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Field and well evidence for major unconformities in north Sarawak, compared to southwest Sabah, Malaysia

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Abstract: A review of biostratigraphic and lithofacies data is used to show that there is no major unconformity in the stratigraphic record of north Sarawak or southwest Sabah near the end of the Early Miocene (approximately 17-15 Ma). The existence of such an unconformity has been cited in many papers in the past decade and used as a data point in the construction of regional geological hypotheses. Exploration well and outcrop data identifies two major unconformities in SW Sabah (the base and top of Stage III; BMU and DRU; roughly 24 and 13-12 Ma), and in offshore west Sarawak a third unconformity (MMU c. 16 Ma) which fades in effect towards onshore Sarawak. In recent years the names of these distinct unconformities have become conflated as workers had overlooked the origins and definitions of these features. This history is reviewed here in order to clarify future work.

Keywords: Sarawak, Sabah, stratigraphy, unconformities

INTRODUCTION

Many papers cite the presence of an unconformity close to the Early to Middle Miocene boundary in north Sarawak, which is often identified as the Deep Regional Unconformity (DRU) of Sabah (Sandal, 1996; Hutchison, 2005; Morley, 2016; Kessler & Jong, 2016, Hennig-Breitfeld *et al.*, 2019) and it is assigned an age that appears to correlate it to the Middle Miocene Unconformity as defined by Ho Kiam Fui (1978) and Doust (1981) in the Luconia Province of Sarawak (Figure 1: called the “Doust MMU” by Lunt, 2019, to distinguish it from other unconformities in the region with the same MMU acronym). The Doust MMU reflects a major acceleration in extension that resulted in a buried topography unconformity (Hutchison & Vijayan, 2010; Madon *et al.*, 2013), whereas the DRU was a pause during the early stages of the Sabah Orogeny (Levell, 1987; Hutchison, 1996). It is important to establish if these tectonic movements occurred at the same, or different times, as each alternative history will have important implications for regional geological reconstructions.

This review examines an extensive library of archived and modern data to determine what unconformities have been recognised and the source of the underlying stratigraphic observations, and especially the quality of those observations. This includes whether data is a simple estimate, or has evidence related to palaeontology or other age dating techniques, as well as the nature of shifts in depositional facies across the proposed unconformities.

HISTORICAL DATA ON MAJOR UNCONFORMITIES

The Doust MMU

The dating of the Doust MMU is well established. The multiple wells across Luconia that drilled through this horizon in the 1970s and early 80s dated the marine siliciclastic beds below and before the event as being within the *Globigerinoides bisphericus* - *Globigerinatella insueta* Zone. Note that *Gd. bisphericus* is a junior synonym for *Gd. sicanus*, which is sometimes assigned to the genus *Praeorbulina* (where the species name has its gender modified to *sicana*; Blow, 1969; Postuma, 1971). This Zone followed the naming convention of Postuma (1971) but the review of Hageman *et al.* (1987) noted the scarcity of the species *G. insueta* in the region, and consequently the extinction of *Gd. sicanus* was used as a proxy for what became known as SN8 (Sarawak N8, following the simple numerical zonal names of Blow, 1979). On modern time scales the range of *Gd. sicanus* extends from 16.4 to 14.56 Ma (Wade *et al.*, 2011). The absence of *Orbulina* (evolution at 15.1 Ma) below the Doust MMU was eventually considered good negative evidence (supported by more recent sidewall core analysis on Talang-1, see below) that the abrupt subsidence and transgression of the Doust MMU occurred between 16.4 and 15.1 Ma (on modern time scales). Assigning such a narrow age range to a break-up type unconformity is not unusual as they appear to have occurred as very rapid subsidence events (cf. Pindell *et al.*, 2014) with minimal erosion and loss of stratigraphic record,

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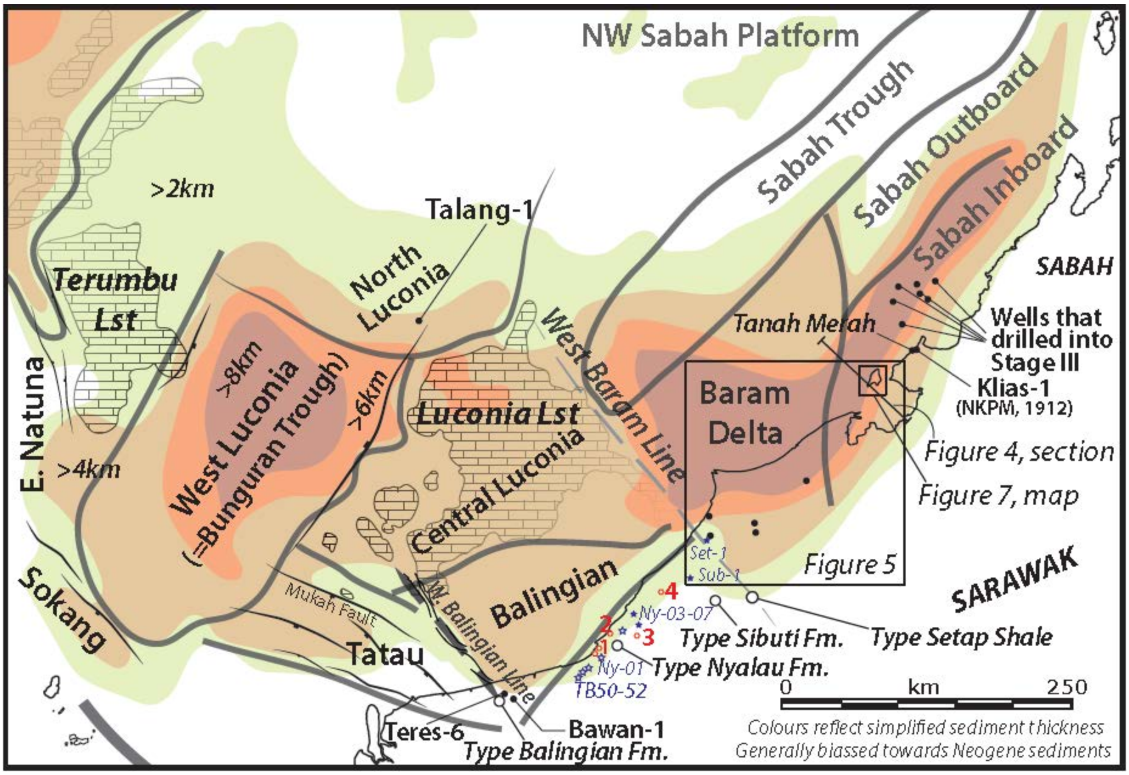

Figure 1: Location map. Numbers in blue are the outcrop locations of Breitfeld *at al*. (2020). Solid symbols are those with biostratigraphic analysis. Numbered polygons in red are core-holes of Rahdon (1974) 1= RD/72-1 & -2, 2= WRD73-1, 3=RD/73-1, 4=RD/73-5.

apart from local truncation and slumping of angular fault scarps (van Vliet & Krebs, 2009).

Many reports cite some strontium isotopic dating from a deep water well (Talang-1, drilled 2006 in the North Luconia Province, Robinson *et al.*, 2009) to suggest an older age for the Doust MMU (e.g. Hutchison & Vijayan, 2010; Madon *et al.*, 2013; Aurelio *et al.*, 2014; Morley, 2016). On the basis of a single sample below the MMU dated as 18.5–19 Ma, and a strontium age of 16.1–16.3 Ma in a sidewall core sample from Zone N8 just above, these workers thought the MMU was Early Miocene, and that there was a 2 to 2.5 million year hiatus at the unconformity. However, the MMU location drilled by Talang-1 was not on the top of a horst but the front-slope (scarp) of a cuesta in the buried topography (Figure 2). There is about 200 m of un-sampled pre-MMU clastics above the depth of the well sample, which is visible on seismic. The underlying Cycle II-III clastics drilled by the well to the top Cycle I unconformity (=Base Miocene Unconformity or BMU) is only 250 m thick in this well (the Cycles scheme is shown on Figure 3). This means the 18.5–19 Ma Sr isotope age is from a depth about halfway through the undifferentiated Cycle II-III section, and not from a level close to the top of Cycle III and the Doust MMU.

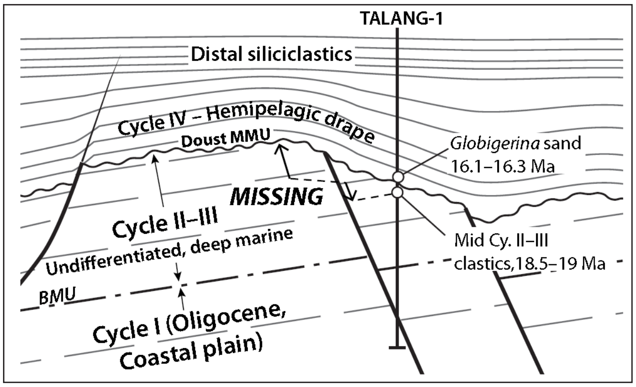

Figure 2: Schematic sketch of the Talang-1 location in North Luconia, and the geometry of beading around the Doust MMU. Not sampled by this well is approximately 200 m of upper Cycle II-III. Based on seismic in Robinson *et al.* (2009).

The hiatus implied by these early workers is not a valid observation. On top of the buried topography is an extremely condensed hemipelagic marl with rates of deposition of about 20 m/Ma, which is the same rate of deposition found in ODP hemipelagic deposits in the central South China Sea (SCS; Madon *et al.*, 2013; Qianyu *et al.*, 2005). This globigerine ooze *is* the hiatus expected over the MMU. That is, there was a siliciclastic hiatus, but no pause in the accumulation of open oceanic planktonic detritus. The age of 16.1–16.3 Ma from the N8 base *Globigerina* ooze is probably a better indication for the age of the Doust MMU subsidence.

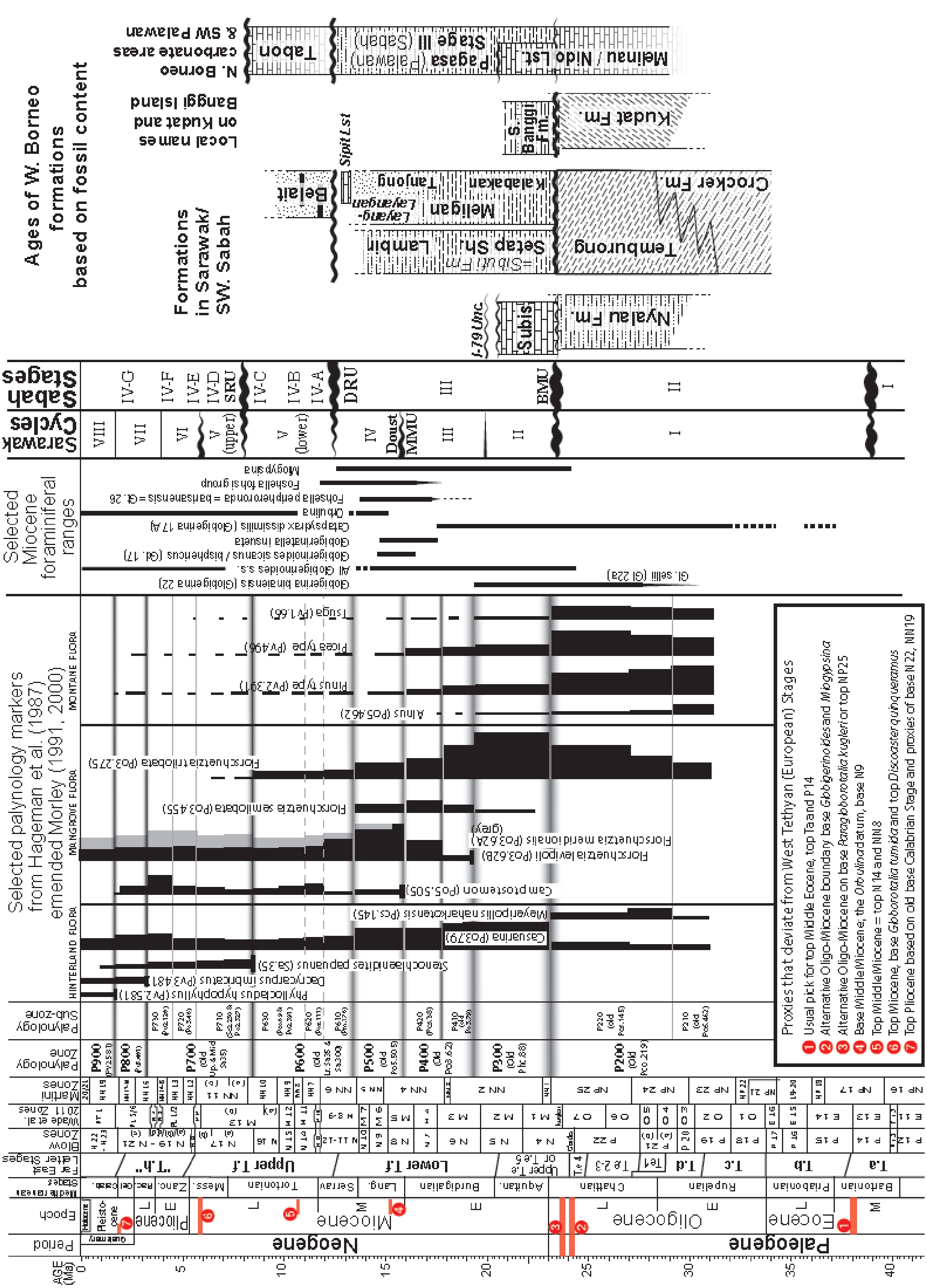

Figure 3: Stratigraphic summary and time scale based on Ogg *et al.* (2016). The microfossil ranges on this chart have been stable since at least the mid 1980s, only the time scale has improved and the taxonomy of some forms has changed.

In light of other events ambiguously called the MMU in SE Asia, Madon *et al.* suggested re-naming the MMU in Luconia as EMU (Early Miocene Unconformity) but this may not be as clear-cut as first interpreted. In addition to the readjustment of age described above, the formal definition of the top of the Early Miocene is the boundary of the Burdigalian to Langhian Stages which is placed at 15.97 ± 0.05 Ma (Cohen *et al.*, 2013). Considering the precision of age measurement from strontium isotopes (no raw data, sea water reference curve information or calibration standards were included in the Robinson *et al.* 2009 report, which can shift an Sr age by several hundred thousand years) it can be said that the Doust MMU and the Early to Middle Miocene boundary have virtually identical ages, but it cannot be said that the Doust MMU is clearly in the Early Miocene.

The geographic extent of the Doust MMU subsidence can be traced by the deposition of the siliciclastic-starved Luconia limestone that followed this subsidence event. This limestone, along with the symmetrically equivalent Terumbu Limestone of East Natuna on the other side of the Bunguran Trough is shown on Figure 1. This symmetry clearly shows that the focal area of the tectonic movement that triggered the transgressive limestones over a buried topography unconformity was the Bunguran Trough. The magnitude of the unconformity diminished away from the trough, and the disappearance of Luconia Limestones is the defining difference between the Central Luconia and Balingian Provinces.

The Deep Regional Unconformity

The age of the Deep Regional Unconformity (DRU) was first described in the report of van Hoorn (1977), but repeated in a published paper by Levell (1987). The DRU was an abrupt pause in uplift of the first phase of the Sabah Orogeny and it was well after the *Orbulina* datum and also after the extinction of all *Praeorbulina* species (younger than 14.56 Ma on modern time scales). Several wells could refine this age to be after the extinction of what is now called *Fohsella peripheroronda* (then called *Globorotalia barisanensis*; which defines the base of the *Gt. peripheroacuta* Zone cited by Levell), and before the extinction of the entire *Fohsella* lineage; i.e., between 13.77 to 11.7 Ma on modern time scales. Fossil distribution above and below the unconformity subjectively suggests that the DRU event was in the younger part of this age range, as several hundred feet of deep marine *Gt. peripheroacuta* Zone sediments were uplifted, and in places eroded, before the onset of the terminal transgression. Uplift may have gradually decelerated before the terminal event, and the transgression onto the eroded central part of the uplift was almost certainly diachronous, but the age cited here is a turning point, tied between un-eroded wells on seismic, representing the time when the subsidence and transgression of the DRU surface began. There is no evidence that this event is diachronous over several million years, as speculated in many reports (e.g., Hall *et al.*, 2008).

Confusion on age arose because van Hoorn's (1977) detailed report, which drew the "DRU" within the Middle Miocene, was not published. A few years later a very short summary was published in Bol & van Hoorn (1980). In this latter summary some schematic lithofacies sections were drawn against a very simple age scale, and on them the DRU was placed at the level of the Early to Middle Miocene boundary. Levell reproduced these low-resolution schematics in his 1987 paper, even though his text specifically pointed to an age within the Middle Miocene. Levell's Figure 8 of the mapped extent of the DRU was also labeled as "early Middle Miocene, ca. 15 Ma". This was not an accurate statement, as even in 1987 the *Orbulina* datum that is well below the DRU was dated at 15.2 Ma, the pre-DRU extinction of *Globorotalia peripheroronda* at 14.6 Ma, with the base Langhian, base Middle Miocene dated at 16.5 Ma (Berggren *et al.*, 1985). These absolute ages were all prior to important revisions to the integrated time scale in Berggren *et al.* (1995) and minor revisions in Gradstein *et al.* (2004). The "ca. 15 Ma" therefore appears to have been an inappropriate rounding error for a slightly younger age, and a value that is slightly younger still on modern time scales.

In conclusion, the buried topography event of the Doust MMU and DRU of Sabah are not age equivalent but roughly 3½ to 4 million years apart. The maps of Levell show the DRU erosional surface diminishing in SW Sabah. As noted above, the extent of the Doust MMU is very strongly focused around the Bunguran Trough and it fades in facies contrast to the east across the Balingian Province where excellent quality 3D seismic sees no tectonic contrast, and facies analysis has only a weak indication of a small transgression/ relative sea-level rise at this time (Lunt & Madon, 2017a).

The Nyalau Unconformity

The term Nyalau Unconformity was proposed by Hennig-Breitfeld *et al.* (2019) for an unconformity across Sarawak at about 17 Ma, thought to be associated with a change in the trend of the palaeo-coastline from NW-SE to NE-SW. This, they acknowledged, was the long-recognised change in palaeogeography associated with the Cycle II to III boundary (Hageman, 1987; Madon, 1999; Hutchison, 2005, p. 99-101). Hageman *et al.* (1987) listed the biostratigraphic data associated with this Cycle boundary, and Lunt & Madon (2017a) updated this to a modern time scale as being at approximately 19 Ma. In addition to being about the same age as a gradual change in sediment supply (see Figures 36H to F in Hutchison, 2005, spanning about 3 million years), the Cycle II-III boundary event was primarily the rapid subsidence of roughly W-E graben faults in SW offshore Sarawak (see Mat-Zin & Swarbrick, 1997, the base of their sequence T3; Mukah Fault and related faults on Figure 1 here), and the associated transgression onto the surrounding highs.

Hennig-Breitfeld *et al.* cited a large range of different ages assigned by various workers to the BMU, TCU, MMU and DRU [Base Miocene Unc., Top Crocker Unc., Middle Miocene Unc. and Deep Regional Unc.] but without considering how any of these reported ages were derived. Thus, having artificially created confusion they then proposed their new Nyalau Unconformity as a solution to this apparent complexity, stating: "*On land, we see the main event at c. 17 Ma is marked by the Nyalau Unconformity, and not at c. 15.5 Ma*". This is not a recommended approach to stratigraphy as apart from having no definition of the new unconformity, other than a gradual shift in facies and coastline, which cannot be a primary definition of any unconformity, there was no evaluation of age, of either the new or historical data. In addition, there was no consideration of the character, or geographic variation, of each of the multiple cited unconformities as part of a geological framework. There is a danger that such work, with a large number of sources referenced, but no underlying age data, is then re-cited as a definition or an authority on Early Miocene unconformities in Sarawak and south Sabah, – as it was in Breitfeld *et al.* (2020) and Burley *et al.* (2020).

In 2020 Breitfeld *et al.* published data on five samples said to be below the Nyalau Unconformity, even though the unconformity itself was not identified in this report. Their stratigraphic summary shows the unconformity had been interpreted between the Nyalau Formation and the Kakus Member, the latter being originally defined as a diachronous paralic and coal-bearing facies near the top of the Nyalau Formation (Liechti, 1960). Two samples were reported by Breitfeld *et al.* (TB50 and Ny01; see Figure 1) in the Kakus Mbr., but there were no biostratigraphic analyses of these samples. The Kakus Mbr. is distinct as it yields brackish water arenaceous fauna and lignites (*Miliammina*, *Trochammina* and *Ammobaculites* sp.; Liechti, 1960). In contrast the main Nyalau Formation generally contains a few lignites but also has periodic, thin, marine calcareous horizons. Core-holes as deep as 400 feet reported in Rahdon (1974) from the same area sampled by Beitfeld *et al.* (Figure 1, red symbols and numbers) were described as coastal swamp deposits, tidal mud-flats with channel-fill, and were dated using palynology as being from Zone Pcs.145 or the modern P200 zone of Late Oligocene age. At the base of one of these core holes (RD/73-1) was a 20 foot thick sandy limestone with Te2-4 fauna including *Spiroclypeus* and *Heterostegina*. Core-hole RD73-5 of Rahdon, in the north approaching Subis (red 4 on Figure 1), is dated by palynology as Zone Phc.88 or modern Zone P300. In this core there were multiple argillaceous limestones up to 30 feet thick of Te5-Tf age (with *Miogypsina*) and some of the claystones contained planktonic and inner to middle neritic benthic foraminifera, which are not seen at all in the Oligocene (P200) claystones of the other cores. The presence of *Globigerina binaiensis* and *Catapsydrax dissimilis* along with the carbonate facies *Miogypsina* indicates an age between about 24 and 19.4 Ma, i.e., early Early Miocene. These ages, based on many tens of analyses, contradict the ages estimated for the Kakus Member from two unanalysed samples in Breitfeld *et al.* (2020).

The Nyalau Formation is usually defined as the coastal plain, sand-rich siliciclastic lithofacies below the transgression of the Subis Limestone or the marly and marine Sibuti and Tangap Formations (Liechti, 1960; Rahdon, 1971; Levell & Tan, 1986; Madon, 1999). However, Levell & Tan pointed out, some sand-rich marginal marine facies in younger units in the proximal southwest of Sarawak have also been given this lithofacies-based formation name. This terminal Nyalau Fm. transgressive event was drawn on a much-cited Sawarak Shell Cycles summary diagram of Veenhof (1997; e.g. Figure 14.3 of Madon & Abolins, 1999; Figure 4 of Lunt & Madon, 2017a).

The Subis Limestone and nearby outcrops sampled by Breitfeld *et al.* (Su-1 and Ny03 to 07, Figure 1) are all Letter Stage Te5 or older. All five sample contain Te5 *Spiroclypeus* or *Eulepidina*, dated as older than 20 Ma (Allan *et al.*, 2000; van Gorsel *et al.*, 2014). Three samples contain the base Te5 marker *Miogypsina*, but two do not and could be older, from the Oligocene, Te2-4. These samples without *Miogypsina* are directly comparable to the Te2-4 sandy carbonates found with Oligocene palynomorphs in borehole RD/73-1 of Rahdon (1974).

Two marine claystones of Breitfeld *et al.* were plotted by them to be above their Nyalau Unconformity (Set-01a and 1b, located a few kilometres south of the Bulak Setap-3 well site). These contained planktonic foraminifera with *Catapsydrax dissimilis* and either *Globigerinoide*s species or *Dentoglobigerina altispira* suggesting a general Early Miocene age, anywhere between the base of Zone N4 and the top of N6. All this data is completely consistent with the base Te5 flood of the Subis Limestone being the basal Cycle II transgression of Veenhof (1997), and that this was the most important stratigraphic event of this period (the BMU seen in other areas, always at the base of Te5, which transgressed over an angular unconformity in the Tatau Province; Levell & Tan, 1986; Madon, 1999; Hutchison, 2005).

From the base to the end of the Early Miocene there is historical evidence for just two additional unconformities, all in a narrow age range of 20.5 to 19 Ma and possibly different parts of the same process. First, and regionally, there was the appearance of a new central Borneo sediment source between 20 and 21 Ma that terminated the Subis and many other Te5 Limestones around Borneo (Lunt & Woodroof, 2021). At almost the same time there was uplift in the Tatau province from a compressional event that resulted in the I-79 unconformity (Madon, 1999; Hutchison, 2005, Figure 36H), which is dated at approximately 19-20 Ma, just before the first appearance datum of *Florschuetzia levipoli* (van Gorsel *et al.*, 2014), but also slightly older than the extinction of *Globigerina binaiensis* at 19.4 Ma. The local compression of the I-79 Unconformity occurs just below the base of Cycle III and was followed by a widespread subsidence event. This subsidence has long been associated with the onset of extensional faulting such as the Mukah Fault (Brolsma, 1981) and it is also the subsidence at the base of Sequence T3S of Mat-Zin & Swarbrick (1997) mentioned above.

This 20-21 Ma appearance of a new Borneo sediment source, and the 19-20 Ma subsidence under western offshore Sarawak are probably stages in the tectonic re-configuration that led to the gradual change in coastline and sediment supply during the mid-Early Miocene drawn by Madon (1999) and Hutchison (2005; Figures 36G,F).

On the stratigraphic summary of Hennig-Breitfeld *et al.* (2019), and briefly in their text, their "Nyalau Unconformity" was correlated with the "Crocker-Temburong" to Belait Formation unconformity on Labuan Island (the DRU of Levell, 1987; see Figure 4 here), and also the base of the Balingian Formation in the onshore Tatau Province. They specifically state that they "*interpret the TCU to be of similar age to the Nyalau Unconformity, thus representing an equivalent and enabling a correlation of these two important unconformities in Sarawak and Sabah*". In Burley *et al.* (2020) Hennig-Breitfeld *et al.*'s "Nyalau Unconformity" was considered to be the unconformity in the north of Labuan Island, and they further stated that "*a similar age is interpreted for the Early Miocene Unconformity (EMU) by Madon et al. (2013) which may correlate to the top Nyalau Unconformity and the TCU*". The un-supported date of "*ca. 17 Ma*" was re-cited by Burley *et al.*

In all the above review the only unconformity with an audited age close to c. 17 Ma was the Cycle II-III boundary of Hageman *et al.* that was updated to modern times scales by Lunt & Madon, as being just before the extinction datum of *Globigerina binaiensis* (19.4 Ma) and also older than the evolution datum of *Globorotalia barisanensis* (now *Fohsella peripheroronda*), estimated at about 17 to 17½ Ma. However, it needs to be stressed that neither this, nor any other source, was cited as supporting data for the proposed age of "*ca. 17 Ma*" of Hennig-Breitfeld *et al.* for a major regional unconformity.

There is only an approximate age for the evolution datum of *Fohsella peripheroronda* as this is a very simple morphology with a rounded keel before the appearance of the distinct carinate keel in the adult chambers (=*Fohsella peripheroacuta*). While a few rare or tentative records of older *F. peripheroronda* are in the early Early Miocene the quantitative summary of IODP data (mikrotax.org website) suggests the forms only become common in Zone N7/M4, about 17 to 17½ Ma.

OUTCROP AND ONSHORE WELL LOCATIONS

The only onshore work that has suggested, from analytical data, an unconformity near the end of the Early Miocene was a report by Simmons *et al.* (1999). This has been re-cited by Hall *et al.* (2008) and also Morley (2016). The following quote from Simmons *et al.* is based on their single north Sarawak ENT location shown on Figure 5:

"*Here the Sibuti Formation contains planktonic foraminifera indicative of an Early Miocene age (presence of Globigerinoides obliquus, absence of Orbulina spp.) … with Sphenolithus heteromorphus … suggests a late Early Miocene age …. The overlying mudstones and sandstones of the Lambir Formation are no older than intra-Middle Miocene based on the co-occurrence of Florschutezia trilobata and Camptostemon sp. This suggests that there is an unconformity between the Setap and Lambir formations at this locality, with the earliest Middle Miocene being absent. The presence of slight angular disconformity in the outcrop and abrupt change in depositional environments supports this possibility*." This interpretation has been re-cited as "*about 17 Ma* (C.K. Morley, pers. comm.., 2007, based on Simmons *et al.*, 1999)" in Hall *et al.* (2008) and "*17–16 Ma (M. Simmons pers. comm., 1997)*." by Morley, 2016.

As noted by Lunt (2020) the only marker that was used by Simmons *et al.* to indicate a gap was the absence of *Camptostemon* in the older samples, a marker which these workers had assumed to have a lowest occurrence within the Middle Miocene. As a result of this assumption, it appeared that mid-Middle Miocene sediments were overlying the late Early Miocene, the latter based on the absence of *Orbulina* (which evolved at the base of Zone N9 and long used as proxy marker for the base Middle Miocene; 15.1 Ma vs top Burdigalian at 15.97 Ma). As noted in many old

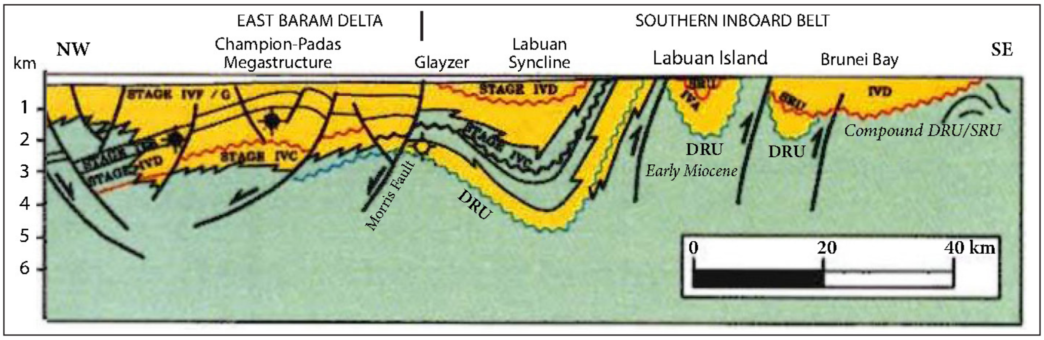

Figure 4: Cross-section from Madon *et al.* (1999) based on seismic that ties the DRU penetrated in offshore wells to Labuan Island. Location shown on Figure 1.

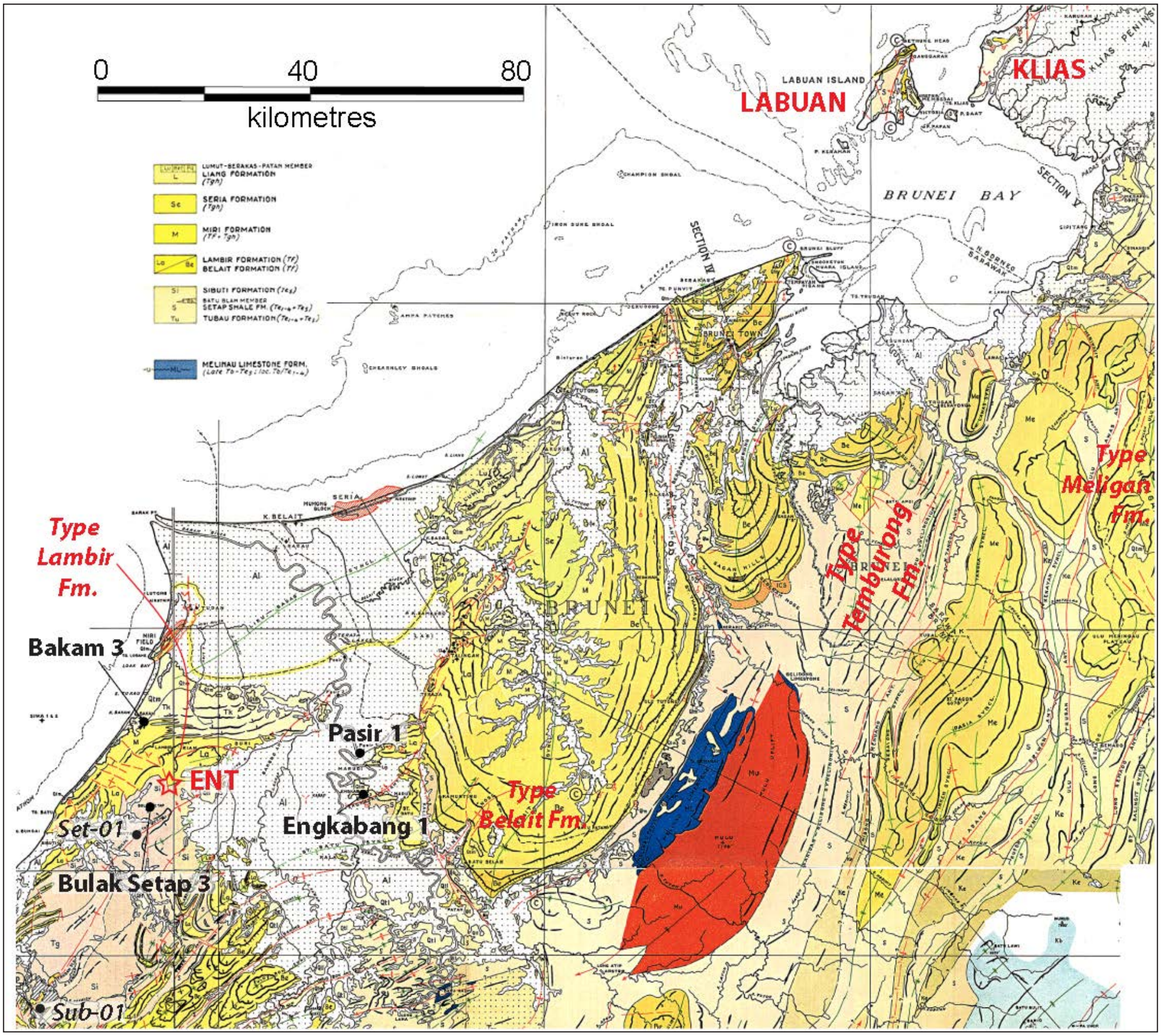

Figure 5: Field locations over the geological map of Liechti (1960). The ENT site was the only section studied by Simmons *et al.* (1999) in north Sarawak. Samples Set-01 and Sub-01 in the lower left of the map are locations of Brietfeld *et al.* (2020), the other location of these authors being 40 km or more to the SW (see Figure 1).

reports but especially Hageman *et al.*'s detailed 1987 review, *Camptostemon* is found to the base of the Middle Miocene, and Hageman *et al.*'s Figure 1 places the oldest records of *Camptostemon* in Borneo just below the *Orbulina* datum.

Two points can be deduced from this. First, the absence of *Orbulina* below a lithofacies change and presence of *Camptostemon* above it does not indicate a time gap and missing section. The sediments below are probably Early Miocene and those above are Middle Miocene (but no younger, based on the presence of *Florschuetzia trilobata*). Secondly, if there was an unconformity at this lithofacies transition it would be dated as about 15 Ma, not 17-16 Ma.

In addition to this there is the confounding issue that the lithofacies succession in north Sarawak is one of shallowing up in the environment of deposition (Sibuti Fm. into Lambir Fm.; Liechti, 1960), but *Orbulina* is a planktonic foraminifera that matures into the taxonomically important adult stage in fairly deep oceanic waters (outer neritic to bathyal depth equivalents, Hemleben *et al.*, 1989; thermocline to sub-thermocline depths, Aze *et al.*, 2011). In a shallowing-up succession its absence in the progressively shallower marine facies is just as likely to be due to environmental restrictions rather than indicating an age older than its evolutionary appearance. Therefore, the clay-rich Sibuti Formation to sandy Lambir Formation transition could have been within the Middle Miocene, and the true base of the Middle Miocene could be lower in the underlying section, within a shallow marine part of the

Sibuti Formation that lacked *Orbulina* for environmental reasons. (N.B. the Sibuti Formation is a calcareous, marly facies of the more widely mapped Setap Shale Formation.)

For reference, the *Gd. sicanus* and *Praeorbulina* species used to pick zone N8 are all found in shallow oceanic, mixed-layer waters above the thermocline (Aze *et al.*, 2011). While not noted by Simmons *et al.* (1999) in their field samples, both forms are present in the upper Setap Shale/Sibuti and below base Lambir Fm. at Engkabang-1, with *Orbulina* present in the highest wells samples.

The subjective observation of slight angular discordance in bedding and an abrupt change in environment of deposition is suggested to be insignificant, based on well records not available to Simmons *et al.* (1999); see below.

Wells onshore

The Bulak-Setap-3 (1951-2), the Pasir-3 (1954) and the Engkabang-1 (1959-60; and shallow Engkabang-2, 1960) all began drilling ("spudded") in clays with minor sands as young as the *Gd bisphericus/G'tella insueta* Zone (=N8). The Engkabang-2 reported some 1000' below the first sample examined at 40' down to 1130' as being from the *Gr. barisanensis* Zone (basal Middle Miocene, N9 or N10), which correlates with the more detailed records from Engkabang-1 (re-analysed by Core Laboratories, 2010). Sarawak Shell Berhad recorded environment of deposition from microfauna continuously in the drill-cuttings samples from these wells. In the wells near the ENT field outcrops the upper part of the Early Miocene was holomarine inner or middle neritic with increasing inner neritic influence up-section until coastal plain mixed with inner neritic facies were reported in the upper (*Gr barisanensis* Zone) of Pasir-1 (Figure 6).

An apparently complete later Early through Middle Miocene succession can be reconstructed from three old wells presented in Rahdon (1971). The Bulak Setap-3 well (about 8 km SW from the ENT section of Simmons *et al.*, 1999; shown on Figures 5 & 6) had no samples analysed until 520' into the well where samples indicate the *Gd sicanus* Zone in a middle neritic setting with occasional outer neritic influences.

The well Bakam-3 (1956) is about 14 km NW of ENT, and it spudded near the top of the Lambir Formation where it grades into the overlying Tukau Formation (a brackish to fluvial, lignite-bearing sand-rich formation; Liechti, 1960). In the absence of marine microfossils, Bakam-3 was dated using palynology, and the basal section of the well was in the Po5.505 zone (named after the old alpha-numeric taxonomy name for *Camptostemon*). There was about 3000 feet of this section, of dominantly lower coastal plain sediments but with occasional inner neritic floods. The overlying 5700' of this well to ground level was placed in Zone Sa.300 of later Middle through early Late Miocene, named after rare *Stenochlaenidites areolaris* that is not found any older, but more importantly this zone is above the extinction of *Florschuetzia semilobata*. Dipmeter data is only available from the upper half of the well, typically 20˚ towards the north. Cores in the lower part of the well had similar dip magnitudes (10-20˚), but lack orientation information.

The Pasir-1 well (1954; about 33 km east of ENT) spans the Middle Miocene but had no palynology carried out. The whole well was assigned to the *Gr. barisanensis* Zone to *Gd bisphericus/G'tella insueta* Zone. The environmental summary of this well shows a gradual transition from middle to occasionally outer neritic facies passing up into inner neritic sediment, then mixed inner neritic with sandy lower coastal plain sediments, with lower coastal plain sediments becoming gradually more dominant up-section. Dipmeter data shows no change across this transition, being consistently around 20˚ and towards the north.

THE LABUAN ISLAND SECTION

On Labuan Island (Figure 7) Simmons *et al.* (1999) thought they saw the same transition as in their north Sarawak ENT section: "*On the island of Labuan a similar situation exists where the uppermost Setap present (outcrop LL in Fig. 7) is Early Miocene in age based on the abundance of F. trilobata, presence of Praedapollis sp. and absence of Camptostemon sp., whilst the lowest paralic sands (outcrop KB in Fig. 7) are intra-Middle Miocene based on the presence of Camptostemon sp.*" However, as noted by Lunt (2020) this was a known outcrop for the DRU tied by seismic to multiple wells just offshore (Figures 1 & 4). Lunt also noted that this age range was already known to van Hoorn (1977) who had reported that the beds below this event were dated as Zone Po3.62 (now palynology zone P400) of Early Miocene age, below a major and erosional lithostratigraphic change, with a conglomerate above, that then passed up into coal-rich coastal plain sediments (Belait Fm.) dated as Zone Po5.505 (P500, the old *Camptostemon* Zone).

In the offshore wells studied by van Hoorn (1977) and Levell (1987) the Stage III sediments below the DRU are invariably deep outer neritic to upper bathyal clays, with only rare sands, and the Stage IV beds above are sand-rich, delta plain to shallow marine deposits, as described by Levell (1987).

On Labuan Island Madon (1994) also concluded a major unconformity existed between what would become the LL (Tanjung Layang Layangan) and KB (Tg. Kubong Bluff) sites of Simmons *et al.* (1999). Based on sedimentary facies, Madon re-assigned a sandy section below the DRU to an open marine depositional setting, which he named the Layang-Layangan Member. Madon noted that this was a very different sedimentary facies to the overlying, locally coal-bearing, delta-top Belait Formation.

More recently Burley *et al.* (2020) have studied several sections below the unconformity on Labuan Island and have confirmed dates at a few sites of early to middle Early Miocene age (Figure 14 of Burley *et al.*), and confirmed

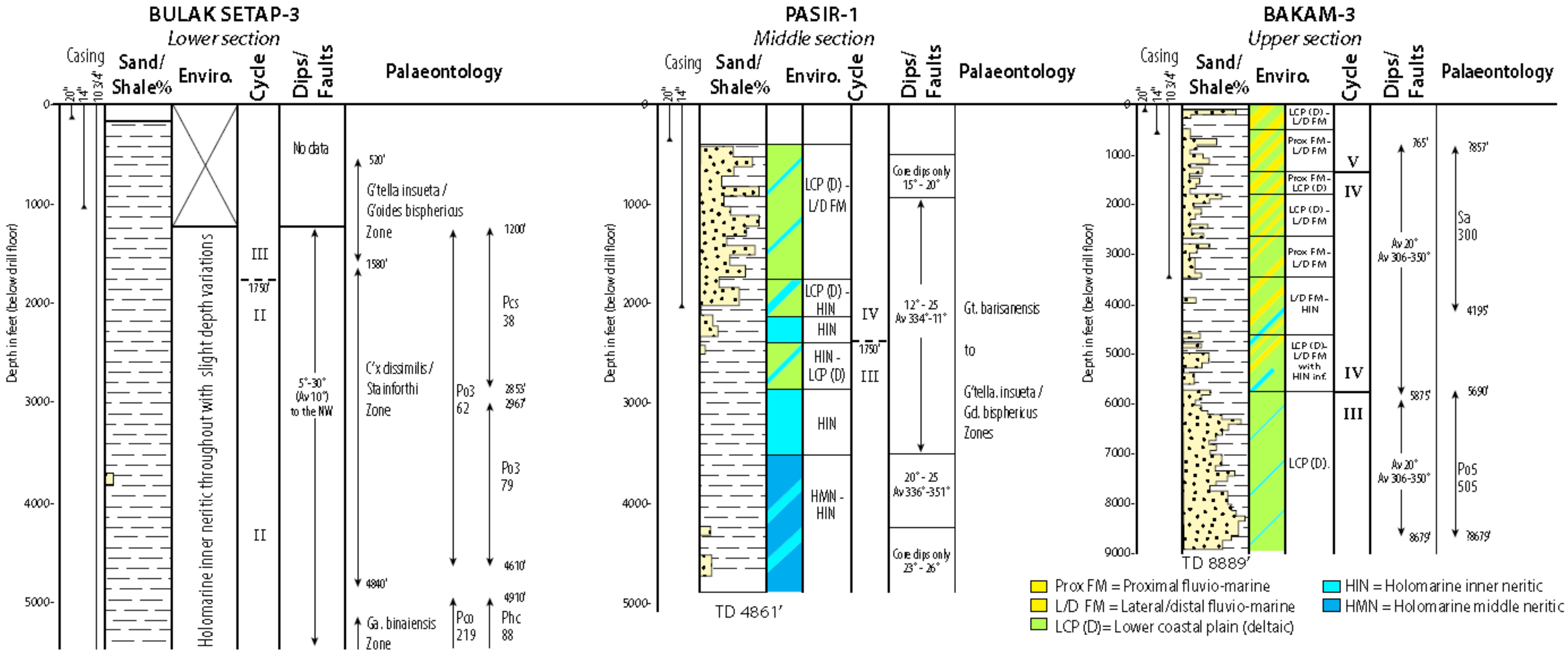

Figure 6: Montage of wells summaries from Rahdon (1971). Bulak Setap-3, Bakam-3 are close to and either side of the ENT field section of Simmons *et al.* (1999). Pasir-1 is about 30 km east of ENT and covers any possible small gap between the other two wells. The data has been re-drawn here but is not edited. Note the depth scale of Pasir-1 is twice that of the other wells.

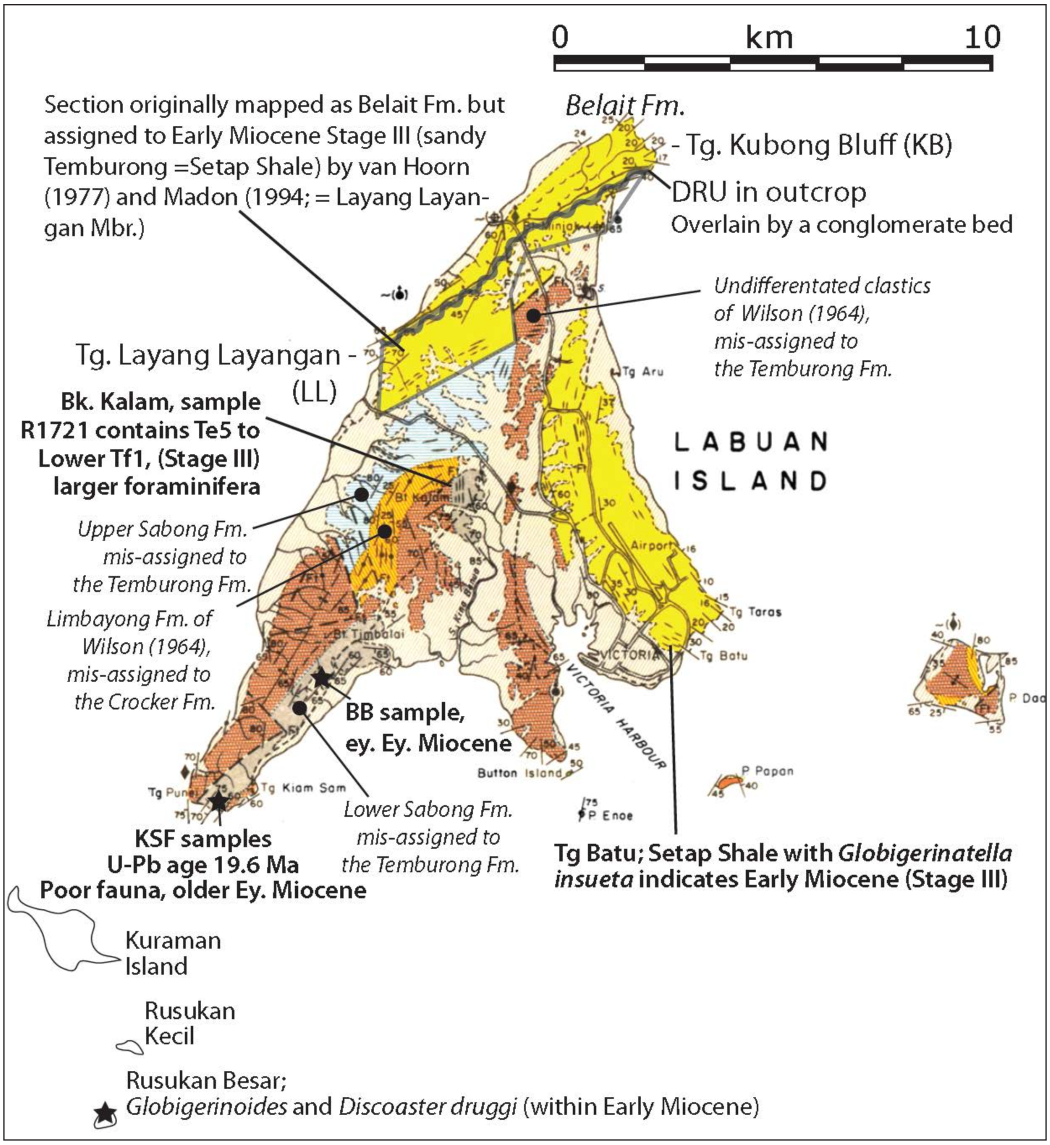

Figure 7: Summary map of Labuan Island, based on the geological map of Wilson (1964).

bathyal foraminifera are present. Unfortunately, Burley *et al.*'s paper retains the old mapping name of Temburong Formation (from Wilson 1964; see below) which is a misnomer as this name only applies to the older part of the Setap Shale that was separated by Brondijk (1962) for sediments older than Te5 (older than base Miocene). In retaining the wrong name for these outcrops they conflated the TCU with the DRU; events that Levell (1987) and Hazebroek & Tan (1993) had both noted were the two most important tectonic unconformities in NW Borneo, and spaced about ten million years apart on modern time scales.

Age diagnostic micro- and nannofossil were obtained by Burley *et al.* in three sites: at the Bebuloh Quarry (BB; Figure 7) a sample contained various *Globigerinoides* species, *Catapsydrax dissimilis* and *Globigerina binaiensis* as well as the nannofossils *Discoaster druggii* and *Triquetrorhabdulus carinatus* which indicates an age between about 22.8 Ma (base NN2) and 19.4 Ma. At the Kiam Sam shore section (KSF samples) a U-Pb age of a zircon in a tuff gave an age of 19.6 Ma (±0.1 Ma analytical precision) but very sparse microflora and fauna. *Globoquadrina dehiscens* indicates and age no older than about base Miocene and *G. binaiensis* no younger than 19.4 Ma (very close to the radiometric age of the tuff). On Rusukan Besar Island to the south a few samples contained *Globigerinoides* and *Catapsydrax dissimilis* (extinct at 17.6 Ma) indicating an Early Miocene age (the extinction datum of *Gd. primordius* cited by Burley *et al.* is not a reliable N5 age marker as the morphotype survives as the juvenile stage in descendants). The nannofossil *Discoaster druggi* again indicates an age no older than base Zone NN2 at 22.8 Ma.

The environment of deposition for these samples is indicated to be bathyal by the regular presence of the agglutinated foraminifera *Glomospira gordialis*, *Karreriella bradyi* and *Rhabdammina* spp., together with the calcareous benthic taxa *Globocassidulina* spp., *Stilostomella* spp., *Planulina wuellestorfi* and *Gyroidina lamarckiana* (Burley *et al.*, 2020).

The naming of the formations on Labuan Island

The mapping of Wilson (1964) captures the difficulty of using lithofacies as stratigraphic units. His work was compiled just after Brondijk (1962) had formally defined the Temburong Formation as an older part of the previously long ranging "Setap Shale" lithofacies (see also Hazebroek & Tan, 1993). The Temburong Formation was usually sandy but, most importantly, it was separated from the younger Setap Shale *sensu stricto* by a contrast in deformation, with an important unconformity between them, and with the deformation of Temburong or top Crocker Fm. dated as having terminated almost on the Letter Stage Te4 to Te5 boundary (the BMU, see Lunt, 2022 for a review of the type Temburong area). Both deposits were deep marine facies. The unconformity between Temburong and Setap formations was not Brondijk's observation alone. It had been a long-standing observation across the region since Reinhard & Wenk (1951), Bowen & Wright (1957) and Liechti (1960). Brondijk simply recognised it was necessary to apply this regional unconformity to subdivide otherwise monotonous and very thick (c. 20,000 feet; Liechti, 1960) clay-flysch units in north Sarawak.

Wilson (1964, his Figure 6) also recognised that there is a major unconformity between Temburong/Crocker and Meligan/Setap at either the Te4-5 boundary, or slightly within basal Te5; the same event as present at the base of the South Banggi Limestone over the Crocker/Kudat Formation in north Sabah (although, confusingly for non-stratigraphers, this boundary was then considered to be well within the Miocene, based on now outdated concepts of the Oligo-Miocene boundary).

On Labuan Island, and the adjacent Klias Peninsula, the section below the coaly, deltaic and non-marine Belait Fm., was originally mapped as Setap Shale by Heybroek & Crews (1954), as a lithostratigraphic Group with several local Formation units depending on the proportions of sand to clay. Even in 1954 it was noted that the rare fossils found in Klias and Labuan were part of "*the Setap transgression [that] occurred in the beginning of Te5-times, all age determination on foraminifera pointing to Te5 and many samples showing Sibuti affinities*" (introduction to Heybroek & Crews, 1954). One of the few palaeontological control points was on Labuan Island in sample R1721 of Heybroek & Crews (1954) in the Bukit Kalam area that contained *Lepidocyclina, Miogypsinoides* and *Miogypsina* as debris within a deep marine claystone, which the transported larger foraminifera date as Te5 to Lower Tf1 age; within Sabah Stage III.

On the Klias Peninsula a few instances of limestone debris-flows are known to contain Te5 fauna (the Tanah Merah area including the Klias-1 well drilled to 1880 feet, in 1912 by *Netherlandsche Petroleum Maatschappij*, as well as shallow boreholes nearby, with limestones containing *Spiroclypeus* and *Miogypsina*). The Tanah Merah coastal location was studied recently by Junaidi Asis *et al.* (2018) who confirmed this Early Miocene age.

Other historical instances of Te5 or Tf fossils include *Globigerinatella* of late Te5 to Tf1 age found in Setap Shale near Tanjong Batu on Labuan Island by Wilson (1964); and on Klias Peninsula the Setap Shale near Tanah Merah and Batu Linting also contains late Te5 to early Tf *Globigerinatella* fauna (also Wilson, 1964).

This all indicates that the Labuan and Klias Peninsula areas are localised sandy facies within the Setap Shale Formation. The divisions of the Setap Shale of Heybroek & Crews (1954) were the Lower and Upper Sabong Formation, and the Limbayong and Nosong Formations. However, Wilson (1964) noted "*a sharp contact has been encountered in punch coreholes drilled by the Shell Company on Labuan Island between yielding mudstone of the Setap Shale Formation and hard shale of the Temburong Formation.*" He seems to have assigned some stratigraphic importance to this contrast in hardness but it is not supported by any other data.

The work of Wilson placed a lot of emphasis on lithological character, probably in the paucity of microfossil data, to determine stratigraphic position and regional correlation. For example, in describing outcrops in his mapping quadrangle that also covered onshore Sabah, SE of the Klias Peninsula: "*One of the most characteristic features of the Crocker Formation is the erratic nature of the stratification, as described below. This contrasts with the more regular rhythmic bedding of the Temburong Formation*" … "*On the banks of rivers and in railway cuttings, the Temburong Formation frequently forms spectacular exposures of regular rhythmic sequences of siltstone and shale*".

Therefore, it seems that most of the sediments on Labuan Island and the Klias Peninsula were re-assigned to the Temburong and Crocker Formation by Wilson for purely lithological reasons. There is no data in his report to suggest otherwise. It is significant to note that the Bukit Kalam site containing Early Miocene Te5 to Tf1 microfauna is virtually at the contact of "Temburong Fm." to "Crocker Fm." of Wilson's mapping. In addition, the new data from Burley *et al.* (2020) of sparse biostratigraphy and the radiometric ages of tuffs confirms an Early Miocene (post Temburong) age. It was therefore an incorrect judgment for Wilson to re-assign these outcrops to the Temburong Formation as all data indicates they are from a sand-prone facies of the Setap Shale Formation.

DISCUSSION

The historical data on the MMU and DRU, already discussed in previous papers (Lunt & Madon, 2017a,b) is compiled here with additional data from northern Sarawak and SW Sabah. The confusion in recent publications about the identity and correlation of unconformities requires resolution because such a framework, of times of change in sedimentary systems, is crucial evidence for any regional geological synthesis.

There is no evidence supporting a regional "Nyalau Unconformity" at about 17 Ma, although there is an extensional event restricted to SW Sarawak of a slightly older age. This Cycle II to III boundary event might be the base of the Balingian Formation unconformity as drawn by Hennig-Breitfeld *et al.* (2019), as the latter formation is characterized by P400 to P500 floras (overlap of *Florschuetzia trilobata* with *F. levipoli* and rare *F semilobata*; Murtaza *et al.*, 2018). Wells nearby such as Bawan-1 and Teres-6 drilled below the base Balingian Fm. unconformity and sampled Zone P300 floras (consistent but low number of montane flora, but lacking *F. levipoli*). The base of the Balingian Formation is a low angle, locally erosional unconformity between similar lower coastal plain deposits.

The Doust MMU of Luconia to East Natuna is dated at 16 Ma and is only seen around the flanks of the Bunguran Trough, the subsidence of which is thought to be the cause of the buried topography unconformity on the surrounding flanks. This is overlain by transgressive Luconia and Terumbu Limestones.

The sedimentary record in onshore north Sarawak shows no recognisable unconformity in the later Early Miocene. There is no significant age gap in the stratigraphic record, and the abrupt facies shift and slight angular discordance noted in a single field section (ENT) is not supported by data from multiple surrounding wells that only observe a long-term facies trend to shallower marine and coastal sedimentary settings.

The major contrast, of coastal plain overlying bathyal sedimentary facies, across the DRU of west Sabah (13-12 Ma) also appears to fade southwards, and may be present in north Sarawak as a weak but apparently conformable transgressive event. The Labuan area, and most of inboard Sabah mapped by Levell (1987) had been subject to uplift in latest Early or early Middle Miocene age before a pause in tectonism. This first stage of the Sabah Orogeny had uplifted bathyal Setap Shale (outcrop name) or Stage III (sequence name used in wells drilled offshore), and over this locally erosional surface (the DRU) the subsequent subsidence allowed thick coastal plain sediments to be deposited (Stage IV-A). Neither this uplift, nor the pause resulting in the DRU, can be recognised in north Sarawak, about 180 km to the southwest of Labuan, except as a transgression or relative sea-level rise of apparently the same age (called the Cycle IV to V boundary in the Sarawak stratigraphic scheme). This basal Cycle V transgression was picked by the operator of Bakam-3 near to the highest *Florschuetzia semilobata* (top of the P500 Zone) where it was expressed as an uphole increase in marine content of samples along with an associated change from sands to clays. This slight shift to marine conditions within a much longer stable environmental interval has a very similar magnitude to the correlatable transgression recognised in the Balingian Province (Lunt & Madon, 2017a), where it is dated as within nannofossil Zone NN6 (13.5 to 11.5 Ma).

While absent in north Sarawak, the first stage of the Sabah Orogeny uplift that paused at the DRU appears to have been widespread elsewhere in Borneo. The associated regressive sedimentation included the Meligan and Tanjong Formation delta systems in north Central Borneo that prograded north (Lunt & Madon, 2017b) from uplift in north central Borneo. These deltaic sediments are capped by a limestone-bearing transgression (Sipit, Kunak Road and related limestones dated within the early to middle Middle Miocene, between N9 and the end of Lower Tf), above which deep marine clays were then deposited shortly before the *Fohsella* extinction datum at 11.7 Ma (Lunt & Madon, 2017b). This abrupt subsidence appears to correlate to the 13-12 Ma DRU subsidence.

In the Luconia and Balingian Provinces offshore Sarawak an abrupt subsidence and relative sea-level rise can be dated as 13-12 Ma (biostratigraphy and strontium isotopic dating at multiple sites, Lunt & Madon, 2017a; Lunt, 2021). This regional framework suggests that the high rate of sedimentation into the north Sarawak and Brunei area dominated over a weak local tectonic effect at the Cycle IV to V boundary.

This geographic variation in the expression of both uplifts and subsidence events is typical of tectonic unconformities, and the correct identification and study of these trends is crucial for palaeogeographic mapping.

CONCLUSIONS

Analysis of original data resolves the identity of regional unconformities across Sarawak and into SW Sabah. The Base Miocene Unconformity (=Top Crocker Unconformity) is seen onshore Sarawak as the transgression at the base of the Subis Limestone and the Cycle I-II unconformity in the Balingian area, as well as subsidence in North Luconia. Regionally this unconformity is dated at the Letter Stage Te4 to Te5 boundary, a proxy for the Oligo-Miocene boundary in SE Asia.

In the later Early Miocene through Middle Miocene times there were two major unconformities; the Doust MMU and the DRU, and these have well-established peak ages of activity (c. 16 Ma and 13-12 Ma respectively). They both also have distinctly different areas of expression, and different types of facies contrast across the unconformity surfaces. The Doust MMU is strongly focused around the Bunguran Trough, offshore west Sarawak, where it was a subsidence event over an extensional, buried topography unconformity, and it fades rapidly away from this area. Neither this, nor any age equivalent unconformity can be recognised in onshore north Sarawak. A mid Middle Miocene

(DRU) event can be recognised in north Sarawak, where it appears to be a weak but correlatable transgressive event within a thick, prograding delta series.

The character of the DRU event is very different to the Doust MMU. Prior to the unconformity there had been uplift and erosion of the bathyal Early Miocene clays in west Sabah during the latest Early and early Middle Miocene. This was approximately coeval with the onset of shallowing up sedimentation across north Sarawak, and both these are thought to be part of broader uplift across northern Borneo that was associated with the first phase of the Sabah Orogeny. The DRU represents a pause at the end of the first phase of this orogeny, followed by subsidence and transgression. While this subsidence and transgression is seen to varying degrees over a wide area of northern Borneo the uplift and erosion of slightly older bathyal clays is most strongly focused in the area just offshore west Sabah.

This simple geological reconstruction is based on a carefully validated examination of the biostratigraphic data. However, this review highlights a historical neglect of integrated stratigraphy, which has had effects beyond just the inevitable confusion of stratigraphic names. There appears to have been poorly constrained interpretation that has been subject to confirmation bias, in this case an assumption of a major unconformity in north Sarawak at about 15-17 Ma. This mis-interpretation has been re-cited and adopted as evidence to support inappropriate tectonic and palaeogeographic models.

All unconformities in congeneric sedimentary systems produce stratigraphic effects with predictable and testable geographic expression. The geological framework proposed here is a therefore testable hypothesis that describes a history of sedimentation, constrained by biostratigraphic datums, as well as both gradual and abrupt facies shifts as reflected in their microfaunal content. This 3D description though time predicts what facies will be found at un-sampled sites within, and adjacent to, the study area, especially areas tied by seismic data. Even though micropalaeontology is both an essential part of such a 4D sedimentary model and also part of the testing process, this type of data is mostly absent in the papers reviewed here, or sometimes present in small amounts but mis-used.

What has been lacking is an objective treatment of observation of both clearly defined stratigraphic units and of events, as well as the biostratigraphic age control, and as caveats on data history and context. This is not easily achieved across different sedimentary facies, from open marine to coastal plain, but the technical tools are available. Recent initiatives by Petronas to ease access to subsurface data will greatly help clarify many similar errors that have been perpetuated in the published record of SE Asian geology. However, what is lacking are the experienced specialists who know how to use this data, and how to construct compelling cases to change long stagnant geological concepts.

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CONFLICT OF INTEREST

The author has no conflicts of interest to declare in connection with this article.

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