

# A review of the Sarawak Cycles: History and modern application

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**Abstract:** This review examines the history of the Sarawak “Cycles” and their application in subdividing offshore Cenozoic stratigraphy. The Cycles are widely but inconsistently used, at least in part because important reports and data collections were never published (e.g. Geiger, 1964; Hageman *et al.*, 1987; Hageman maps, 1985, eventually reproduced in Madon, 1999 and Hutchison, 2005; and Taylor *et al.*, 1997) or were published in highly abridged summaries only (Ho Kiam Fui, 1978; Hageman, 1987; Mansor *et al.*, 1999). The lack of a data-audit trail left open possibilities for ambiguity and confusion, as has been commented on by several workers (e.g. Snedden *et al.*, 1995; Ismail & Tucker, 1999).

This account reviews the major contributions, published and unpublished, and the concepts of the Cycles, especially over times of geological change. The data behind the model is cited in order to give confidence when integrating Sarawak stratigraphic data into a regional geological model.

The Cycles began with an assumption that transgressions over regressive surfaces were distinct and approximately synchronous events for correlation. By including biostratigraphic data these transgressive events could be traced into clay-dominated areas, where lithological and seismic contrast was weak. This integrated approach was carried out through the 1970’s and 80’s, during which time the data pushed the model towards a three dimensional view of sedimentation, with the basin shape evolving and changing through time. However, development of a full tectono-stratigraphic model paused during the period of accelerated seismic capabilities of the 1990’s and early 21<sup>st</sup> Century. While geophysical data coverage increased, application of geological analyses decreased, and the integrated approach lost momentum. This review aims to re-establish the role of the Cycles as a part of a large scale geological model.

An initial integration with regional geological events is attempted, linking some of the Cycle boundaries with times of known tectonic change.

**Keywords:** Sarawak, stratigraphy, Cycles, history, application

## INTRODUCTION

A method was required to sub-divide and correlate well sections in the thick deltaic sediments deposited offshore Sarawak. Subdivision would allow different facies to be mapped and their development traced through time, while correlation would allow time equivalence to be demonstrated independent of facies. However correlation was made hard in a section where age diagnostic fossils are so scarce that evolution and extinction datums can rarely be observed with any confidence. Work on this problem began before high quality seismic and sequence stratigraphy were available. The report of Doust *et al.* (1977) shows how the earliest seismic improved up to the mid 1970s but, even with modern data, the task of proving correlation and building an integrated stratigraphy remains difficult. Early workers recognised about eight phases of sedimentation they called “Cycles”. Understanding how these Cycles were recognised and how they fit a regional model remains important.

The first stratigraphic model based on Cycles led to the identification of geographic areas, each with its own distinct stratigraphy. The Central Luconia Province, named after the Luconia Shoals where modern reefs are exposed between the locations of the G2 and G10 wells (Figure 1), is the area where reefal carbonates were seen on seismic and drilled with commercial success. The Balingian Province, named after a coastal town, is the area south of where the

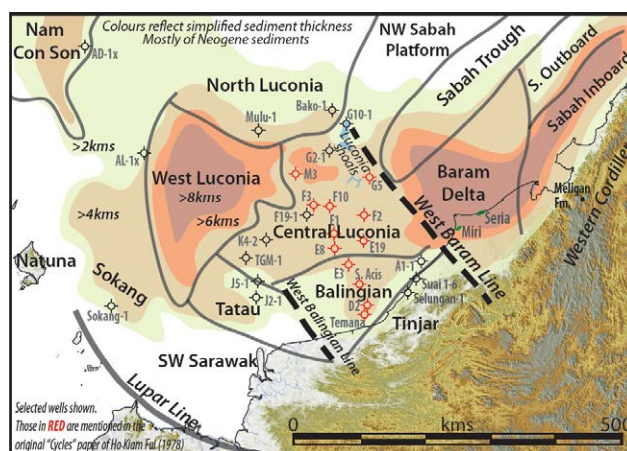


Figure 1: Location map.

reefs pinch-out, characterised by mixed fluvial to shallow marine sands and clays, and only very rare, thin limestones, deposited from Oligocene to Recent times. Seismic also showed that just west of Balingian town there was a major reduction in basement depth over a step-like feature called the West Balingian Line and much thinner clastic strata were drilled over the Tatau Province. Northwest of the Tatau Province, and west of Central Luconia, the Neogene sediments thickened considerable and this area was named the West Luconia Province. The North Luconia province is

beyond the main Neogene clinoform, in deep water, with no Luconia reefs. Finally, onshore there was uplift where an older Miocene trend has been over-printed by a later Miocene uplift that is parallel to the present day coastline. In the coastal and nearshore areas there is strong reverse faulting, so this southern area, with its own distinct geological history, is called the Tinjar province.

The challenge was how to correlate, and predict facies into un-drilled areas, in this broad region of sedimentation, with its gradual trend from coastal plain sediments in the south to open marine environments in the north, and how to correlate from clastic to carbonate facies in order to combine their sedimentological histories

### HISTORY OF STUDIES

The tools required to identify different facies in Sarawak sediments were developed early on, but the ability to correlate and thereby map facies variation at a specific time has always been challenging. Age diagnostic fossils occurred only rarely and consequently indicated only a general age, and individual data points could not be discounted from being either caving in cuttings samples, or reworked.

Some fossils grade from an ancestral form into a series of descendants. The evolutionary grade can quickly and reliably indicate an approximate age for a sample, independent of evolution or extinction datums, but with the fast rates of sedimentation seen in most parts of Sarawak these approximate ages are of very low resolution (relative to the thickness of sediment in an exploration well). This is case for the *Florschuetzia* and related mangrove pollen that are common in the Oligocene and younger clastic sediments of Sarawak. In the marine carbonates, some genera of larger foraminifera such as *Lepidocyclina* and *Miogypsina*, evolved in a gradual series, and with some rigour workers can identify “species” based on fairly precise morphological criteria. This method often fails because of observation bias and drift of species concepts, as well as sample quality and recovery problems. Correlating between the exclusive facies of pollen-free limestones and foraminifera-free coastal plain sediments remains an issue. Approximate ages have long been available, but explorers needed higher resolution correlation through marine and non-marine facies.

### THE ORIGINAL DEVELOPMENT OF “CYCLES”

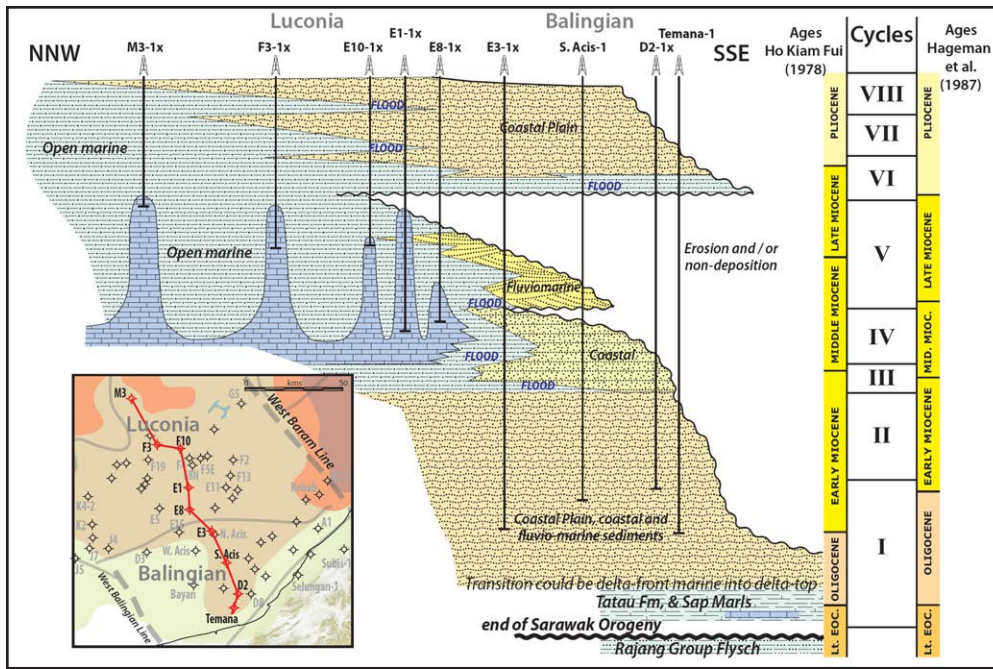
Work by Shell during the first part of the 20th century in the Miri and Seria fields of northernmost Sarawak and Brunei, found that the young clastics there could be correlated on what they called “Faunal Bands” of usually multiple, non-age diagnostic foraminiferal species, with the centre of the bands known as “Horizons”, and a number of bands called “Faunal Zones” (cf. Hageman *et al.*, 1987). In an unpublished report by Geiger in 1964, Shell stratigraphers thought the same technique could be used for the problem of correlating the older sediments of the entire offshore Sarawak area, which had been problematic due to a monotonous biostratigraphic and lithostratigraphic nature. Initial work on exploration wells in the Balingian Province

had some success, with acmes of foraminifera interpreted as correlatable transgressions, but since wells further southwest lacked foraminifera, palynology was added to the suite of analyses needed to tackle the problem. By the time of the first publication describing the Shell method (Ho Kiam Fui, 1977 [internal report] and 1978 [published]) the utility of nanofossils in correlation had yet to be proven, as it was only at that time that their biostratigraphic application in ideal open oceanic conditions was being established (e.g. Martini, 1971; the NN and NP zones defined).

The work by Shell identified eight units thought to be correlatable through the Late Eocene to Pleistocene of Sarawak. Their confidence in predicting this model into new exploration areas was based on the fact that they had stepped away from the empirical model of Miri and Seria by recognising relative sea-level changes. These might vary in the magnitude, but by definition should affect the entire basin simultaneously. The simple repetitive nature of the sea-level change led to the name “Cycles”, and the Cycles I to VIII were born. To distinguish between the similar cycles, and to allow correlation with standard time scales, the Cycle transgressive events were tied to planktonic foraminifera zones (Postuma, 1962 and Berggren, 1972; after the important SE Asian updates of Bolli, 1966, but prior to the final Blow’s 1979 “N” and “P” zones). Wherever there were limestones the larger foraminifera Letter Stages and degree of evolution studies on the Lepidocyclinids (Ho Kiam Fui, 1973; 1976) were used.

The Cycles were defined by an initial transgression changing gradually to a regression, as noted by Ho (1978): “*Since cycle boundaries are defined by the contact between the most transgressive and the most regressive sediments, they are generally marked by a change in lithology, e.g. marine clay overlying coastal sand. The lithological contrast frequently gives rise to seismic horizons which can be regionally mapped. The base of Cycle VI, marked by a well developed transgression, provides the best example of regional mapping of a cycle boundary. It has been mapped over some 15,000 sq. miles in the western part of Sarawak and can be followed over 100 miles into the Central Luconia Province.*” In this example the base of Cycle VI was originally dated as slightly older than the extinction of *Globigerina nepenthes*, a distinct, but generally low abundance fossil that died out at 4.6 Ma (N.B. all ages refer to Wade *et al.*, 2011 unless specified). Note that well-known but generally deeper water age-index species such as *Globorotalia tumida* or *Pulleniatina* (evolved at 5.5 and 6.4 Ma respectively) and are rarely found in the shelf sediments of the Sarawak area deposited after the base Cycle VI transgression. The base Cycle VI event is shown on Ho’s Figure 7 (redrawn as Figure 2 here) as an unconformity of outstanding magnitude across the Balingian Province.

In 1987 a Shell team led by Hans Hageman wrote an unpublished update to Ho Kiam Fui’s work, using a larger number of wells, and the important advances in planktonic zones and time scales that occurred in the late 1970’s and early 1980’s. The milestone work of Berggren *et al.* (1985),



**Figure 2:** The original sketch of the “Cycles” by Ho Kiam Fui (1978), with Hageman *et al.*’s up-dated age scale. No evidence is shown here for the Cycle I to II boundary for reasons discussed in the text/ Location map also shows key wells for Cycle I to Cycle II transition, and the line of section in Figure 3.

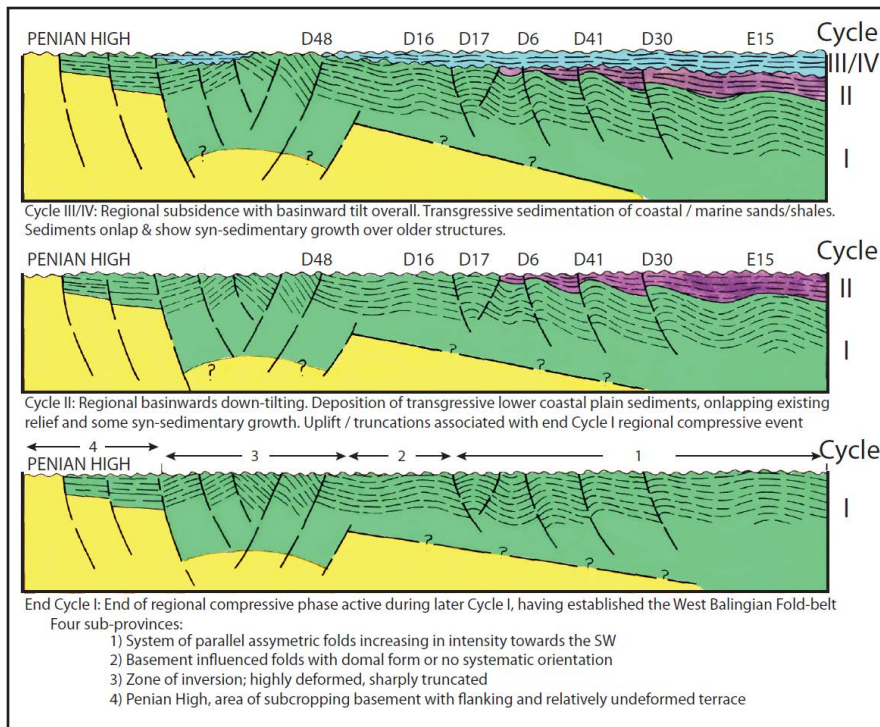
fitting biostratigraphic data to a cross-discipline standard time scale, plus taxonomic work by Stainforth *et al.* (1975), Blow (1979), Kennett & Srinivasan (1983) and the large, multidiscipline integration in Bolli, Saunders & Perch-Nielsen (1985), were all major publications that occurred between the Sarawak Cycle publication of Ho and the report of Hageman *et al.* Consequently in Hageman *et al.*’s 1987 work the cycle boundaries were fitted to a much more integrated set of stratigraphic controls. This point is worth stressing as some later papers (e.g. Ismail & Tucker, 1999) claimed that Ho’s original Cycles concept fitted well to 3rd order eustatic sea-level changes but in contrast Hageman *et al.*’s revision did not. This is an invalid conclusion as both Ho and Hageman *et al.* were looking at the same events, except Hageman *et al.* had more well penetrations and much better technologies for dating them. A summary of the Cycles after the revision of Hageman *et al.* is as follows.

**EARLY WORKER’S VIEW OF CYCLE I TRANSITION INTO CYCLE II**

In the original work of Ho (1978) and continuing into papers by Doust (1981) the Cycles I and II were usually lumped together, including sharing the same facies symbols on diagrams (e.g. Figure 2 here), as if workers knew of a bounding event, but had insufficient evidence to define the cause of it. Wells and seismic up until this time had tentatively identified an angular unconformity in the southwest, over the Tatau-Balingian margin but this was usually not annotated as top Cycle I in old well reports. The paper by Hageman (1987, his Figure 4, partly re-drawn as Figure 5 here) was the first to suggest a regression and subsequent transgression in basal Miocene times, but this interpretation was based on observations in two areas correlated by a pollen zone. In the southwest there was an unconformity and erosion (Figure 3; and by 1987 well reports were using this unconformity as

top Cycle I; see the unpublished review of Cycle I sediments by Levell & Tan, 1986), while at apparently the same time there was a transgression and flood of limestone in the northeast. However there was, and still is, a lack of deep wells in between to correlate these two areas. In Ho’s 1978 paper this transgression of limestone (in outcrop; the Subis Limestone) is shown on his Figure 2 as being at the top of Cycle I, which seems contrary to the Cycles concept given by Ho in the same paper. The limestone was also cited in the review by Levell & Tan (1986) as being at the top of Cycle I in Subis, Suai, G2-1, and G10-1 wells. Other wells such as A1-1 had also reached this limestone, which is dated consistently as Te5, basal Miocene, but these wells did not drill through to the underlying clastics.

The reason why the transgressive event was placed below a Cycle boundary was that palynological analysis had identified a unique and important change in the flora and pollen of the region as a correlatable datum. In reports up to 1987 this event defined the top of pollen zone Pcs.145, but later (in the report of Hageman *et al.*, 1987) the nomenclature changed, and this event was re-named the S200-S300 pollen zonal boundary. This event was a “distinct change in floral association from montane to hinterland, peat swamp and mangrove floras (mainly Pcs. 156 [*Rhizophora*] and Pco.219 [*Brownlowia*]) marked a very important and significant event in the vegetation of NW Borneo during approximate Late Oligocene/Early Miocene time. This remarkable change in floral association may be caused by the following: change in climate from cool and temperate to hot and humid climate.” (Hageman *et al.*, 1987). This singular and distinct change from seasonal to ever-wet climate was still noted as a major climatic event at the Oligo-Miocene boundary after much additional work by Morley (2000). Note that the clean limestones at Subis-2, G2-1, G10-1 contain no pollen and cannot be dated by



**Figure 3:** A Shell diagram from the later 1970's showing a composite interpretation of the transition from Cycle I to II and II in the coastal plain deposits on the northeast margin of the West Balingian Line fault. A tilting event was recognised to be the terminal part of the late Cycle I compression. The very top of the Penian High remained uncovered during Cycle I and was only transgressed during later Cycle III and IV.

palynology. This pollen event was seen in the first clastic sediments below the Te5 limestone in G10-1. (In G2-1 and G2-1 re-drill there was lost circulation for several hundred feet over the contact between the base of the limestone and top of clastics). The Subis-1 and -2 wells were not analysed for palynology, and it was only the Suai-5 well (1955) and A1-1 (1969), on the southwestern limit of the Te5 marine transgression, that had age data. In Suai-5 there is a main carbonate interval some 500 feet thick, plus three thin limestone beds of 30-50 feet in the surrounding mudstone section. Cores in these limestone contain good Te5 fauna and the intra Early Miocene planktonic species *Globigerina binaensis* occurs for a few hundred feet above the highest limestone. A 1977 report by Sulaiman (unpublished) noted that the Pcs.145 zone occurred to just above the highest of these limestones, and also reported that the A1-1 also had Pcs.145 floras in the interbedded carbonates and clastics at the top of the Te5 limestone there. This data therefore appeared to indicate that the intra Te5 limestone flood occurred before the climate change event, but both events are close to the Oligo-Miocene boundary.

Most exploration well data was in the southwest where the facies were dominated by lower coastal plain clastics and there were no marine deposits to calibrate the pollen zones (e.g. K4-2, E15-1, West Acis-1, Bayan and Temana oil fields, extensively covered in Levell & Tan, 1986). In West Acis-1 (drilled in 1989 and with nannofossil analysis) the first consistent marine beds are interpreted to be within Cycle III and dated as within Zone NN4 (i.e. slightly younger than 17½ Ma).

In the southwest the top Pcs.145 climate change event was noted to be just above the angular unconformity that, as noted above, was used from the mid 1980s to define

the top of Cycle I. Levell & Tan (1986) noted that “the unconformity is at or very close to the top of the Pcs.145 subzone. In fact, the upward revisions of the unconformity in D18-1 and C5-1, now mean that in no well in W. Balingian is the Base Cycle II unconformity picked more than about 100' below top Pcs145 subzone.” In many reports the unconformity is known as the “Intra 145 unconformity”. This information indicates that a tectonic unconformity occurred first, possibly followed by a marine transgression, but the tectonism was soon followed by a climate change event. The precise relationship between the transgression and the climate change is not clear. Hageman *et al.* (1987, his Figure 5) drew the Subis Limestone in Subis-2 above the Cycle I to II boundary, but by the time the Jintan Deep well proposal was made (1995), this limestone, which was the primary objective, had become known as the “Cycle II Carbonate” and was assumed to be immediately above the top of Cycle I.

Shell's seismic data from the late 1970's indicated that tilting into the basin occurred at the cycle boundary, so a transgression would appear in the more marine basinwards side, but its movement into the western lower coastal plain area would be limited (Figure 3). Hageman's 1987 and later Shell figures included half an unconformity symbol at the Cycle I to II boundary, and this apparent tectonic boundary also had a contrast in deformation on seismic, as well as in the well dipmeter data. Shell's cross-section (Figure 3) shows how the end Cycle I tectonism resulted in the “West Balingian Fold Belt”; a system of parallel asymmetric folds increasing in intensity to the southwest, as well as basement involved domal folds including inversion of the deep section.

This early usage of the Cycles had therefore begun to recognise the effects of tectonism overprinting a simple sea-

level cyclicity. There is, however, still a lack of well-studied sections over the Oligo-Miocene boundary to understand the relationship between a correlatable climate change event, a tectonic event, and the only limestone flood in the north and northeast during a 12 million year period. A few wells such as Sompotan-1 (drilled by Agip in 1990) had drilled through a transgressive event on the Te1-4 to Te5 Oligo-Miocene boundary, coinciding with the extinction of the Oligocene (and Pcs 145) palynomorph *Meyeripollis naharkotensis*, but few other wells have reached this event and been studied in detail. The Sompotan-1 analyses did not follow the Shell palynology scheme, and did not recognise the climatic event.

Hageman *et al.* (1987) correlated the top of Cycle I with the “Base Miocene Unconformity” (BMU) in Sabah, which is referred to as the Base Meligan Unconformity by field mappers, now widely known as the Top Crocker Unconformity, and dated as close to the Te4 to Te5 boundary (cf. Liechti, 1960 and Lunt & Madon, in press). Based on more modern knowledge of the age of the intra Te5 transgression, these events seem to correlate well, but neither Hageman *et al.* nor subsequent industry workers, have tried to develop this correlation into a more regional geological model linking the tilting and folding of the Tatau Province to the more severe deformation of Temburong and older formations in Sabah.

#### EARLY WORKER’S VIEW OF CYCLE II TRANSITION INTO CYCLE III

The later part of Cycle II is thought to contain a regressive event, as noted by the northeastwards extent of the erosional unconformity on the maps of Hageman (1985, Figure 36 H in Hutchison, 2005). This relatively even tilting might be due to uplift further west, possibly the inversion of the Sokang Trough (Raharja *et al.*, 2013), but data is lacking as the major inversion unconformity in Sokang has never been drilled and is undated.

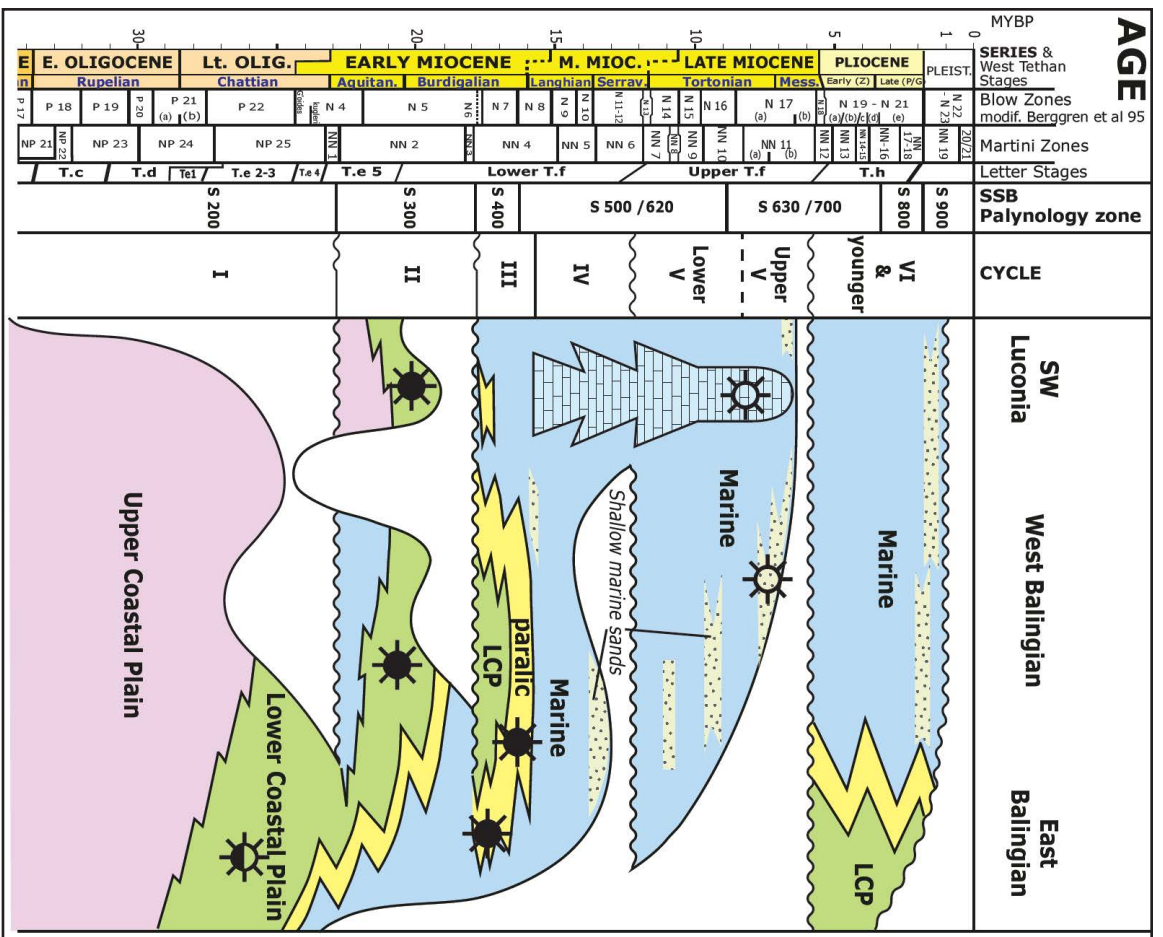
This regressive event is strongly overprinted by the major transgression that characterised the base of Cycle III, as noted on Hageman’s (1987) relative sea-level curve (Figure 5), where it represents the first major marine flood over a large part of the basin, after at least ten million years of delta-top and coastal plain aggradation. In the southwest, over the margins of the high Tatau Province the boundary is also seen as a low-angle discordance on seismic, as well as a dipmeter contrast in wells. The contrast in both palaeoenvironmental setting and the thickness of Cycle III is most pronounced on the northern flank of the Tatau Province. In the summary diagrams of Hageman *et al.* the basal transgressive sediments lacked *Globigerina binaiensis* (extinct at 19.4 Ma) but contained *Catapsydrax dissimilis* (extinct at 17.6 Ma). As mentioned above, the transgression brought the first flood of marine fossils to West Acis-1, within Zone NN4 (between 14.8 and 17.8 Ma). From palynology the unconformity became known as the “Intra 79” or “I-79 event” after the pollen zone “Po3.79” (= S410 pollen zone in the new scheme) in which it occurred. The base of Po3.79

/ S410 was defined on the lowest downhole occurrence of Po3.62 *Sonneratia* type mangrove pollen (*Florschuetzia levipoli* and *F. meridionalis*) in about the base of the Early Miocene (possibly earliest Miocene, Morley pers.comm).

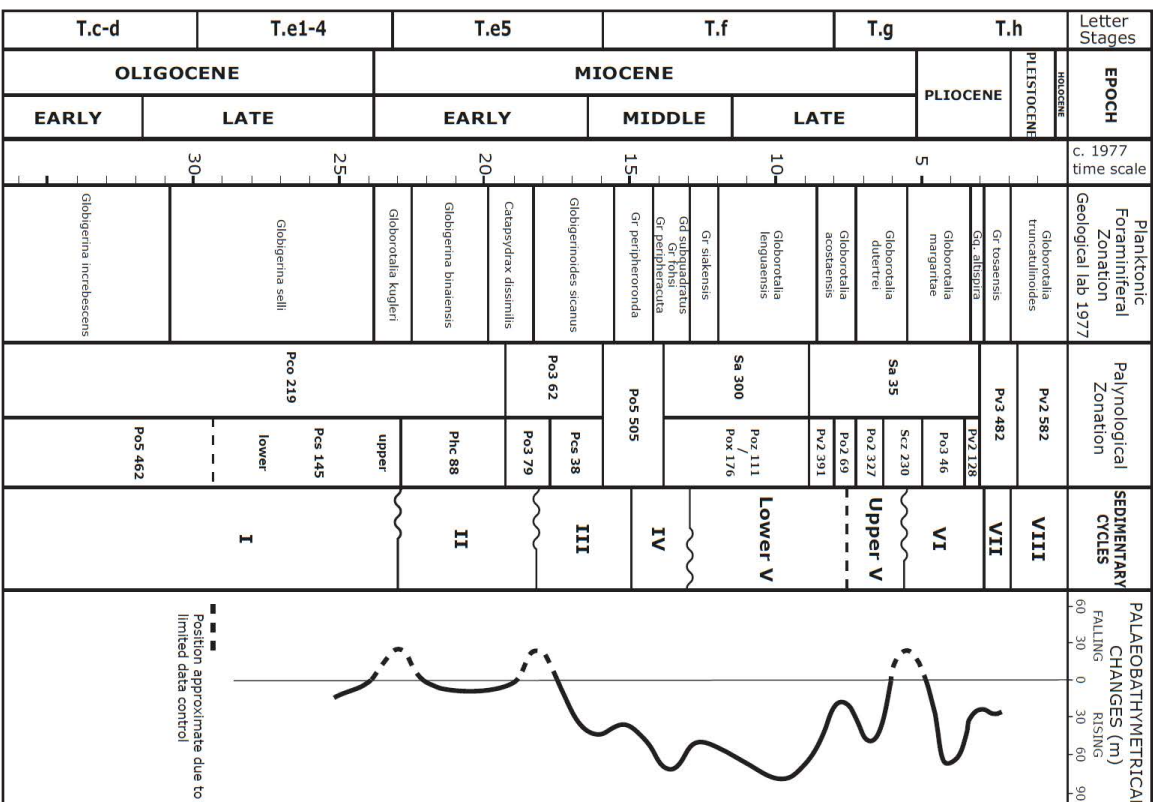
Away from north Tatau, in the already shallow marine sediments of central and eastern Balingian and Central Luconia, the Cycle II to III transgression is much harder to recognise (see the variation from West to East Balingian in Figure 4, by Veenhof). The thickness of the Cycle III section is very variable, indicating that the transgression was not uniform and that it may be due to tectonic subsidence increasing in magnitude to the west. In the east, near the coast, Shell detected a regression of about the same age as the transgression in the west. This was based primarily on early 1950’s work on the Suai wells, and surrounding outcrops. Here the presence of *Globorotalia barisanensis* (now *Fohsella peripheroronda*, evolution datum estimated at about 17 to 17½ Ma; very close to Shell’s pick for basal Cycle III) dated a transition from marine Setap Shales to the much sandier and deltaic (less marine) Lambir Formation. The transition in the Suai wells was also above the extinction datum of *Globigerina binaiensis* and well before the *Orbulina* datum (rare *Orbulina* is found in the Lambir Formation in these wells) or the evolution of *Globigerinoides sicanius* (N8) or *Sphaeroidinellopsis* (mid Miocene & younger). Outcropping Cycle II Setap Shale around the wells have limestone stringers with *Flosculinella reicheli* / *globulosa*, and the Bakong Anticline outcrop of basal Lambir Formation contain the descendant *F. bontangensis* (along with Early Miocene indicators *Austrotrillina* and *Miogypsinoidea*) indicating that the shallowing in this area was in mid Lower Tertiary, roughly 16 to 18 Ma on modern time scales (Adams, 1984; Lunt & Allan, 2004). This shallowing is also seen at the same time to the northeast in the type Meligan Formation (Bowen & Wright, 1957; location on Figure 1).

The age control on this regressive event in the east is therefore robust, however in the northwest, where the transgressive event is more abrupt, the transgression may be slightly older (based on the marine flood being just older than *Catapsydrax dissimilis* extinction at 17.6 Ma), and the regression at Suai is possibly more gradual. Nonetheless, events around the Cycle II to III boundary seem to be a dual effect of extension and subsidence of the Bunguran Trough in the west (location on Figure 19), and uplift to the east from central Borneo to south central Sabah.

The northwestern focus of the Cycle II to III transgression with a major unconformity and time gap over the subsiding high of the Tatau Province is illustrated in the cross sections of Figures 3 and 6 here. It is shown in map form in Hageman’s 1985, unpublished maps (later published by Hutchison, 2005), and also by Madon (1999). Also note that within Cycle III a few thin reefal limestone beds are known in the central and northeastern areas (F1, E11, F13 to E8 area, Figure 7) but these are not widespread, although in many areas the sediments are calcareous with bioclast-rich horizons. These calcareous facies are dominantly off-reef to open marine shelfal sediments (Lapre & Thornton, 1970).



**Figure 4:** An updated diagram for the Cycles (re-drawn from Veehof, 1997, with a modern time scale; similar diagrams to this are also found in Shell reports from the late 1980's), showing how some of the Cycle boundaries are more strongly expressed in different areas: a character that needs to be related to a wider geological and tectonic model.



**Figure 5:** Hageman's published 1987 cycles summary, which retained the older palynology zonal nomenclature (e.g. top of Cycle I was at, or very slightly below, top Pcs.145 Zone). The transgression at base Cycle II was based on the Te5 larger foraminifera in limestones in northeast Balingian. Note how biostratigraphic schemes have improved since 1987 by comparison with the modern scheme on Figure 4.

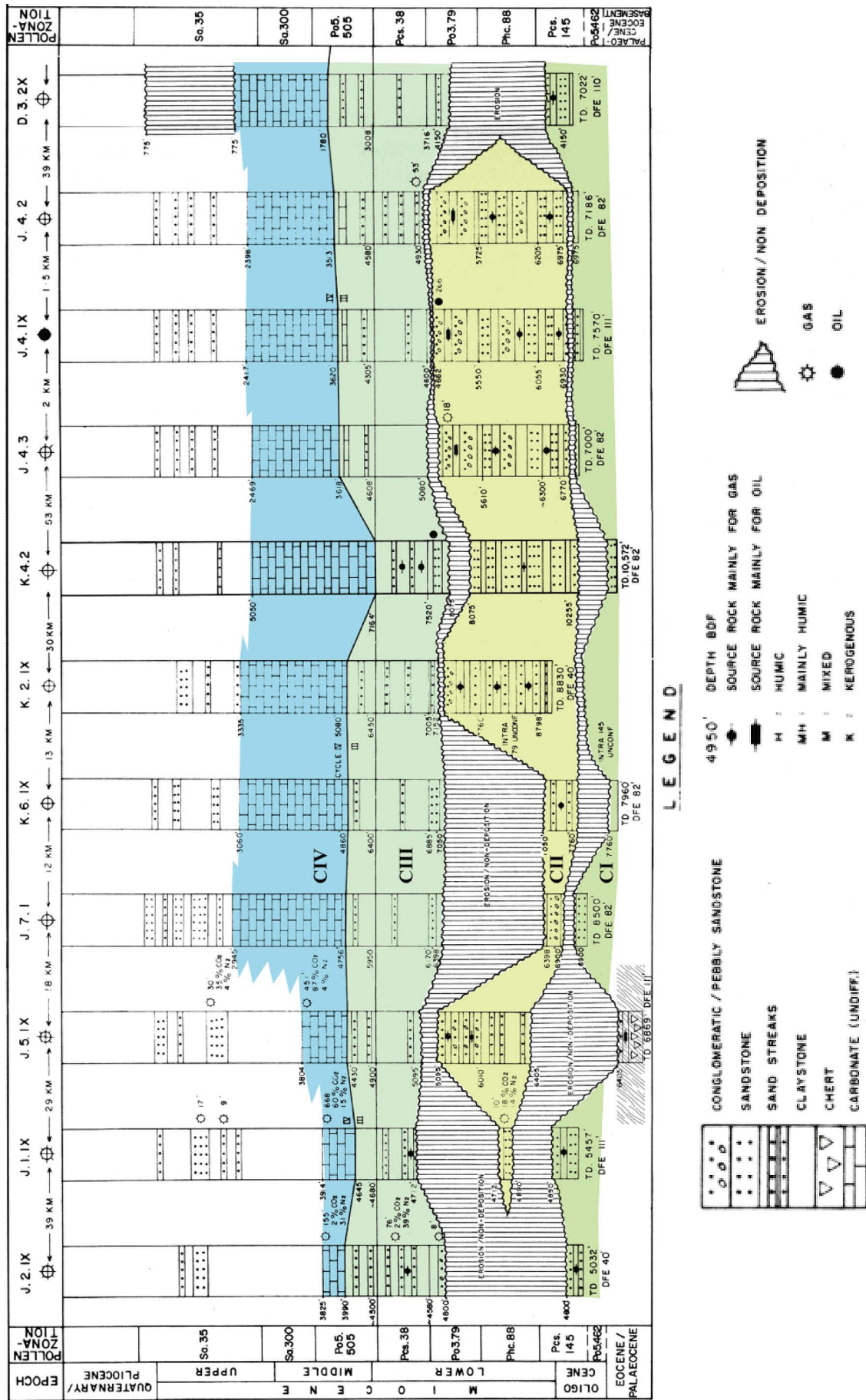


Figure 6: A graphically summary of the Cycles I to IV in the Tatau Province. Cycle III is the first unit with marine sediments, often mixed with lower coastal plain deposits in in the lower part and its base is usually adjusted slightly to the unconformity seen on dipmeter or seismic data. Cycle III is seen to cover areas to the south and southwest that have no Cycle II.

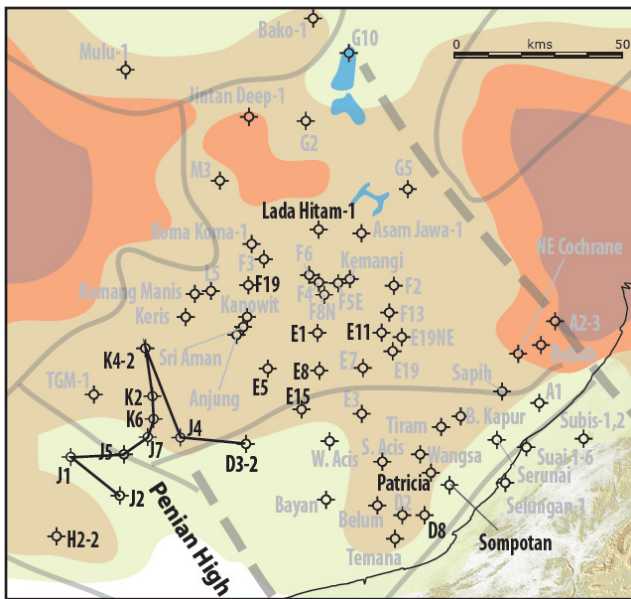


Figure 7: Location map for key wells with data on the Cycle II to Cycle III transition, including the line of section in Figure 6.

### EARLY WORKER'S VIEW OF CYCLE III TRANSITION INTO CYCLE IV

The Cycle III to IV boundary was originally dated within the total range of *Globigerinoides sicanus* (16.4 to 14.6 Ma). The *Orbulina* datum (evolution at 15.1 Ma) is rarely recorded in Sarawak as this event seems to coincide with the onset of limestone deposition and consequently is not recognisable due to the strong change in facies. In the few wells such as F19-1 (Figures 7, 13), where Cycle III to IV was drilled in a non-reefal location, *Orbulina* was frequently recorded in the deep water facies above the transgression, but it in drill-bit cuttings samples occurrences can “cave” and contaminate cuttings samples from deeper

section, and its evolutionary datum cannot be distinguished. Re-analysis of F19-1 (ELF, 1988, unpublished, location shown on Figure 7), where Cycle III to IV is a marked log break in open marine facies, the Cycle boundary is close to the extinction datum of *Discoaster deflandrei* (15.6 Ma; one possible occurrence of this fossil just above the boundary, better records just below) and *Sphenolithus heteromorphus* (no older than 17.7 Ma, ICS GTS2012) present as low as the Cycle boundary. In this well *Austrorillina*, first noted by Shell in basal Cycle IV marls, was reconfirmed by ELF.

Re-analysis of the E5-1 well in 1990 by Robertson Research observed that upon drilling through the base of the limestone (see Figure 8), just below a casing point and upon reaching new mudstone samples, the age index markers *Sphenolithus heteromorphus*, *Praeorbulina glomerosa*, *P. circularis* and *Globigerinoides sicanus* (no older than 16.4 Ma), and a single *Orbulina* were observed. A poor fauna, lacking plankton, was noted in the overlying basal limestone, but it included the distinct genus *Austrorillina*. This dates the transition from clastics to reefal limestone as in the later part of the “*Globigerinoides sicanus* Zone” of the Shell workers. Other wells such as E7-1, F13-1 &-2, E11-1 have *Austrorillina* in the basal Cycle IV limestone. As noted by Adams (1984) and Lunt & Allan (2004) *Austrorillina* became extinct within Zone N9, roughly 14½ to 15 Ma, very close to the base of the Middle Miocene, so there is no indication of any missing section at the Cycle III to IV boundary. The Cycle III to IV boundary was considered by Hageman *et al.* to be older than the DRU in Sabah (where there are pre DRU beds with *Orbulina* and *Fohsella foshi*, the latter evolving at 13.3 Ma (cf. Levell, 1987).

In Lada Hitam-1 (Figure 7) the original biostratigraphy report was unaware of casing just below the base of Cycle IV and a single instance of *Orbulina* below this, as well as many samples with *Sphenolithus heteromorphus*, suggested possible N9 just below the event, but certainly the cycle

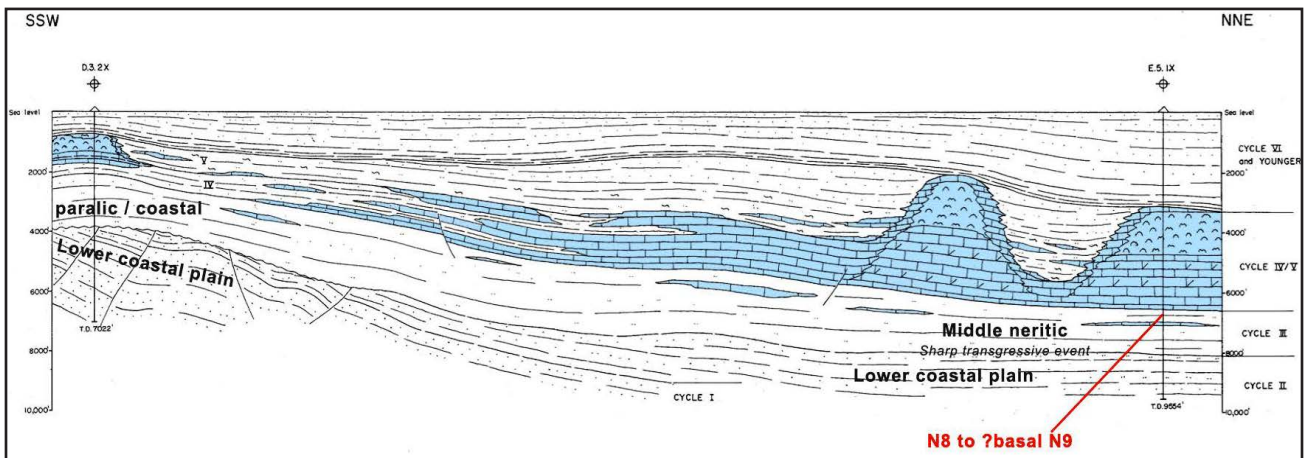


Figure 8: A sketch between the Cycle V carbonate (see also Epting, 1988, and Kosa, 2012) and the E5-1 well that has good biostratigraphic data on the Cycle III to IV boundary, with casing at the base of the limestone allowing un-caved samples from upper Cycle III to be identified as N8 ?basal N9, and limestone in the basal carbonate containing the distinct form *Austrorillina* that became extinct close to the Early to Middle Miocene boundary (van Gorsel *et al.*, 2014). Note that Cycle II pinches out onto the flank of the high where D3-2 was drilled, see also Figure 6.



boundary is much younger than 17.8 Ma. Snedden *et al.* (1995) refer to re-examination of this well by Mobil Oil and the occurrence of N7 to N8 planktonic foraminifera below the base limestone, base Cycle IV.

In the Balingian area the Cycle III to IV boundary is very weakly expressed (cf. Veenhof, 1997; Figure 4 here) with just a modest transgression seen in wells such as Serunai-1 within Zone NN4, base N8 (above base *G. sicanus*, roughly 16½ Ma, with *Austrotrillina* associated with the onset of the flood), or just below TD of NE Cochrane-1 in Figure 17. Good quality 3D seismic over the Balingian Province shows none of the extensional block-faulting that is present below the carbonates in Luconia (see the modern summary over the Cycle III to IV boundary in Kosa, 2015, his Figure 3) and which increases in intensity towards the Bunguran Trough.

Symmetrically across the Bunguran Trough, in northeast Natuna, there had also been exploration of Luconia-like reefs, but with success limited to the super-giant but CO2 polluted D-Alpha gas field. Far fewer wells drilled into the pre-limestone section and also marine border negotiation between Indonesia and Vietnam halted all exploration investment during the 1980's and 90's. However it is interesting to note that the Terumbu Limestone was initiated after a prolonged period of clastic deposition and, like the Luconia carbonates, can be shown to have been initiated at a time between the evolution of *Praeorbulina* and *Orbulina* is preserved in the underlying clastics sediments (AL-1x; Figure 1) and the extinction datum of *Austrotrillina* (present in AD-1x, at the base of the carbonate), and well before the Lower T<sub>f</sub> mass extinction of carbonate facies foraminifera at about 12½ to 13 Ma.

Note that the Cycle III to IV boundary was the first feature called the mid Miocene unconformity or MMU; a term that has been very ambiguously applied due to a lack of knowledge of its history. Many people have seen major unconformities of about this age across Southeast Asia. The term used here follows Shell's definition and early use of the phrase in the Luconia and surrounding areas of the South China Sea. The term was not used by Ho (1978) and his diagram shows no unconformity at the base of the Cycle IV limestones. The unconformity symbol first appeared in publications in Doust (1981, his Figure 8) who described the event as: "*The most important subsidence commenced in middle Miocene time (at the same time as the subsidence in the China basin) along a network of NNE-SSW trending normal faults*". In spite of its informal nature this term, and the abbreviation, gradually found its way into publications, but the summary of Doust remains the best "type" definition of the offshore Sarawak MMU, especially as it identifies the NNE-SSW Bunguran Trough fault trend as the associated tectonism.

In modern work there has been a tendency to place the MMU in the Middle Miocene, as seems to befit the name, but this is incorrect. Madon *et al.*, 2013 and Morley & Swiecicki (2014) informally re-named the event the Early Miocene Unconformity (EMU), following data detailed

above, that places it right at the end of the Early Miocene (although strictly speaking, if the base Langhian Stage is used to define the base of the Middle Miocene this would be at 15.97 Ma, and maybe this might place the MMU just within the basal limit of that definition of Middle Miocene).

Using combined stratigraphic data from off-reef, North Luconia, wells the pre- MMU sediments can be seen to be a consistent section of clays with minor sands, silts, or calcareous bioclastic sands with general shelf foraminifera and also containing nannofossil Zone NN4 and foraminifera Zone N7 to earliest N8 markers. There is invariably a log-break reflecting the MMU facies change and a marked reduction, up-hole, in any silts or sands, and a sudden increase in hemipelagic, deepwater marls. This is a very pronounced facies change reflecting sudden subsidence and a sharp reduction in the rate and energy of sedimentation (e.g. Figure 19.3 in Madon, 1999). The distal clays and marls overlying the facies / log break are usually highly condensed, but the presence of NN4 index *Helicosphaera ampliaperta*, NN5 index *Sphenolithus heteromorphus*, and mid N9 and older *Praeorbulina* species and *Globigerinoides sicanus* in both old and several modern wells, in the basal hemipelagic facies is crucial in dating the main subsidence unconformity as before the middle of Zone N9 or the top of NN4. Note that clastic-starved hemipelagic sediments are the least likely setting for re-working of nanno- or microfossils, so these taxonomically distinct extinction datums should be ranked as reliable data. The magnitude of facies change also means that such a sudden cut-off of sediment supply is likely to have been a very rapid event, not diachronous to any recognisable degree.

In many wells there is a thin unit of extremely condensed sedimentation containing NN6 and perhaps part of NN7, and some analysts use the top of this extremely sediment-starved episode, which can be a good seismic reflector, as the indicator for the unconformity, in mid to later Middle Miocene times, at roughly 12 or 11 Ma. The onset of new clays on-lapping over the condensed section depends on local topography and distance from sediment supply, but in most deepwater Sarawak wells this seems to have occurred just before the extinction datum of *Paragloborotalia mayeri* (10.5 Ma), which is a common proxy for top Middle Miocene in the region. [Note that the base Tortonian and thereby the base Late Miocene *sensu stricto* is at c. 11.6 Ma, but for many decades the proxy for top Middle Miocene in SE Asia has been the extinction datum of *Paragloborotalia mayeri* (10.5 Ma, top N14) or evolution of *Discoaster hamatus*, base NN9, appeared at almost exactly the same time as an old interpretation of top Middle Miocene (base Tortonian given as 10½ Ma in Berggren *et al.*, 1985). In other words, when the MMU was first named, the Middle Miocene was longer by a million years. Some authors have suggested this pseudo-"MMU" event has been re-dated as basal Late Miocene, but in reality the time scale has moved, not the top of the slightly diachronous condensed biostratigraphic interval.]

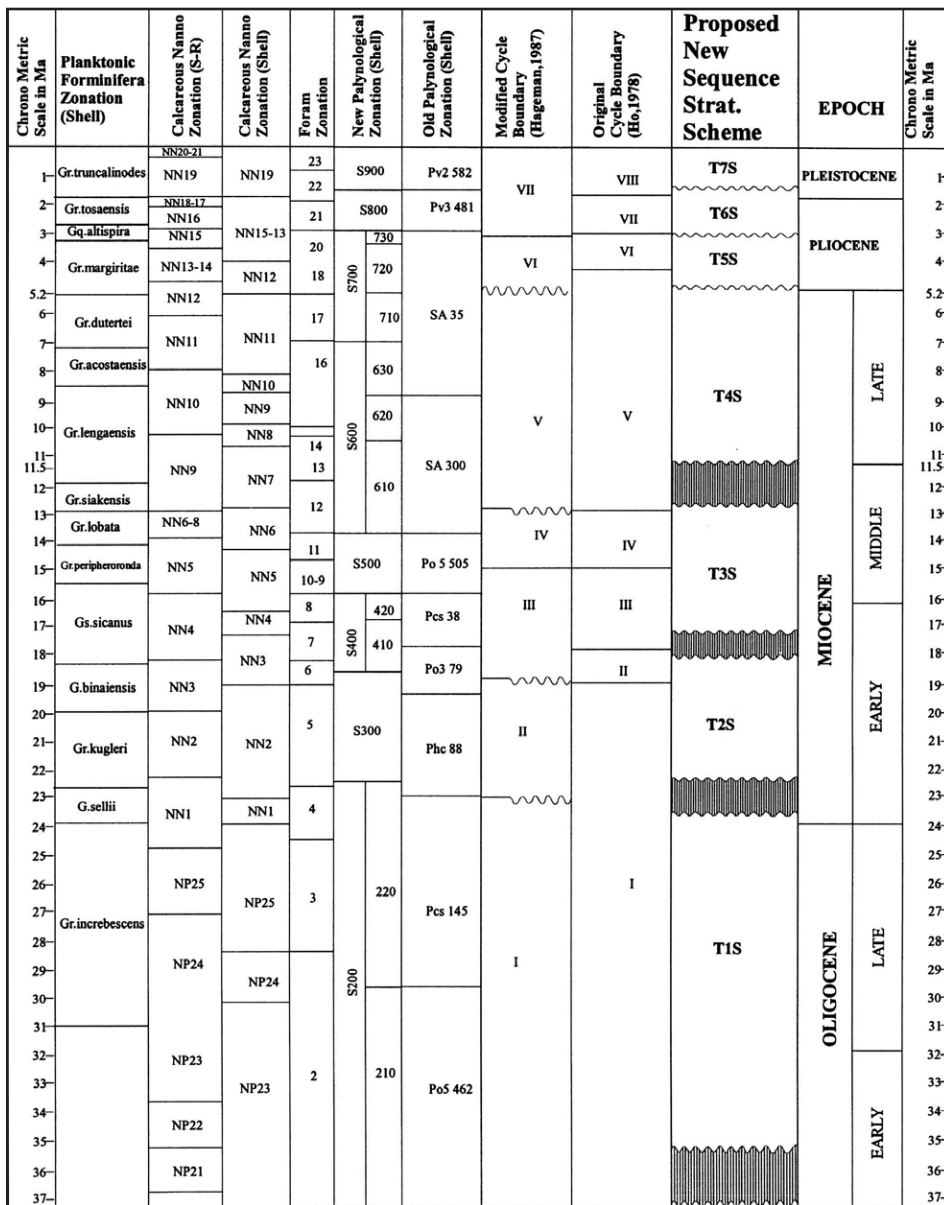


Figure 9: The stratigraphic scale of Ismail (1996) and Ismail & Tucker (1999). Note how the different nannofossil schemes, by (S-R) Simon-Robertson and Shell are unresolved.

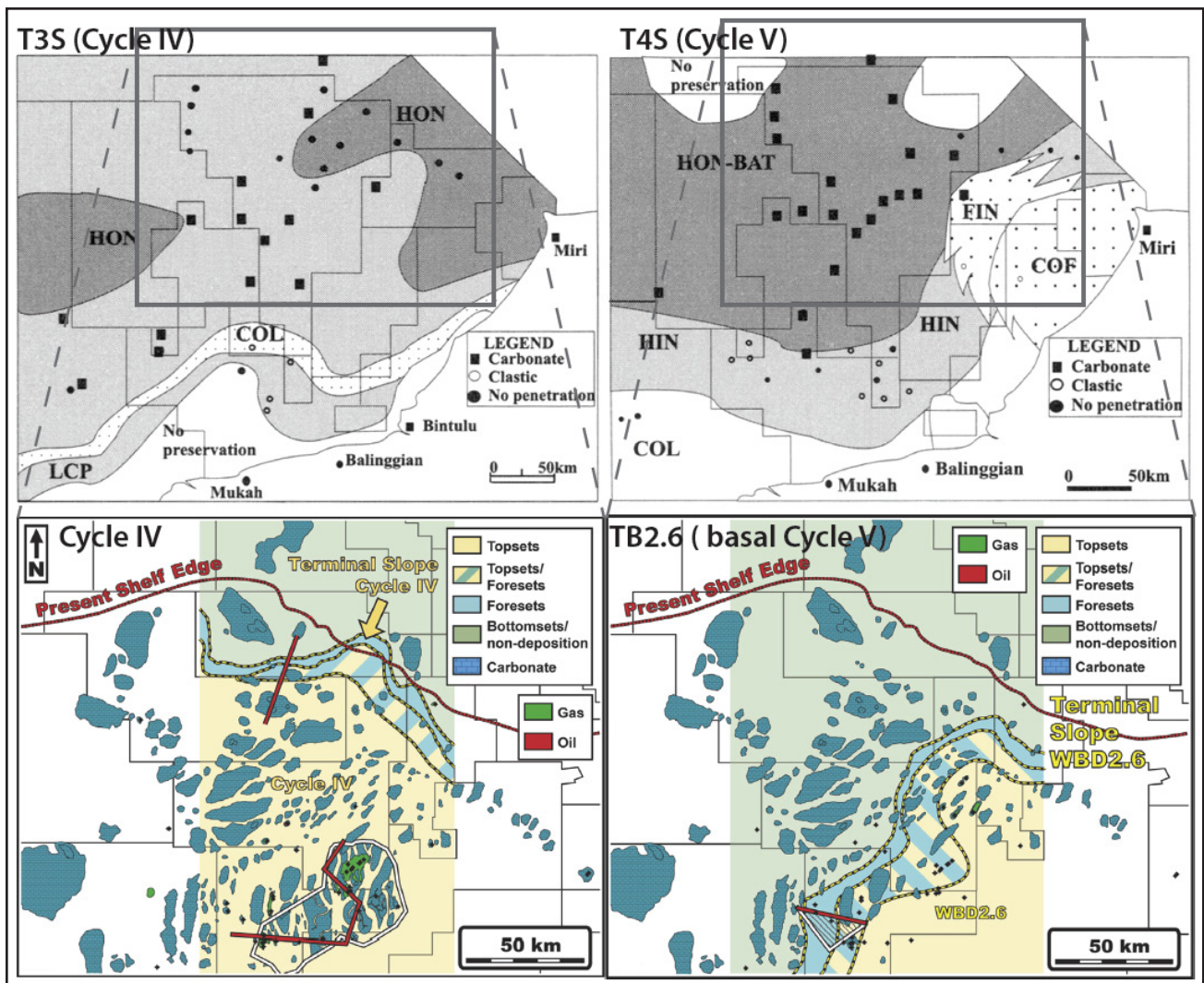
### EARLY WORKER'S VIEW OF CYCLE IV TRANSITION INTO CYCLE V

The Cycle IV to V boundary has been recognised as a widespread transgression, and the summary diagram of Veenhof (1997, reproduced as Figure 4 here), and the unpublished maps of Hageman (1985) still suggests a period of pre-transgression erosion in the southeast or east (Balingian Province). A review of well data has not been able to substantiate this, as this erosion is often compounded by the much stronger base Cycle VI unconformity.

In Central Luconia the Cycle IV to V boundary was recognised in only a few wells as the section is usually drilled within the carbonates, where the aggradation of exclusively shallow marine facies precludes the lithological contrast required to recognise a transgressive surface. Hageman *et al.* (1987) identified the event in clastic sections only in the F19-1, E15-1 and J-2 wells. In E15-1 it occurs near the highest of the *Fohsella* lineage (extinct at 11.7 Ma,

specimens inconsistent in the well so no precise top can be given) and below the extinction of *Globigerinoides subquadratus* (extinct at 11.4 Ma). Larger foraminifera in limestone stringers as high as 1000' below the base Cycle V transgression in E 15-1 are Lower Tf Letter Stage (older than c. 12 Ma), with degree of enclosure in *Lepidocyclina* indicative of early Middle Miocene age (Ho, 1973, 76). The cycle boundary is not as well dated in the other wells mentioned. However in large numbers of wells there is a lower part of the Luconia limestone with Lower Tf larger foraminifera including the distinct form *Miogypsina* which became extinct at about 12½ Ma.

Reviews such as Doust & deMiroshedji (1979) have noted that after the initial transgression Cycle V was largely a regressive sequence, with sands increasing up-section. This was a particular concern to explorationists as the prograding delta front and prodelta sands and silty muds would become hydrocarbon thief beds as they downlap and onlap onto the



**Figure 10:** The Cycle IV to V maps from Ismail & Swarbrick (1997) and Cycle IV to basal V (TB2.6) maps of Kosa (2015), showing the same effects of the transition at this cycle boundary, a deepening of the central and northern parts of the area, but very soon after, or simultaneous with this a rapid influx of sediment from the east impinges on the northeast side of re-formed basin.

reefal buildups. Increasing sand upwards meant that the younger Cycle V has a higher risk of reefal traps leaking hydrocarbons laterally into sands and silty muds. Mapping and well data indicated that this risk was lower around central and northern Luconia where holomarine claystone deposition persisted for longer, but it was significant in West Luconia as the Rajang delta prograded and covered the reefs, and in the east where a few reefs were exposed to the advancing Baram delta (see maps in Figure 10).

Based on this limited data set the Cycle IV to V transition might be considered a less significant Cycle boundary, but this is a bias in the limited data over-printed by facies control, as seismic shows the effects of this transgression are regionally strong. On Hageman's 1985 Cycle IV and V maps (Figures 37 D and E in Hutchison, 2005) this period saw a tilting of the offshore Sarawak down to the northwest and with an area of uplift and erosion in the southeast. This uplifted area had been drilled into at that time by Patricia-1, South Acis-1 (both 1962) and D8-1 (1978) although, as noted below, most movement and erosion in

this southeastern uplift may have occurred after this initial tilting. Once again Hageman drew this cycle boundary with half an unconformity symbol, indicating cross-basin variation in magnitude.

Lapre & Thornton (1970) noted that by the start of Cycle V times uplifted fault blocks were established and higher relief reefs were growing on these features. This is not a clear-cut geometric division, as other workers (e.g. Vahrenkamp, 1996; 1998) have noted this replacement of widespread platform by isolated pinnacles occurred within their lower TB2.3, during a time of accelerated subsidence at the Cycle III to IV boundary.

The same Cycle IV to V subsidence / transgression seems to have produced the low relief biohermal carbonate around D3-2, on the flanks of the Penian High (see Figure 8) illustrated in Epting (1988) and Kosa (2012), which differs from other Luconia reefs by its high stratigraphic position and shallow burial location, as well as not having being initiated by the major events at the base of Cycle IV. As such it is not a good example of a typical reef for the region.

### EARLY WORKER'S VIEW OF CYCLE V TRANSITION INTO CYCLE VI

Figure 8 of Ho (1978) shows that by the later Middle Miocene a new sedimentary setting had been established with clastic input derived from the southeast, prograding northwestwards. This diagram, which was based on the Baram Delta, shows the Cycles concept clearly defined as repetitions of transgression over regressive surfaces. The outstanding magnitude of the Cycle V to VI boundary for the main Sarawak (Balingian) area, as drawn by Doust (1981, his Figure 8) and Ho (1978, his Figure 7), contrasts sharply with the summary of the same cycles in the Baram area (Ho, 1978, his Figure 8). In the Balingian area the Cycle V to VI boundary is much larger, with much more erosion. Ho clearly recognised that there was a later Miocene nearshore uplift in Sarawak that was weaker in Brunei. In contrast Lapre & Thornton (1970) noted in the Luconia carbonate area that the Cycle V to VI boundary was only seen as a “regional transgression during a structurally stable period” (as shown in Figure 8). As noted by Ho (1978, quoted earlier) the seismic was clear that this was the same transgressive event. The age of the sediments transgressing over the often angular unconformity were latest Miocene in age (containing *D. quinqueramus* at the base of the transgression in some wells).

### EARLY WORKER'S VIEW OF CYCLE VI TO CYCLE VIII

At this point the Cycle scheme of Shell was correlated with the older studies in nearshore Brunei. These very young sediments are usually not sampled by wells in Balingian, Luconia and Tatau provinces, being drilled before the surface casing is set. For the record, from Hageman *et al.* (1987) the Cycle VI to VII boundary was defined as a mid-Pliocene transgression, perhaps just above the extinction datums of *Globorotalia margaritae* and *Sphenolithus abies* (3.8 and 3.7 Ma respectively). The Cycle VII to VIII boundary is intra Late Pliocene near the extinction datum of *Globigerinoides obliquus extremus* and *D. pentaradiatus* (2 and 2.5 Ma).

### THE ROLE OF EUSTASY

The 1987 GSM paper of Hageman has a relative sea-level curve constructed on Sarawak well observations and for the first time a paper included a comparison to the new eustatic sea level curves. Hageman concluded there was fair correlation from Middle Miocene through Pliocene, but that there was no correlation in the Early Miocene and older.

In the early 1990's drilling began in deep water North Luconia and more consistent planktonic zonal data was found in older Miocene sections. A 1994 pre-drill seismic review by Snedden *et al.* was followed up by a 1995 post-drill report subtitled “sedimentary cycles versus sequence stratigraphy” (Snedden *et al.*, 1995). This title was a misnomer as the top Cycle III MMU was the dominant unconformity in the region with a condensed section above, but the review examined just Cycles I to III. The problems in recognising the Cycle I to II event, discussed above, weakens the case

to use this small sub-set of data to test the Cycles against any other scheme. Cycle III was summarised by Snedden *et al.* (1995) as “a transitional unit, with dramatic differences in thickness as a function of tectonics and erosion at the Middle Miocene unconformity”.

Snedden *et al.* pointed out the difficulties in carrying out this work “Without documentation it is difficult to determine the source and age of some of the [pre-existing] scales used for calibration of the sedimentary cycles. Calibration of this data, particularly the older data, with current planktonic foraminiferal zonations and geochronometric scales may have also introduced some of the inconsistencies.” As a result for picking the older Cycle boundaries Snedden *et al.* (1995, p.6) considered the precision to be “within about one half of a planktonic foraminiferal zones”. This was an unfair representation of the uncertainty in biostratigraphic data. Sometimes this data can offer good correlation but be of uncertain age in millions of years but this should not be represented as high uncertainty. In other cases the identification of weaker events, such as the form *Globigerinatella* (that is rare in SE Asia, and has a history of shifting correlation to evolving numerical time scales) clearly mean uncertainty poor reliability.

The Snedden group study was published in Mansor *et al.* (1999) in a very short paper. This publication simply stated their conclusion, that their choice of seismic interpretation was more successful in predicting the facies in the Mulu-1 well than a different technique based on marine flooding surfaces (the genetic stratigraphic approach of Galloway, 1989a; b), which has similarities to the original Cycles approach. There was no comment about control on observation bias in this short paper, but one is available now if one considers the independent work of Hageman, especially his 1985 summary maps, which were unpublished at the time of Mansor *et al.* (1999). The key figure of Mansor *et al.*'s paper (their Figure 4) shows contrasting palaeogeographic maps, one attributed to the Genetic or Cycles based approach and one to the Sequence stratigraphic approach. They select the Sequence stratigraphic diagram as best matching the Mulu-1 well results, thus supporting their conclusions. In fact both match the well results, as the Genetic or Cycles map is of the older Cycle II succession and the Sequence stratigraphic map is of Cycle III (15-18 Ma, as stated on the diagram). These match the Hageman (1985) maps that were eventually published in Hutchison (2005) (cf. his Figures 36 G and H). This independent data shows that the difference between the contrasted maps in Mansor *et al.*'s (1999) Figure 4 is the depth of the datum chosen for each map, not one of technique. A subjective conclusion is that the Hageman Cycle maps gave the best overall result, as the projection of these maps north to the Mulu area suggest the Cycle II to III sediments at Mulu-1 should be in a distal position on a marine delta-top, which is supported by the presence in sidewall cores and cuttings below casing of deeper middle foraminifera *Heterolepa dutemplei*, *Lenticulina* and *Uvigerina crassicosata*. The two alternative models shown in Mansor *et al.* (1994) interpreted

the palaeoenvironment as shallower than this (near coastal, very shallow marine or lower coastal plain settings).

In addition, the correlation of Snedden *et al.*'s (1994; 1995) work to eustatic sea level curves fails, as the number and overall magnitude of eustatic events does not match the number of relative sea-level changes and sequence boundaries observed by these authors. As they note, without the access to original data on the Cycles, it is hard to know the ages of those events, so correlation to the eustatic events is only an estimate. However, the chosen correlation places the base Cycle III marine transgression above the nearest transgressive systems tract [TST] and within a slightly regressive highstand, and an additional eustatic sequence boundary was placed within Cycle II, but neither this event, nor its subsequent TST, has been seen in Sarawak. The 30 Ma event they add has never been seen in the region. The eustatic curve has sea-level falls at 15.5 and 16.5, of similar magnitude and duration, but only one of these has been selected to shown as effective, and another event at 23.7 Ma is also not identified. On the other hand the outstanding, massive, event of the top Cycle III does not reflect any outstanding character on the eustatic chart. These sentences are just repetition of the points already made in the 1987 publication by Hageman (quoted above) in his comparison of the Sarawak relative sea-level curve to the global eustatic sea-level curve before the Middle Miocene.

Regrettably, just at the time the Cycles concept was being forced by data away from simple cyclicity to a three-dimensional tectonostratigraphic model, best matching the modern interpretation, it was effectively abandoned.

In the absence of the original data on the Cycles in the public domain, their replacement by eustatic concepts within the Sarawak exploration industry seemed unstoppable. Work from the time of Taylor *et al.*, 1997 [unpublished PETRONAS / Shell] and Hazebroek & Tan (1993; mostly on Sabah) routinely included the eustatic sea-level curve as a stratigraphic reference. In some operator's reports stratigraphy was reported in the terms of the "global eustatic sequences" (Haq *et al.*, 1987). For example TB2.1 to TB2.6 covering Cycle II to intra lower Cycle V. Stratigraphy became more model-driven than evidence-driven, simply because evidence was not available, and even in the few companies with good libraries, it was hard to understand by the non-specialist.

The empirical observations of Hageman and many others were ignored in the rush to recognise the expected global eustatic signature. The clearly tectonic nature of the Cycle I to II and Cycle V to VI boundaries was forgotten, as was the very pronounced uneven nature of the change in basin transgression during Cycle III and at the base of Cycle IV, as so clearly recognised in the evaluation studies by Snedden *et al.* (1994; 1995).

### ISMAL'S SEQUENCES

It was not just original data on Cycles that held was being held back and hampering scientific progress, as the framework for eustasy-driven sequence stratigraphy was also

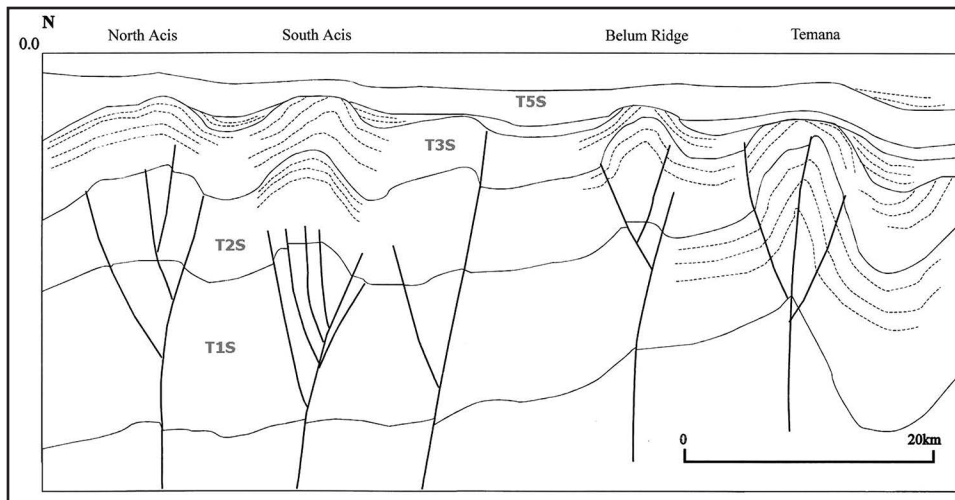
mostly unavailable for independent examination (Andrew Miall was one of the main critics of the way the technique was being applied; e.g., Miall, 1991; Miall & Miall, 2001), as well as its confusing terminology. However, the petroleum industry's fervour for sequence stratigraphy came at the same time as computer advances increased quality and quantity of seismic data, including common 3D data sets, and during the mid-to-late 1990s some industry geologists sought to establish a new school of stratigraphy. There were, however, some independent workers.

After completing a PhD thesis (1996) Ismail Mat Zin of PETRONAS published two papers (1997 with Swarbrick, and 1999 with Tucker) on the stratigraphic development of offshore Sarawak. Although dominantly the work of a single postgraduate, as compared to exploration teams over longer periods in oil companies, the importance of this work should not be understated. While companies were becoming more restricted to individual blocks and prospect-focussed, Ismail based his thesis on regional seismic lines tied to wells, and was a fresh and independent look at the concepts of the Cycles and the larger stratigraphic picture.

The thesis reviewed, but could not critique, the biostratigraphic components that underlies the older Cycles work. As noted earlier, Ismail did not appear to have been aware of the un-published review of Hageman *et al.* (1987), only the published Hageman (1987) summary. Ismail's work clearly documents major sedimentary units and he concluded that "*All the Late Oligocene to Late Miocene sequence boundaries are probably tectonically induced, rather than related to global eustatic sea-level falls*". Without access to Hageman *et al.*'s (1987) revisions, Ismail had to leave open the possibility that some of Ho's original but very simplified estimates of the Cycle boundary ages appeared to be close to eustatic sea-level changes, and therefore may have been caused by them. As a result of this apparent correlation of the Cycles to eustasy Ismail abandoned the Cycles and proposed his own tectonostratigraphic units, T1S to T7S, noting that the five units from Oligocene to the base of the Pliocene having strongly angular tectonic discordancies between them. Ismail still independently arrived at roughly the same conclusions as unpublished industry workers. In effect his T1S sequence equals Cycle I, T2S is Cycle II, T3S is both Cycle III and Cycle IV, T4S is Cycle V and latest Miocene through Pleistocene T5S to T7S was Cycles VI to VIII (Figure 9).

After the 1980's and early 1990's rush to a eustatic description of stratigraphy, this observation by Ismail was a very important result as it showed the dominance of tectonics as a control of facies and geological development in Sarawak. His work included seismic lines far to the northwest that were not part of earlier publications on Sarawak.

Regional Line 7 of Ismail in the west showed how T3S / base Cycle III was the start of thick and rapid sedimentation over the Tatau and West Luconia Provinces. It was the onset of the fault-driven formation of the West Luconia Province (eastern Bunguran Trough), pulling down the northern flank of the Tatau Province. At the same time his isochore maps



**Figure 11:** North Acis structure on the left, drilled as the E3-1 wildcat. Section from Ismail & Tucker (1999). Note this is not the crest of the North Acis structure - and also note lack of T4S at N Acis the deformation may actually be late Cycle V in age.

show that between T2S and T3S the overall sediment wedge had rotated, in T2S the sediment reduced to a NW to SE trending coastline [close to the West Balingian Line fault] and thickening towards the NE, but in T3S the coastline had moved to be on a similar trend as the modern coast, with sediment thickening towards the NNW (Figure 3.10 & 3.11, Ismail, 1996). This result is remarkably similar to the unpublished maps of Hageman, 1985; Figure 36 F to H in Hutchison, 2005). Also apparently unknown to Ismail was that the well H2-2x is close to this regional line, and this well reached Rajang Group clastic basement dated as latest Palaeocene or early Eocene (*Discocyclina*, *Nummulites*, *Alveolina*, *Globorotalia cf wilcoxensis* and *Globorotalia cf velascoensis*) immediately overlain by a transgressive carbonate with *Miogypsina*, *Lepidocyclina*, *Globigerinoides* and *Orbulina*, which dates his upper T3S, and Shells' Cycle IV, sediments overlying this unconformity as early Middle Miocene.

Similarly Ismail & Swarbrick (1997) independently mapped the effects of the Cycle IV to V (T3S to T4S) transition, with his maps shown here in Figure 10 along with later, similar, maps by Kosa (2015). Both these seismic studies mapped the same strong subsidence and transgressive effect which Kosa, on a denser data set, associated with a coastline moving by some 200 kms to the southeast. However palaeontology and lithostratigraphy indicate that this particular feature was not a coastline, as discussed later, although the observed magnitude of the transgression is important.

Ismail's thesis and publications showed some excellent sections over the west Balingian area showing T3S sediments folded possibly with T4S onlapping (but other seismic on this feature suggests first folding in T4S times; see one summary sketch in Figure 11). There was continuing compression and local erosion through T4S (Cycle V) times before an end to this tectonism and subsequent transgression by T5S (Cycle VI).

### MODERN ANALYSES

In 2003 Morrison & Wong published a summary of the modern Shell approach to stratigraphy across all of

NW Borneo. They noted the interplay of eustatic sea-level change and local tectonic events, but adopted a eustatic cycle model for correlation in the hope this would allow synchronous high-resolution correlation, independent of potentially diachronous tectonism. An unstated assumption in this model was that the ages of eustatic sea level changes and the ages of Sarawak Cycle boundaries and Sabah Sequence Stages (Bruce & van Hoorn, 1977; van Hoorn, 1977) had all been dated with similar, and probably high, levels of precision.

The new model still did not balance well with observed large scale geology, for example Hageman (1987) had clearly identified the dominant first widespread transgression to marine conditions in Sarawak was during Cycle III accelerating into Cycle IV, and yet the Morrison and Wong (2003) scheme showed relative stasis over Cycle II to mid Cycle IV. A sceptic could infer interpretation-bias as his Figures 7, 8 and 9 (summaries for Balingian, Luconia and West Baram) have a "snap to fit" appearance, where every unconformity is correlated to a eustatic sequence boundary. This implies that no non-eustatic event had created an unconformity, a suggestion at odds with the observations of earlier workers and the more modern seismic-based work of Ismail.

Important geological characters such as the change in basin orientation offshore Sarawak during Cycle III, and the events that triggered the Cycle IV Luconia limestone were down-played. In Sabah the events of the DRU and subsequent compressive phases were taken for granted but little effort was made to fit these into a regional geological model. Their scheme shows a heavy reliance on seismic correlation and geometries to describe geology.

### PETRONAS CHRONOSEQUENCE STUDIES

From about 2006 to 2008 PETRONAS attempted to use a technique adapted from ODP summaries, called graphic correlation, to take advantage of the now stabilised time scale (Gradstein *et al.*, 2004) to date and correlate well section across Sabah and Sarawak. The principle was that in any one well, plotting extinction and evolution datums against the known age of the datums in millions of years

could give a stratigraphic profile, which in the clastic-rich sections off NW Borneo should show offset (steps) at the unconformities, and a curve reflecting the burial compaction profile of the sediment.

Ignoring the fact that this technique excluded non-marine palynology which was the key tool for the coastal plain sediments that dominate the oil producing southwest part of the Sarawak area, there are several important criticisms of this technique.

Firstly, enough markers need to be present in many successive samples, so the depth of the extinction datum is clear (and maybe evolution datums, depending of risk of caving). As noticed by the early workers, this was long recognised as the major problem for biostratigraphy in Sarawak sediments. A recorded last occurrence is more likely to a flood at an unknown time before the true extinction datum. In other words the graphic correlation “points” are not points, but should have estimated error bars added for sample quality and especially facies control.

Secondly, the graphic correlation technique treats all data as equal, but fossil data is not that simple (see Chapter 3 of Lunt, 2013). In other words some of the data-points with estimated error bars are far more reliable than others (i.e. there is significant error in yet another dimension of observation).

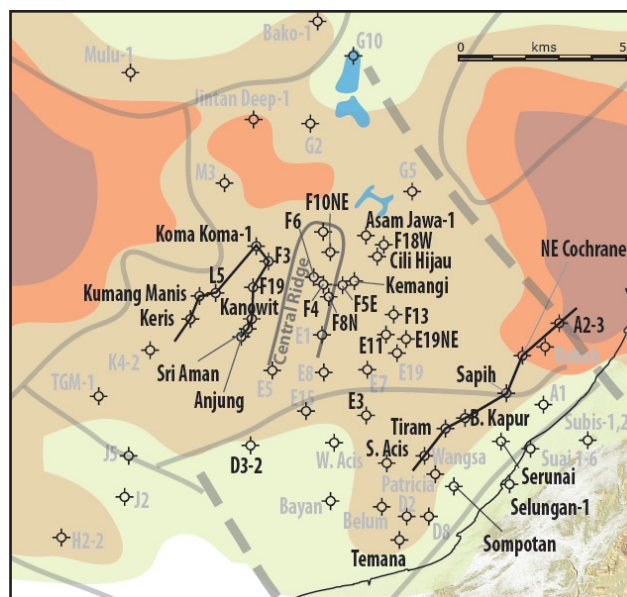
Thirdly, offset-steps, the implied unconformities or sequence boundaries, are often highly interpretative, and with a reduced number of low-error data-points the likelihood of mis-picking sequence boundaries increases.

The graphic correlation technique was not pursued further when it was realised the technique could not independently see the Cycles and the known major shifts in stratigraphy at the Cycle boundaries.

### SHELL SEISMIC-BASED WORK

In 2012, 2013 and 2015 seismic-only interpretation was used to suggest a concept called “rivers of Luconia” and a palaeogeography that had fluvial systems passing between stumps of temporarily extinct reefs during forced regressions, with these reefs continuing to grow on the same sites when transgression resumed. Seismic from a reef over the Penian High was used as an example of the clastic to carbonate stratal geometries that were expected under these conditions (Kosa, 2012, online “*Example of an early interpretation of a Luconia carbonate*” from Epting, 1988, through the D3-2 well, see Figure 8 above). This model was then projected into Central Luconia where the majority of Luconia carbonates were interpreted to have had the same “topset” delta top conditions around reefal sites (e.g. Kosa, 2015, his Figure 8A) although older work (Hageman, 1985; Madon, 1999, Figure 12.7; Ismail & Swarbrick, 1997, Figure 8c & d) had indicated outer neritic to upper bathyal sedimentation over central to northwest Luconia.

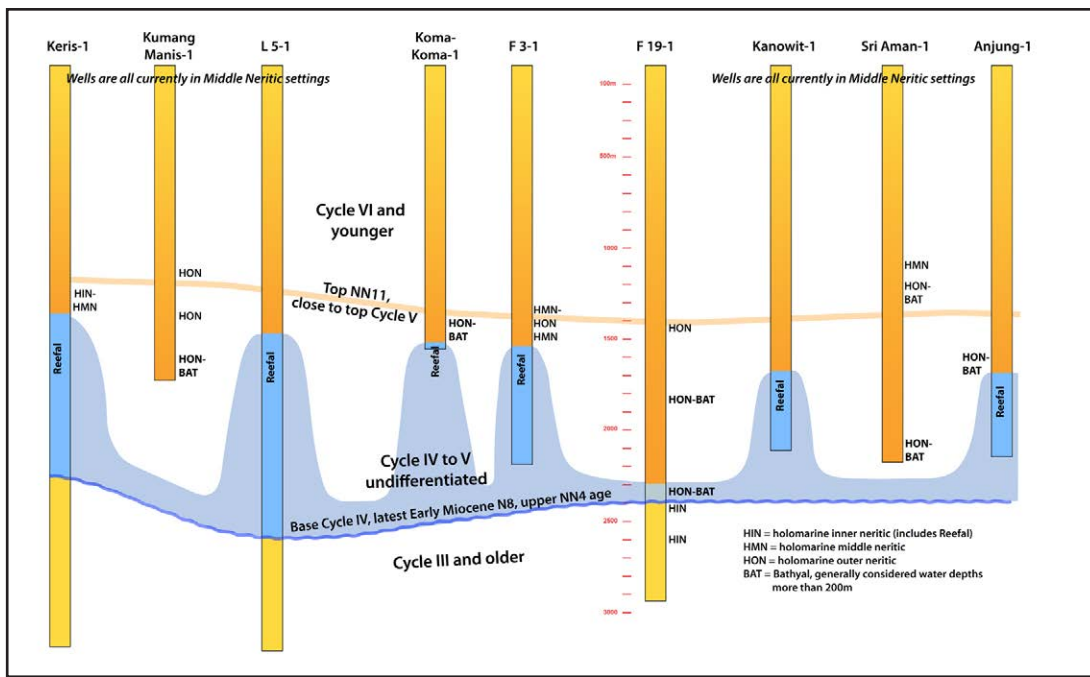
It is a fundamental claim of the “rivers of Luconia” papers that the Luconia reefs were not drowned pinnacles but that they existed within a coastal area. The traditional palaeogeography, in which the palaeo-coastline was always



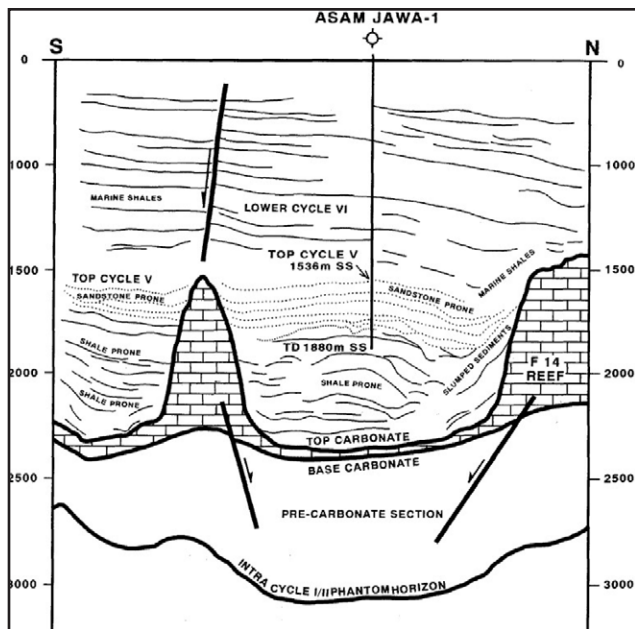
**Figure 12:** Location map. The location of the Central Ridge is copied from Kosa (2015).

far south of the Luconia reefs, was replaced by a model where the coastline was outboard (north) of reefs, and these reefs would continue growth at the next transgression. Kosa (2015) stated “*a series of transgressive/regressive deltas, which during sea-level lowstands have migrated past the temporarily exposed carbonate build-ups towards the continental slopes*”. This seismic interpretation is easily disproved by well data, or at least limited to a short time and very limited location only at the far southeastern limit of the Luconia Province. Firstly, and outside the area mapped by Kosa, there are a series of reefs surrounded by very deep marine clastics that can only be explained by the old model of pinnacles that were isolated far north of land, eventually drowned and overlapped by deep marine clastics (Figure 13). These reefs set a precedent in favour of the old “isolated open ocean pinnacles” model. Within areas mapped on Kosa’s seismic as topset to intermediate topset to foreset there are numerous wells drilled between reefs during TB 3.2 to TB 3.4 times with good analyses showing fully bathyal (often middle to upper bathyal) environments of deposition. These include Asam Jawa-1 F5E-1, F8N-1, F10NE-1, Cili Hijau-1 and F18W-1 (Figures 12 and 14).

This well-data reduces the area for any possible “rivers of Luconia” to the limit of the south-easternmost reefs, from between D3-2 to E11 (Figure 12), which had always been in the holomarine inner neritic zone of Hageman and other older workers (cf. mid Cycle IV and mid-lower Cycle V map of Hageman, 1985; in Hutchison, 2005, also Ismail & Swarbrick, 1997; Figure 10 here). Even in the area around the E11 reef, the adjacent F13, non-reefal open marine bank carbonate area was transgressed to outer or middle neritic conditions by the basal tilting of the Cycle IV to V event, and the adjacent E19NE-1 well similarly transgressed to outer neritic or deeper conditions by the same event, conditions that persisted until sediment gradually filled this



**Figure 13:** A simplified cross-section through multiple wells in west Central Luconia, locations marked on Figure 12, with the base Cycle IV marked as a blue line, and approximate top NN11 marked in brown. Between these two events seismic shows several high-relief reefs of Cycle V (not precisely dated), and three wells drilling at least 300 metres below the top carbonate depth but not reaching limestone. These inter-reef clastic sections were deposited in very deep marine conditions, with deep outer neritic or upper bathyal faunas recovered, as marked. This is contrary to the Kosa (2013) model which suggests aggrading delta tops are the dominant facies between reefs in Luconia. These reefs are outside Kosa’s study area, but several reefs and the less often drilled inter-reef wells in Kosa’s study area have the same stratigraphic relationship as these wells, as shown in Figures 14 and 15.



**Figure 14:** North Central Luconia, showing the same effect as in west Central Luconia (Figure 13) where a well was drilled between two reefal highs and found bathyal faunas between reefs that would have been isolated by deep marine conditions during their main phase of growth (Cycle V). Below top Cycle V as marked in the well the fauna included new deep marine forms that were not recorded in the section above and cannot be named; *Chilostomella oolina*, *Globulimina pupoides*, *Melonis pompilioides*, *Anomalinea colligera*, and the distinct middle bathyal index *Laticarinina pauperata* in 4 samples.

low to reach marine but inner neritic conditions during NN 11 (TB 3.2 to TB 3.4 times). Therefore, even in this southeastern zone, conditions were too deep for coastal or fluvial systems during most of the Late Miocene (until, as Vahrenkamp, 1996 showed, using strontium dating, the south-easternmost reefs were silted-out, killed off, and then finally buried during the Late Miocene).

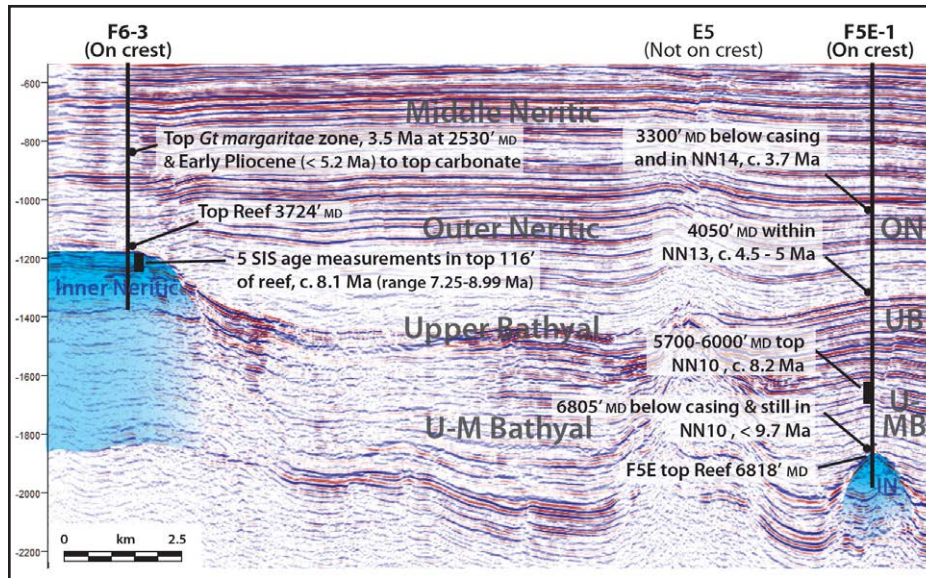
If “rivers of Luconia” and “stacked low relief deltas” had occurred after the onset of widespread carbonate deposition in Cycle IV they would be restricted to just Cycle IV, before the regional IV to V transgression (the transgression between “Cycle IV” and “TB 2.6” maps of Kosa, 2015). However, even in the southeast edge of the Luconia area, sediments during Cycle IV were dominated by marine carbonate facies. None of the wells that drill through the geometries identified on seismic as topsets contain delta-top organic-rich beds. These would be important to record as a potential source of biogenic and perhaps thermogenic gas.

An important difference between the seismic-only and the traditional stratigraphic models is that in the “rivers of Luconia” model there would be very little age difference between carbonate and clastics at roughly the same topographic level, but the traditional model required considerable topographic height between the top of a reef and off-reef clastics of the same age. In the case of an extinct, high relief reef being buried there would be a marked age contrast between the top of the reef and the clastic sediments that would finally cover it. Normally age dating methods in offshore Sarawak precludes accurate correlation between



**Table 1:** Strontium dating of the F6 reef, updated to the same time scale as the modern biostratigraphy datum (GTS04).

Well, and distance of sample below top of reef	<sup>87</sup> Sr/ <sup>86</sup> Sr ratio (NBS987=0.710230)	Mid range Age 1996 report (Ma)	Age GTS04 (Ma)
F6-3, 3736' (-12')	0.70890	11.11	<b>8.99</b>
F6-3, 3744' (-20')	0.70893	9.3	<b>7.25</b>
F6-3, 3751' (-27')	0.70892	9.7	<b>7.64</b>
F6-3, 3767' (-43')	0.70891	10.8	<b>8.48</b>
F6-3, 3840' (-116')	0.70891	10.8	<b>8.48</b>
F6-3, 3895' (-229')	0.70889	11.4	<b>9.36</b>



**Figure 15:** Correlation of F6 reef to the F5E deep test. The age of the last reefal deposits at F6, at about 8 Ma, correlates to bathyal clays at the top of Zone NN10 at least 1700 feet deeper in the F5E well. Sediments at comparable depth to the top F6 reef in F5E are dated as less than 4.5 Ma compared to the reefal age of nearly twice this. This geometry means that Cycle V reefs such as F6 were pinnacles surrounded by very deep marine conditions that later filled with sediment. This is the same relationship shown in less well dated wells to the west in Figure 13.

mudstone and reefal limestone facies. However there is one instance in which such a correlation can be attempted.

As noted above, the location of the F5E-1 well should have drilled clastics from a top-set to intermediate top-set to foreset zone based on Kosa's (2015) seismic mapping from TB 3.2 to TB 3.4 (from end Cycle V to base Cycle VI, roughly 4.5 to 7 Ma or Zone NN11) but the palaeontology is indicative of bathyal conditions. In this well the top of zone NN10 (near top TB 3.1; intra Late Miocene, c. 8.2 Ma) is picked on the evolution of *Discoaster quinqueramus* at about 5700-6000 feet (within a range of a few hundred feet between the lowest record of lowest *D. quinqueramus* / *berggreni* at 5760', and top *D. neohamatus* at 6090'). The F6-1 well, about 12 km from F5E (Figure 15), has strontium dating (Table 1) indicating the age of the final phase of reef growth was also at about 8 Ma, and there is at least 1700 feet of topographic difference between these age equivalent points. Inversely, at about the same topographic level for the end of the F6 reef (now just above 4000 feet MD at both sites, see Figure 15) the reef age of about 8 Ma compares to a well-constrained age of around 4.5 Ma in F5E-1. Such a variance of about 50% of the age predicted by the "stacked low relief deltas" model is well above the potential error in age assignments from strontium isotopes or biostratigraphy. In addition the presence of the Early Pliocene *Globorotalia margaritae* zone immediately over the mid Late Miocene F6 reef crest is a large time gap incompatible with the "stacked low relief deltas" model.

### MURPHY OIL'S STUDIES IN THE BALINGIAN PROVINCE

Murphy Oil (2006, cited in Wilson *et al.*, 2013) dated the upper transgressive carbonate found at the Cycle I to II boundary in several wells and outcrops in places tied by 3D seismic. The top of limestone at Batu Kapur-1 is well dated as mid NN2 (based on nannofossils in a mudstone sidewall core immediately above limestone) and lowest Tf on larger foraminifera in sidewall cores in the limestone, supported by Sr dating at 20 Ma. The base limestone at Batu Kapur-1 is still within the Miocene as *Miogypsina* with mudstone preservation is found in the clastics at TD. The well A1-1 has Letter Stage Te larger foraminifera to near the top of the limestone, indicating the terminal limestone event must be close to the Te-Tf boundary and this is close to 20 Ma (20½ Ma in van Gorsel *et al.*, 2014). This would tentatively suggest the limestone is basal Cycle II and above the Oligo-Miocene boundary climate change event. Murphy also obtained data on the basal Cycle V transgression in the E3/N. Acis, Endau - Rompin area by dating thin transgressive limestones as 12.4 Ma with strontium isotope stratigraphy (Figure 16). A claystone sidewall core just below the transgression yielded bioclasts with an age of 13.4 Ma. This age is very close to the age of the widespread west Sabah Deep Regional Unconformity [DRU].

The work by Murphy Oil has come the closest to dating the uplift events nearshore Sarawak (the edge of the uplift of the Tinjar Province), which was estimated to

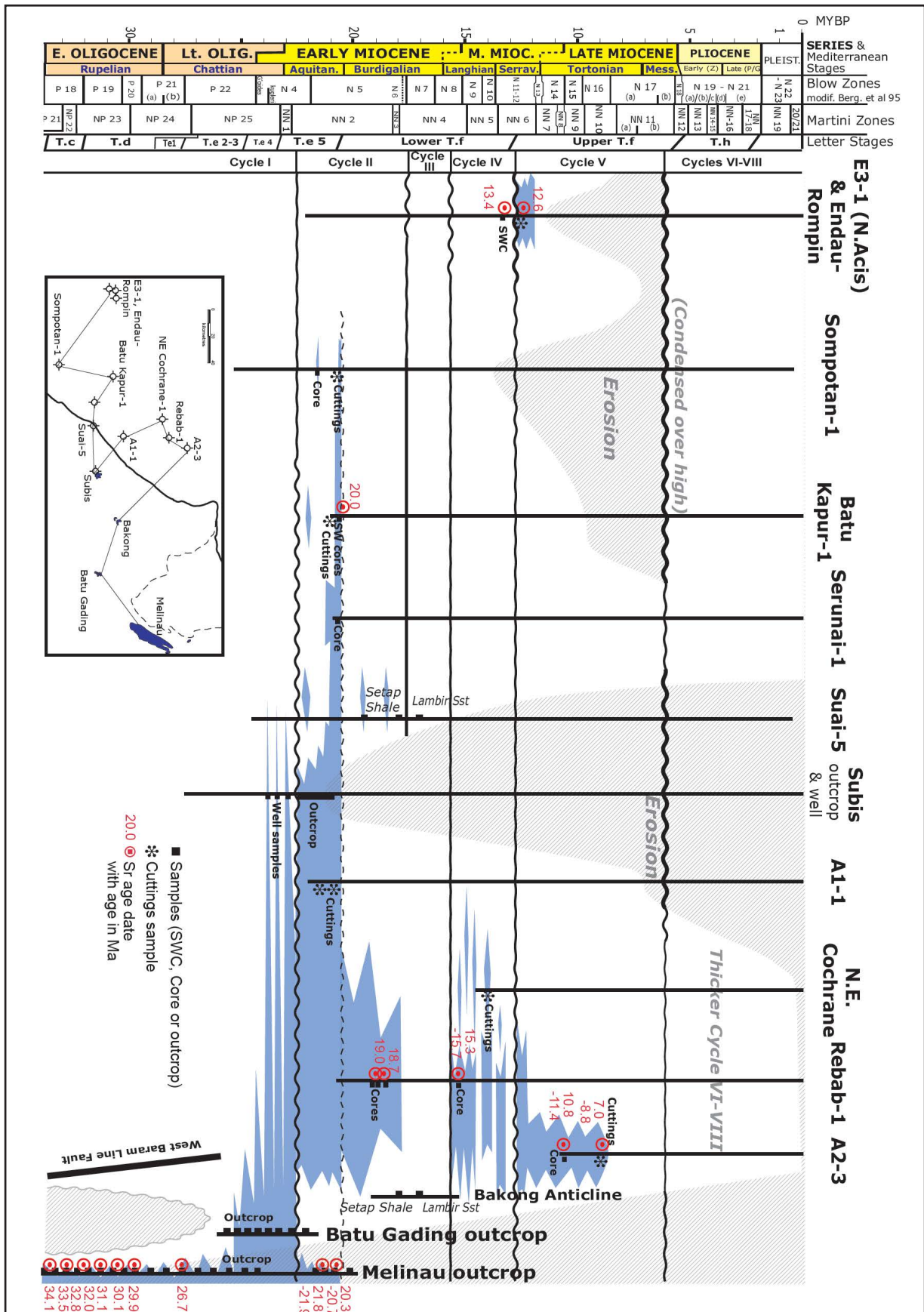
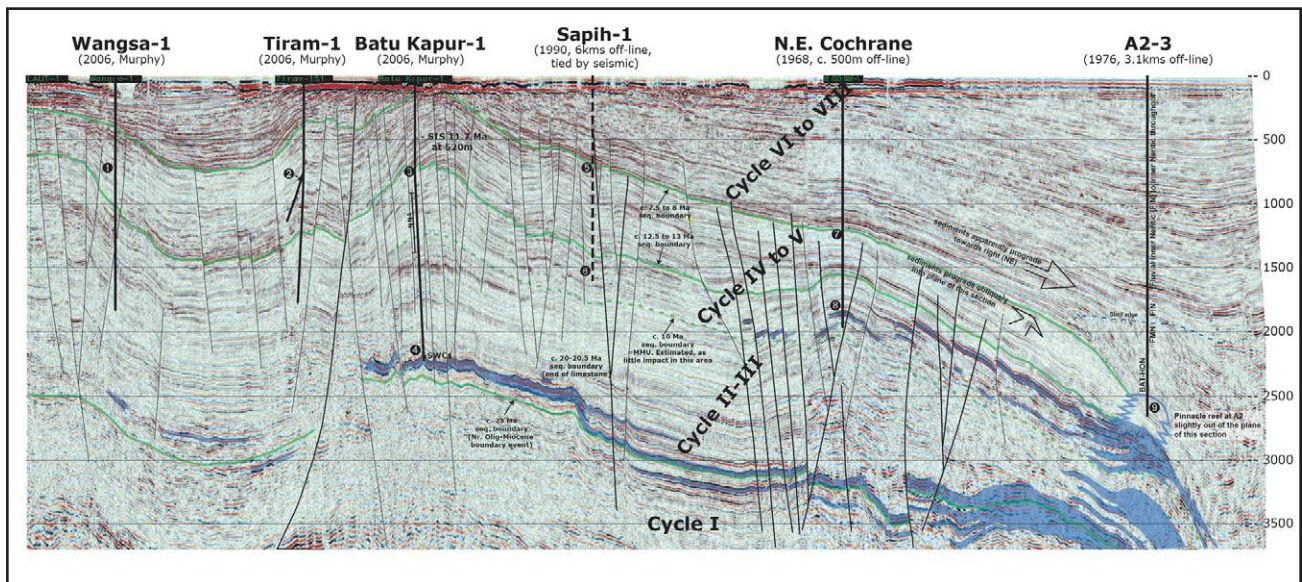


Figure 16: Correlation of the T.e5 limestone flood (after Wilson *et al.*, 2013).

be between 13 and 9 Ma by Hageman. Hageman's 1985 maps showed erosion in the SE Balingian area as early as the start of Cycle V as well as widely at the end of Cycle V. The work of Murphy is important in separating these compound unconformities by using seismic to show structural movement as well as by correlating multiple wells to improve stratigraphic resolution. Some structures such as South Acis do show growth through a large part of Cycle V (although still having Cycle V sand deposition over the slightly uplifted crest) but most neighbouring anticlines and future highs were uplifted most towards the end of Cycle V, strongly eroded, leaving the major unconformity noted by Ho (1978) before being overlapped by Cycle VI. A large 3D seismic survey by Murphy in 2005 showed that localised transpressive folding began in Cycle V, peaked in latest Cycle V with large areas flanking the Tinjau Province being uplifted and eroded, and then some milder structural

movement continued through Pliocene and Pleistocene times. Within this structural development the outstanding feature is the sudden transgression onto an angular unconformity that was the defining event for the Cycle V to VI boundary (Ho, 1978, Figure 7, reproduced as Figure 2 here). This was the boundary between T4S and T5S of Ismail (1996).

Prior to the work of Murphy, dating this event had been difficult as the sediments in this nearshore Balingian area were rapidly deposited and usually only marginally marine, with very rare age diagnostic markers. The Murphy work used 3D seismic to correlate individual reliable data points in a range of wells. In the wells with the least amount of end Cycle V erosion they used geohistory plots (trends of age in Ma against depth) to estimate, by extrapolation, the age of the youngest Cycle V section above the highest reliable data point. This pointed to well locations such as



**Figure 17:** In this oblique-strike line a change can be seen at the Cycle V to VI boundary, which is gradually accelerating subsidence in the northeast, towards the West Baram Line. As a result of this, a geometric break like a shelf-edge appears to prograde towards the NE edge, but in fact sedimentation still came from the SE, and this seismic shelf geometry is only a product of sediment fill and oblique slope stability during sedimentation.

Annotated points: (1) In Wangsa-1, at 856mMD (720 msTWT) is a nanno-fossiliferous sidewall core. *Cyclicargolithus floridanus* with common *S. moriformis* but no *S. heteromorphus* indicates zone NN6; c. 11.8 to 13.5 Ma. (2) In Tiram-1, at 916mMD (800 msTWT) is an abundantly nanno-fossiliferous sidewall core. *Helicosphaera walbersdorfensis* and *Discoaster moorei* indicate zone NN7; c. 10.8 to 11.8 Ma. (3) At 900m (720msTWT) is top NN5 (highest *S. heteromorphus*), near top Cycle III, which correlates to slight folding at NE Cochrane-1 and the end of the broad carbonate platform in the Rebab-1 to A2-3 area. The top of NN4 is between 1140m and 1420m. The regional intra NN4 MMU would occur below this top and closer to base NN4 at 1945-2015m (=c. 1320msTWT). (4) The top of limestone at Batu Kapur-1 is basal Tf Letter Stage, supported by Sr dating at 20 Ma. (5) At this point in the Sapih-1 well (c. 650msTWT, 630 mMD) is a shift from shallow shelf mudstones and silts to very shallow and sand-rich sediments above. The more marine mudstones below are dated as NN10 to basal NN11, and the unconformity close to the zonal boundary (c.8-8.5 Ma), assuming little missing section. (6) The extinction of *Fohsella peripheroronda*; 1776mTVD or 1380msTWT, and the extinction of *Sphenolithus heteromorphus* (1803mTVD, c. 1410msTWT), both within a section of consistently good fauna. At 1760mTVD in the well (1540msTWT) is an abrupt shallowing from middle neritic, open marine to shallow, inner neritic, up-hole, which is probably a sequence boundary. (7) At approx 1450msTWT is the evolution datum of *Neogloboquadrina humerosa* (base N16). The point marked here (approx 1050m in the well) is a significant, long lasting shift from shallow marine to littoral and more sand-rich environments up-hole. (8) A limestone bed from 2620 to 2650m in the well (faulted up to 1844msTWT on this line) contains both *Nephrolepidina* and *Miogypsina* indicating an age older than c.12.7 to 13 Ma (below top Lower Tf) and thereby older than the top of Cycle IV. (9) In the limestone there is *Flosculinella* aff *fennemai* from c. 10,760 to the lowest core sample at 11,270' (near TD, 11,330' / 3453.4m) but no record of *Alveolinella*. *Borelis melo* occurs as low as 11,270' indicating an age no older than late Miocene. The whole fauna is Upper Tf, post c. 12 Ma. This is distinctly younger than the thin limestone near TD in NE Cochane-1. Sr dating suggests an age ranging from 7 to 8 Ma near the top and 10.5 to 11 Ma near TD.

Batu Kapur-1 having been uplifted at between 7½ to 8½ Ma, which correlates well to data in Sapih-1 and NE Cochrane-1 (Figure 17) but with minimal uplift in the former and no uplift in the latter. In both these flanking wells there is a change from more marine sediments below the unconformity to shallower, marginal marine facies above. The incoming of acmes of fossils as the pre-unconformity sediments were drilled allows them to be considered *in situ* samples, and in Sapih-1 the event is in the lower part of NN11 and in NE Cochrane-1 above the evolution of *Neogloboquadrina humerosa* (base N16), both events about 8.5 Ma. Several wells (e.g. Sapih-1, and Sompotan-1 further into the uplifted area) have NN11 nannofossil just above the unconformity suggesting the rapid transgression had begun before about 5½ Ma.

### INTEGRATION OF RESULTS WITH REGIONAL GEOLOGY

The description above should show that the Cycles scheme was only temporarily successful as a simple correlation tool until high quality seismic took over. The original definition of the Cycles, and their very name, stresses their founding concept as a series of transgressions over regressive surfaces, yet since the earliest papers (Ho, 1978; Hageman, 1987), through the work of Ismail (1996), shows that these changes in sedimentary conditions were recognised as having been strongly influenced by tectonism, and a three-dimensional stratigraphic model began to emerge. This review presents a hypothesis that tries to link the character of the tectonic variability of Cycles with a regional geological model.

The Cycle I to Cycle II boundary on the Oligo-Miocene boundary seems to also coincide with the Top Crocker Unconformity in Sabah and the onset of plate drift and sea-floor spreading in the western South China Sea. Lunt & Madon (in press) describes how compression affected latest Oligocene sediments in west Sabah and southernmost Palawan but this compression was terminated virtually on the Oligo-Miocene boundary, as is also seen at the end of Cycle I deformation in Sarawak. A correlation between this tectonic event and the climatic change at the top Pcs.145 (top S200) pollen zone (Levell & Tan, 1986 - unpublished; and Morley, 2000), is possible, as studies on the formation of the South China Sea suggests it was at the Oligo-Miocene boundary (25 Ma; Barckhausen & Roeser, 2004; Barckhausen *et al.*, 2014 - between anomalies 6b and 7 so between about 23.5 and 25 Ma, and 23.6 Ma; Li *et al.*, 2014) that the plates began to drift. The birth and rapid expansion of a new oceanic basin, which persists to the present day, is a likely candidate to have caused the change climate from seasonal to ever-wet conditions, which persist into modern times. The Cycle I to II boundary unconformity was the second break-up type unconformity to affect the South China Sea (SCS); the first being rift to drift north of Palawan which led to deposition of Early Oligocene Nido limestone of north Palawan on its southern flank (cf. Schlüter *et al.*, 1996). As with that older break-up unconformity, and also the younger one at the “MMU” discussed below, the Oligo-Miocene rift

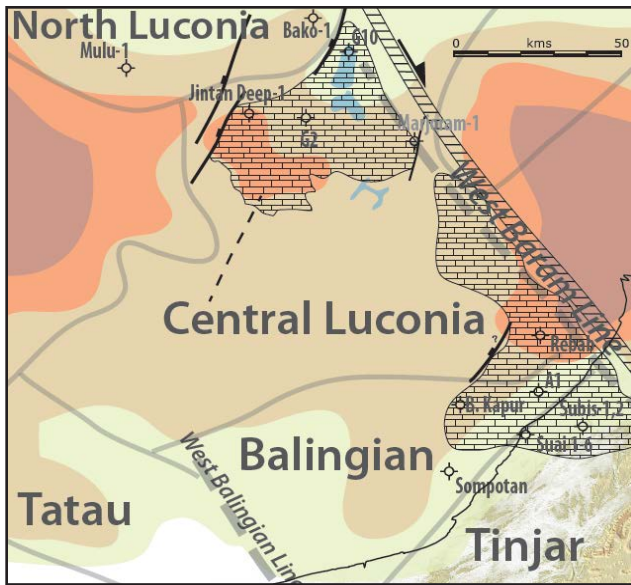
to drift subsidence of the western SCS initiated transgression over its flanks, and after the Oligo-Miocene boundary in offshore Sarawak there was deposition of transgressive Subis limestone along the flank of the West Baram Line (Figure 18). This limestone transgression is dated as within Te5, close to 24 Ma, van Gorsel *et al.*, 2014), and the thickness of the limestone decreases with distance from the margin of the West Baram Line (e.g. Figure 16), which was probably a right lateral wrench that accommodated the new drift and sea-floor spreading in the western SCS.

The age of termination of spreading and plate drift in the SCS is still being debated (see the comparative Table 1 in Li *et al.*, 2014) but the model by Barckhausen & Roeser (2004) and Barckhausen *et al.* (2014) dates this at 20.5 Ma (at anomaly 6A1) which is the age of the termination of the Subis Limestone Te5 limestones (base Cycle II limestones, see combined nannofossil foraminiferal and strontium isotope date in Batu Kapur-1 described above, which is very close to the value of 20½ Ma).

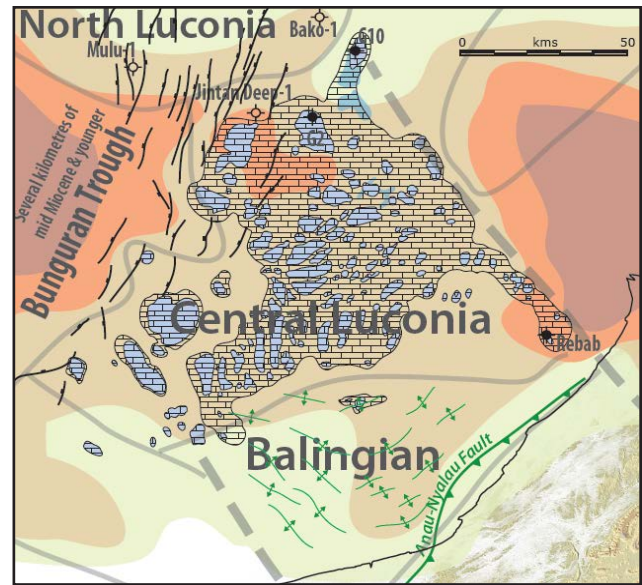
The base Cycle III and base Cycle IV transgressions are strongly focussed in the northwest where the Bunguran Trough was opening (Figure 19). This is the increase in basement subsidence observed on regional seismic at the base of sequence T3S of Ismail & Swarbrick (1997). Associated with this there was also a transgression in the southwest over the eroded high of the Tatau Province. It is probable that uplift in Central Borneo accelerated at this time, with data from the onshore Suai wells and outcrops suggesting that sediment supply from the southeast had begun to increase, replacing the old sediment sources to the southwest that would have been drowning at that time. Hageman's 1985 map for the end Cycle III to base IV palaeogeography indicates that by Cycle IV times this sediment supply was clearly coming from the new sources in Central Borneo. Ismail's seismic showed how Cycle IV transgressed directly over deformed older Cenozoic Rajang Formation near the H2-2 well .

In most parts of the basin, Cycle III is relatively thin, and probably represents the later stages of a long period of deformation of the Sarawak margin (as indicated by numerous normal, reverse, wrench faults), prior to the base Cycle IV transgression (Figure 3).

Cycle IV deposition seems to have been initiated by accelerated subsidence of the Bunguran Trough, and the transgression it produced allowing widespread limestone to form on the horsted highs flanking the rift, Terumbu Limestone on the west flank and Luconia Limestone on the east. The base Cycle IV transgressive surface was called the “break-up unconformity” by Hutchison (2004), based on the deep water Luconia wells and seismically imaged strongly rifted topography that had been the original Middle Miocene Unconformity, “MMU” (Doust, 1981). This was the third break-up type unconformity to affect the SCS. However there is no indication that the Bunguran Trough had any sea-floor spreading. The post-rift Terumbu and Luconia limestones identify the Bunguran Trough as the source of this tectonism as they symmetrically flank the new rift basin,



**Figure 18:** Map showing the location of the Subis equivalent limestone (top Cycle I of early workers, later considered the basal Cycle II transgression).



**Figure 19:** Map showing rifting of the Bunguran Trough and distribution of the Luconia Limestone that were initiated at the base of Cycle IV. Folds and faults in green are younger, active during Cycle V, terminated and eroded by the base Cycle VI unconformity.

and fade away from the rift axis. The transgressive reefal carbonates (or the condensed, clastic-starved deepwater sediments deposited over the rift topography) indicates the age of the peak of the unconformity event. This is dated as younger NN4, N8 (perhaps basal N9 indicated by a few, rare microfossils), or about 15½ Ma. In deep water North Luconia areas the rate of sedimentation dropped considerably the condensed hemipelagic unit indicates almost no siliciclastic supply reached the area until later Middle Miocene times. Morley *et al.* (2016) give comparative sedimentation rates reflecting this.

In central Borneo there is data for strong uplift within N8 times, equivalent to the III to IV boundary (Chambers & Daley, 1995; Guritno & Chambers, 2000; Cloke *et al.*, 1999), by inversion of old graben-bounding faults.

The Cycle IV to V boundary at about 12-13 Ma is indicated by deepening in the northwest and also a strong transgression across, or subsidence of, the Luconia area. However sediment input remained high, and it was at about this time that Ho (1978, his Figure 8, also Tan *et al.*, 1999, Figure 13.7) considered the main progradation of the Baram Delta to have started. Lunt & Madon (in press) discusses how the DRU was a pause in the already active Sabah Orogeny, and that it also peaked at 12-13 Ma, and that this also coincided with strong basement subsidence in eastern Sabah, with rapid drowning of Tabin Limestone reefs, and possibly strong subsidence in central Sabah under what would become the Meliau and Malibau circular basins.

It is known from the work of Sun Oil Malaysia (Jordan & Ford, 1990, unpublished) and Clennell (1991) that, from the Meliau/Malibau area north to the coastal town of Sandakan, the outcropping Tanjong and older formations have a high thermal maturity from burial (with outcrops of

the former typically with vitrinite reflectance of 0.6% Ro), suggesting that several kilometres of sedimentary overburden have been removed from a wide area. In north Sarawak the White Sand Member of the Meligan Formation, age and facies equivalent to the Tanjong Formation, is mapped as well-indurated ridges of quartz sand indicating burial compaction (the formation lacks thermal maturity analyses). The outcropping delta-top and coal bearing Tanjong and Meligan Formations are important lithological markers as they are dated as early Middle Miocene (base N9 *Orbulina* datum to the top of Lower Tf larger foraminifera; a Cycle IV equivalent), so the sediment accommodation space had to have increased to allow about 3 km of overburden to compact the delta-top sands and thermally mature the coals. We also know that very soon after this there was uplift in the southeast and an accelerated sediment supply to deposit the required overburden, as seen on the Baram summary of Ho (1978). Note that the Western Cordillera of Sabah also continued uplift soon after the DRU, as shown on the seismic in Levell (1987), and may have been a sediment source.

Some caution is required when examining the regional aspects of Cycle IV to V and DRU, mid Middle Miocene events, at about 12 to 13 Ma. It should be noted that to the west, and strongly affecting West Natuna (Ginger *et al.*, 1993), but with effects over a wide area from the Malay Basin, Nam Con Son to the west of the SCS, there was another tectonic event that peaked in mid to later Middle Miocene times, about 11 Ma. As most major unconformities have activities lasting several million years, care should be taken to date and map the effects of each unconformity. Current data suggests the Cycle IV to V and DRU events seems to have centred on northern Borneo, whilst the possibly very slightly younger West Natuna end-Middle Miocene event was strongest in that area. At the moment

a tectonic model describing and linking the two periods of change is lacking.

We know that in the later part of Cycle V (mid to later Late Miocene) uplift of the Tinjar Province and areas of eastern Balingian near the Anau - Nyalau thrust fault that de-limits Tinjar becomes very pronounced, with recycling of Cycle IV, III, II and even Cycle I sediments to gradually fill the Balingian and Luconia provinces. This was the main growth phase of the Balingian transpressive anticlines (Gonguet, 2001, also shown in Figure 11 here). This rejuvenated clastic sedimentation began the process of terminating the southern Luconia reefs (Vahrenkamp, 1996).

The near end Miocene base of Cycle VI was a strong tectonic transgression over the southern margin of the Sabah Orogeny, but on current data it does not seem to correlate with any of the shallower regional unconformities identified in Sabah. It is not the same age as the Togopi transgression over eastern Sabah dated by Lunt & Madon (in press) as near end Early Pliocene.

The remaining challenge is therefore to integrate the later Cycles (IV to VII) with the Sabah Orogeny. As noted by Lunt & Madon (in press) olistostrome deposits just offshore west Sabah and south Palawan predate the DRU suggesting, as does seismic, that the DRU is an unconformity surface formed after the first phase of compression had begun, perhaps as old as the latest Early Miocene. Could the onset of uplift and new sand sources in Central Borneo at the Cycle II to III boundary in mid Early Miocene times (roughly 17½ to 18 Ma) be considered the first part of the Sabah Orogeny? Was the opening of the Bungaran Trough at the same time related to the initiation of the Sabah Orogeny? The two structural features are similar in age and orientation. Any tectonic model needs to accommodate crustal extension in the Bungaran / West Luconia area with the onset of crustal uplift in the east (an uplift for which Hutchison *et al.* [2000] proposed a different model; from isostatic rebound after decoupling of an old oceanic plate). It is the role of stratigraphy to map out these changes at time equivalent horizons in order that an accurate tectonic model can be constructed.

## CONCLUSIONS

Over the past decade new biostratigraphic work (Morley *et al.*, 2011; Morley & Swiecicki, 2014) shows that analysis of well samples for flooding surfaces is on the verge of offering a high resolution (1 to 2 Ma intervals) correlation tool for marine shelf to coastal beds from Nam Con Son to north Sarawak, and this may well match at least part of the eustatic sea-level curve. Recent seismic interpretations of Sarawak (e.g. Kosa, 2015) correlate at a similar high resolution, but for more than a decade the study of larger scale geological controls on sedimentology seems to have stalled, in part due to confusion of what the Cycles were and how they fitted the eustatic and regional tectonic models.

The Cycles scheme is geologically more complete than a correlation tool, combining several independent disciplines into a model that is testable with Walther's Law.

This testability means that the Cycles can be made part of a broader scientific investigation. They integrate easily with the tectonic sequence scheme of Ismail (1996-1999), and the cycle boundaries are now fairly well dated in spite of the generally shallow or marginal marine facies that are poor in age diagnostic fossils. It is hoped that this report helps clarify confusion among old reports with different ages for Cycle boundaries, which is inevitable considering the advances in integrated time scales that began with Berggren *et al.* (1995) through to Gradstein *et al.* (2004), and also because most of the key data sources are unpublished.

The floods associated with Cycle boundaries may be more diachronous than the higher resolution events, but their larger size means it may be easier to find the *prima facie* evidence for transgressions (flooding surfaces) that can be so ambiguous and subjective in the high resolution schemes. They therefore remain a useful low resolution correlation tool for a chronostratigraphic framework.

The early Cycles, I to III, seem to be linked to regional extension and subsidence (with local compression) that can be linked to extensional plate stresses in the South China Sea. Probably from within Cycle III times, but certainly from Cycle IV onwards the sedimentary history of Sarawak appears to be closely linked to the long-lasting Sabah Orogeny (about end Early Miocene to Pliocene). The regional framework of the Sarawak Cycles sedimentation model is important for understanding this particular tectonic processes because the Orogeny has eroded data away in the core area.

The original data behind the Cycles model needs to be documented and published in order to contribute to a constructive scientific process. Constructive criticism of the review presented here is therefore welcomed.

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