is found in the Balingian to Tatau area, the Tunggal Conglomerate around the Tatau Horst.

There remains a minor problem with formations such as the Balingian Formation and Begrih Formation in the southwest of the study area, neither of which are well dated. Based on current data, it appears that the Balingian Formation can be replaced by the term Nyalau (I-II undiff.) and the Begrih Formation as Nyalau (III). This scheme could extend the application of formation names further north, offshore, where wells currently use just the Cycles subdivisions, but without reference to facies. For example, in E15-1 to the north (Figure 1) there would be a Nyalau (I) below the highest Pcs.145 in a core sample at about 9100ft and then Nyalau (II) above, passing over the Intra-79 unconformity correlated from seismic, which is slightly below the onset of marine sediments (Setap III) for about 1500 feet, and then the transgression (up-hole) into Cycle IV Luconia carbonates. In this well the stratigraphic units are picked on both age and facies history (tested by seismic), as part of the description of the evolving palaeogeography of the site. The magnitude of change at each boundary is proportional to the proximity to the tectonic cause of the sequence boundary, which at E15-1 is in a median location to most of the Oligocene to Early Miocene events. For example, locations further east of E15-1 show negligible effects of the base Cycle III event, and the section can only be summarised as Cycle II-III undifferentiated.

The stratigraphic literature is rich in examples from geologically passive areas that expect perhaps a 30 m regression at a sequence boundary to be expressed as a 30 m change in relative sea-level at all locations across a basin. This is an assumption based on exogenous (global) controls on relative sea-level. In contrast, in Sarawak, at many times, relative sea-level changed in an endogenic (geographically variable) fashion. Understanding this geographic variability is key to reconstructing the geology and depositional history of tectonically active areas.

NAMING SANDS IN THE NORTHEAST

Un-eroded fluvio-deltaic sediments of Cycle III age are rare in the onshore area, but an important stratigraphic effect can be seen in the north around the Baram Valley that highlights the benefits of using a stratigraphic framework to guide stratigraphic nomenclature, in preference to simple lithofacies-based or geographically-biased formation names. As mentioned above, in the region from the Tinjar Knee to the Ulu Bok Syncline area (the latter location in the centre of Figure 10) a Cycle III coastal sandy facies grades northwestwards into the fluvio-marine inner neritic Lambir Formation (Bukit Batu Syncline) and then shallow marine beds in Bulak Setap-3 and wells offshore. The fluvio-marine facies outcropping onshore has been dated from a few

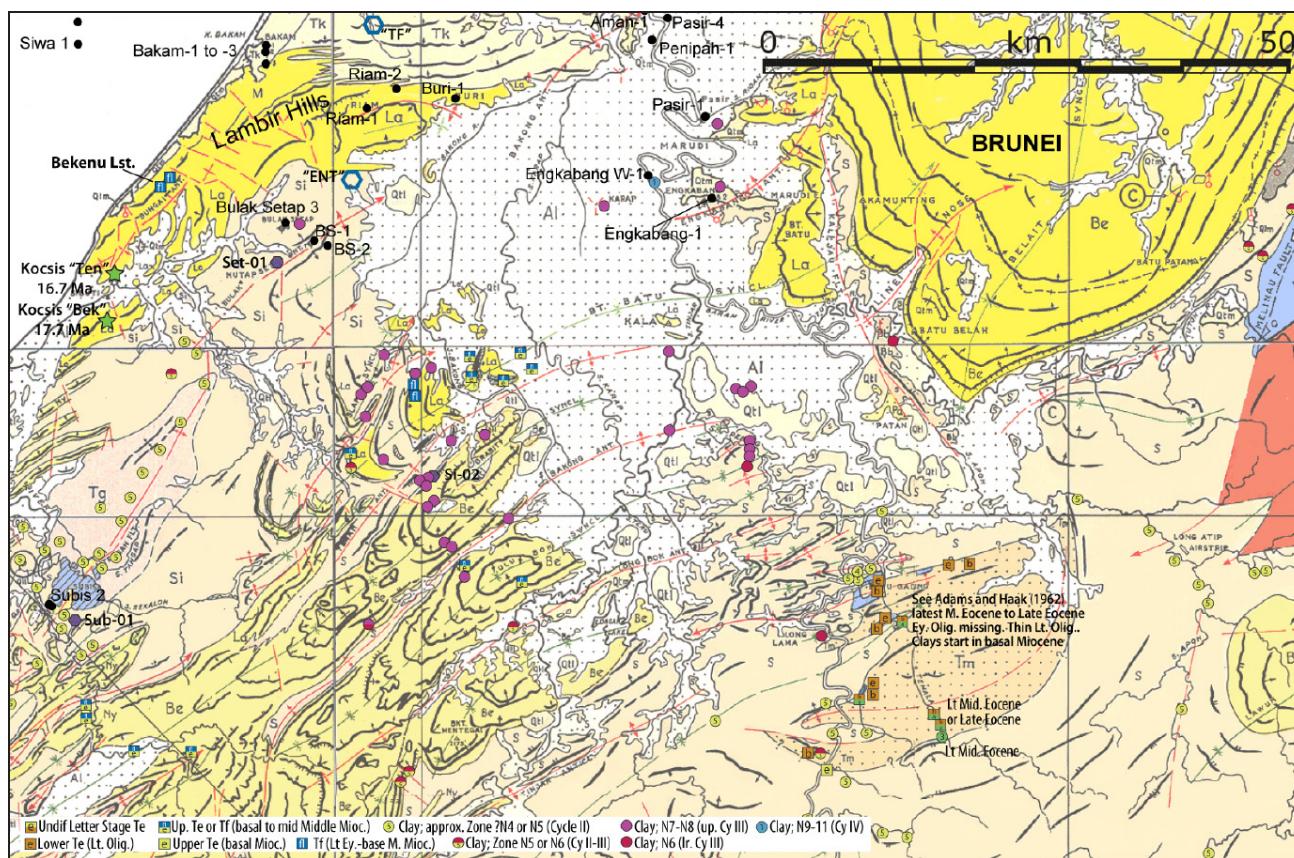


Figure 10: The northeastern extent of coastal plain facies in north Sarawak. The synclines SW of the Sungai Bakong (Bakong River), such as the Ulu Bok Syncline, are mapped as Belait Formation (Be) grading NW into the slightly more marine Lambir Formation, but the usage of the term Belait Formation is arbitrary and probably unwise, as this probably never connected to the type Belait Formation in Brunei (Belait Syncline), across the palaeo-low under the modern Baram River. The Ulu Bok and nearby outcrops are better annotated as Nyalau III. Field samples of Kocsis *et al.* (2022) near the Bekenu Lst. gave Sr ages of 16.7 and 17.7 Ma. The sample sites of Simmons *et al.* (1999; TF, ENT; discussed in Lunt 2022a) are shown, as are the sites Sub-01 and Set-01 of Breitfeld *et al.* (2020). All other symbols are Geological Survey sites.

marine floods as being from the *Globigerina binaiensis* to *Catapsydrax dissimilis* Zones (red and purple circles in Figure 10), and the sand-rich, coastal plain unit in the SE of this area has been mapped, not as Nyalau Formation, but as Belait Formation. This is apparently because this area is 85 to 150 km from the type and main Late Oligocene Nyalau Formation, which is at least 5 million years older, but it is only 50 km from the early Middle Miocene Belait Formation which is roughly 4 million years younger. This is not explicitly stated, but neither is any other reason given for this change in name.

The problem with assuming simple, gradual diachroneity of a lithofacies formation is that it overlooks the absence of any Cycle III sandy, coastal facies in the rare outcrops and wells of the Baram Valley. There are only open marine claystones of the Setap Shale between the Tinjar Knee / Ulu Bok area and the hills of the Belait Syncline on the border with Brunei. This is based on geological survey outcrop data and a few wells sampling Cycle III deep marine clays in the Baram Valley, also dated as from the

Catapsydrax dissimilis to *Globigerinoides bisphericus* Zone (e.g. data from the Engkabang-1, Engkabang-2 and Engkabang West-1 wells). The oldest Belait Formation further NE on the border with Brunei is non-marine and dated from well penetrations as Zone P500 on the presence of *Camptostemon* pollen (Pasar-2, -3; Rahdon, 1971 well summaries, redrawn in Lunt, 2022a).

This stratigraphic framework splits the Belait Formation from any connection with a diachronous reconstruction of Nyalau lithofacies. Instead of there being a coastal sandy facies of intermediate age in an intermediate position (the Baram Valley) there are sand-poor, bathyal clays of the Setap Shales across the Baram Valley, which indicates that the fluvio-deltaic facies outcropping from the Tinjar Knee, Ulu Suai to Ulu Bok had reached a shelf-edge. This edge was located where structural models place the West Baram Line. This break in palaeogeography apparently separates the so-called “Belait Formation” outcrops around the Tinjar Knee from the type Belait Formation to the northeast (see lower left

panel of Figure 8; a shelf-break that persisted as the limit to carbonates shown in the lower right panel of Figure 8). Unfortunately, modern age and facies analyses of outcrop samples are lacking, but it appears most likely that the type Belait Formation found across most of southeast Brunei is related to the White Sandstone Member of the Meligan Formation that outcrops about 60 km east, in northeastern-most Sarawak. The limited old field data on the Meligan section (reviewed in Lunt & Madon, 2017b; and Lunt, 2022b) indicates a rapid acceleration in delta-top sands in early Middle Miocene times (Cycle IV). This hypothesis, requiring testing from modern analytical data, would place the Meligan-Belait sands in a different stratigraphic and sedimentary system to the so-called “Belait” sands in the Tinjar to Ulu Bok area. Consequently it is inappropriate to use the term Belait Formation for coastal plain lithofacies in the northern Tinjar Province.

The naming of formations within a developing tectono-stratigraphic framework is arguably less objective than naming formations on lithofacies alone, but it is constrained by a tested and testable framework, which gives it scientific rigour (ideas are falsifiable). It is no less objective than giving the Subis Limestone a different name to the Luconia limestones, as each reefal, platform limestone has a definition in space and time within a tested stratigraphic framework.

CONCLUSIONS

Data from the Bintulu to Suai cores, as well as outcrop samples, correlates a marine transgression over western Sarawak to the regional Base Miocene Unconformity, and also to the sequence boundary at the top of Cycle I seen on seismic offshore.

This single, step-like transgressive event is seen within a study area about 75 km in length, containing about two kilometres of stratigraphic section, but the onset of transgression is contained within less than a hundred metres of stratigraphic section from outcrops, and much less in the nearby Sompotan-1 well. Either side of this event are relatively monotonous coastal plain, then shallow marine lithofacies. The cores and outcrops correlate this transgression with the regional and abrupt change from seasonal to everwet climate that defines the top of the old palynology Zone Pcs.145 (now top Zone P200), as well as the base Letter Stage Te5 (Upper Te) and apparently the base Zone N4 *Globigerinoides* datum; both marine microfossil events being proxies for the Oligo-Miocene boundary. The Cycle I to II transgression and low angle unconformity in the type area offshore SW Sarawak, roughly 100 km west of the study area, is also dated in many wells to have been at the Pcs.145 palynology event.

The Sarawak Cycles are directly related to an episodically changing palaeogeography. The Cycle I to II transgression saw a flood towards the old hinterland area in the SW. However in the SW, the high rate of sediment

supply diminishes the facies contrast across the Cycle I to II boundary which, in that area, is expressed as a seismic and dipmeter unconformity coinciding with a palaeoclimatic signal. About four million years after this, the Cycle II to III transition had a much stronger effect on lithofacies, with rapid rotation of the direction of sedimentation from SW to NE, becoming SE to NW.

The stratigraphic summary presented here on Figure 9 is a reference framework. The lithofacies before an unconformity (Cycle boundary) must form a coherent palaeogeography, as must the facies afterwards. The unconformity itself must also have a coherent palaeogeography as these endogenic readjustments of basin architecture will have focal areas of activity that fade laterally in a predictable manner. Furthermore the palaeogeography of the unconformities must relate to facies contrast of the enclosing sediments. For example both the Begrih Conglomerate and the Tunggal Conglomerate were products of uplift to the south from the transpressive strain of the Cycle II to III and Cycle III to IV transitions. The former being weaker and not exposing Arip Volcanic rhyolites, but both high energy conglomerates being restricted to the onshore area, and not found distally in any offshore wells. Such conglomerates are fixed in a framework of time and space; apparently located in a zone aligned with the wrench faulting of the Mukah fault trend. This demonstrates that, by predicting where and when certain facies occur, a stratigraphic framework becomes testable, and potentially falsifiable.

Such a geological framework requires age and facies data, which are the key components for testing relationships through Walther’s Law. A history of prior papers discussing onshore Sarawak, particularly the dating of the regionally important Cycle I to II boundary, demonstrates that without such a testable framework it is all too easy to construct a vague and un-falsifiable narrative, which would leave geology to drift towards the demarcation boundary of a reliable science.

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AUTHORS CONTRIBUTION

P.L.: historical review, biostratigraphic analyses, regional geology and fieldwork. M.N. and K.A.L.: regional geology and fieldwork.

CONFLICT OF INTEREST

The authors declare that there are no known conflicts of interest.

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APPENDIX

GPS location (black dots on Figure 3):
from SE to NW –

2.76195391° N, 112.68470639° E;
2.76575601° N, 112.68292463° E;
2.77396946° N, 112.67192625° E;
2.77543445° N, 112.67211614° E;
2.77771169° N, 112.67218041° E

GPS locations of Petros samples SK1 to 7 (Figure 5):

SK-1 – 3.31468701° N, 113.12409289° E;
SK-2 – 3.32531994° N, 113.21266552° E;
SK-3 – 3.45942084° N, 113.37875762° E;
SK-4 – 3.42609853° N, 113.38108385° E;
SK-5 – 3.36203942° N, 113.42369811° E;
SK-6 – 3.30114390° N, 113.36526370° E;
SK-7 – 3.23158142° N, 113.22152940° E

GPS location Begrih Conglomerate:
2.75731407° N, 112.34004750° E

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