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A review of the Letter Stages of Sundaland and their relevance to Sarawak geology

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Abstract: Almost a century ago, the first subdivision of the Cenozoic (Tertiary) stratigraphy of SE Asia was developed at the Geological Survey of the East Indies (Indonesia). This system eventually became known as the Letter Classification, and its subdivisions were called 'Letter Stages'. In this paper an overview of the Letter Stages is given, and their continued use in Southeast Asian stratigraphy is justified. Unfortunately, many instances of mis-application of the Letter Stages have held back stratigraphic and geological studies, so the four most problematic boundaries are described, set to a modern time scale, and placed in a local geological context. Since the 1970s, the Letter Stages have been integrated with planktonic microfossil zones and palynology datums (the latter especially relevant at the Oligo-Miocene boundary), thus allowing the correlation of geological change across different depositional facies. Events with different sedimentary characteristics can be shown to be coeval over a wide area, and this geographic variation in geologic change is essential to describe what must have been complex geological transitions. This important information is lost if the Letter Stages are not used or not correctly identified.

Keywords: Biostratigraphy, SE Asia, Cenozoic, time scales, larger foraminifera

INTRODUCTION

The use of the SE Asian Letter Stages has sometimes been discouraged in publications, and a preference expressed for the use of global Stage names (Aquitanian, Burdigalian etc.). In this review we defend the use of the Letter Stages and also clarify some of the boundaries. We propose that it is the confusion of the Letter Stage boundaries that has degraded these valuable age markers and hence sidelined their use.

A history of the Letter Stages was given in Lunt (2013). A brief summary of that review was that the Epochs of Eocene, Oligocene, Miocene etc. were thought by the early workers to be un-usable in SE Asia, partly because the percentage of extant molluscs, which defined these Epochs in Europe (Lyell, 1833), seemed to fail in the tropics, when compared to the range of well known microfossil groups such as *Nummulites*. Secondly, determining a percentage of extant molluscs required a sizeable mollusc fauna, but such rich assemblages are rarely found, and also required an expert to recognise the large number of Cenozoic and Recent mollusc species. The Geological Survey of the Dutch East Indies (Indonesia) erected an alternative scheme based on the larger foraminifera that are common around Sundaland. This was intended to replace the European Epochs, and began with the *Nummulitique* – an old French alternative name for the Palaeogene (proposed by Emile Haug in 1902), with the end Eocene faunal turnover and then the mid-Oligocene extinction of these previously abundant carbonate-facies forms being distinct biostratigraphic datums that could be correlated with confidence from southern Europe to Sundaland.

This new scheme used letters for names; T for Tertiary and 'a' (oldest) through to 'h' (youngest). As noted in Lunt (2013) the Letter Stages Tg and Th were proposed for a period after a mass extinction of larger foraminifera and, as a result, the percentage of extant molluscs was left in the definition of these youngest Letter Stages (see Leupold & van der Vlerk, 1931). In this scheme the Letter Stage Tg has 35-45% extant molluscs and hence matches Lyell's Older Pliocene, while Th had 50-60% extant molluscs; roughly equivalent to his Younger Pliocene. There was also a "Quaternary" or Pleistocene section in the old time-scale, but the Tg through to "Quaternary" records show no variation in their larger foraminifera content in either Leupold & van der Vlerk (1931) or other older summaries, although we now recognise that several new larger foraminifera appeared during this period (e.g. *Calcarina spengleri, Schlumbergerella, Baculogypsina* and a few others).

Although the early workers developing the Stages avoided committing to precise definitions, by the time of

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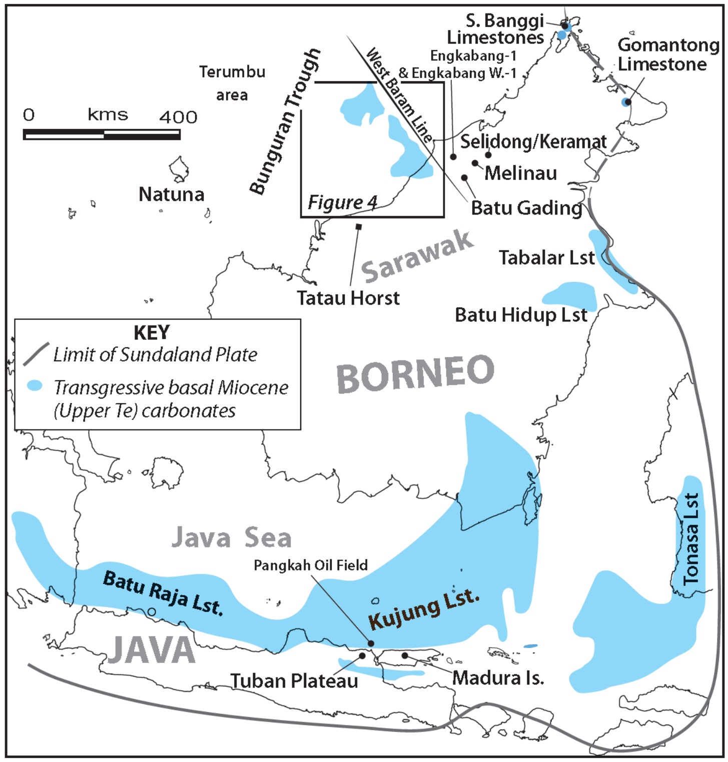

Figure 1: Location map of places mentioned in the text.

Adams (1970, 1984) and comparison to other biostratigraphic schemes, the Letter Stages could be summarised, as shown in Figure 2. The tops of Letter Stages Ta, Tb, Te and Lower Tf (originally top Tf) are based on the extinction of multiple genera. The top of Td was based on the extinction of the super-genus *Nummulites*, but by this time this group had become much reduced in abundance and, as a result, it is not a precise biostratigraphic datum. (Note that the ancestral *Palaeonummulites* survived and that this genus is placed within *Nummulites* by a few workers, confusing the *Nummulites*-extinction issue slightly.) The top of Lower Te is the evolution of *Miogypsina* from *Miogypsinoides*, both common larger foraminifera in most carbonate assemblages and, with the acquisition of distinct lateral chamberlets by the descendent *Miogypsina,* this is a very easy morphological distinction to recognise. The top of Tc was marked by the abrupt appearance in the Mediterranean and Indo-Pacific areas (by migration from the Americas) of *Eulepidina* and *Lepidocyclina* (*Nephrolepidina*), and also of *Neorotalia mecatepecensis* (the ancestral form to *Miogypsinoides*).

The great advantage of the Letter Stages was that, with a little training, any field geologist with a hand-lens could identify the marker taxa and thereby the stratigraphic position of a suitable outcrop. Larger foraminifera are found in many more marine facies around SE Asia than molluscs, including in calciturbidites transported into deep marine deposits. Practical manuals on larger foraminifera identification for field geologists were produced by the Indonesian Geological Survey as long ago as van der Vlerk & Umbgrove (1927), up to Mohler (1946).

Another important advantage of the Letter Stages was that they could be directly observed, whereas one has to interpret European Epochs and Stages through an imprecise process of correlation based on assumptions. The boundaries of Letter Stages were especially clear, in contrast to the European Stage boundaries, which are usually precise only in their type areas (see golden spikes; https://stratigraphy.org/gssps/).

From the late 1980s strontium isotopic methods were developed to date marine carbonates; that is, the same facies in which larger foraminifera occur. A paper by Allan *et al*. (2000) of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) briefly reviews the history of the technique, combined with a compilation of a large number of Sr isotope ratios, as well as larger foraminiferal observations, from across SE Asia and the thick Eocene and younger carbonates of Papua New Guinea.

Most of the strontium dating cited in this study has also been carried out by CSIRO, who used a NBS987 standard of $^{87}Sr/^{86}Sr$ = 0.710235, and ages determined using the McArthur & Howarth (2004) sea-water curve and GTS04 time scale. The combined machine precision and sea-water calibration accuracy of each Sr age is typically about ±0.4 to 0.6 Ma. The trueness of the deduced age is a separate issue, related to local diagenesis. The reported data given below from E11 and F13 gas fields offshore Sarawak is

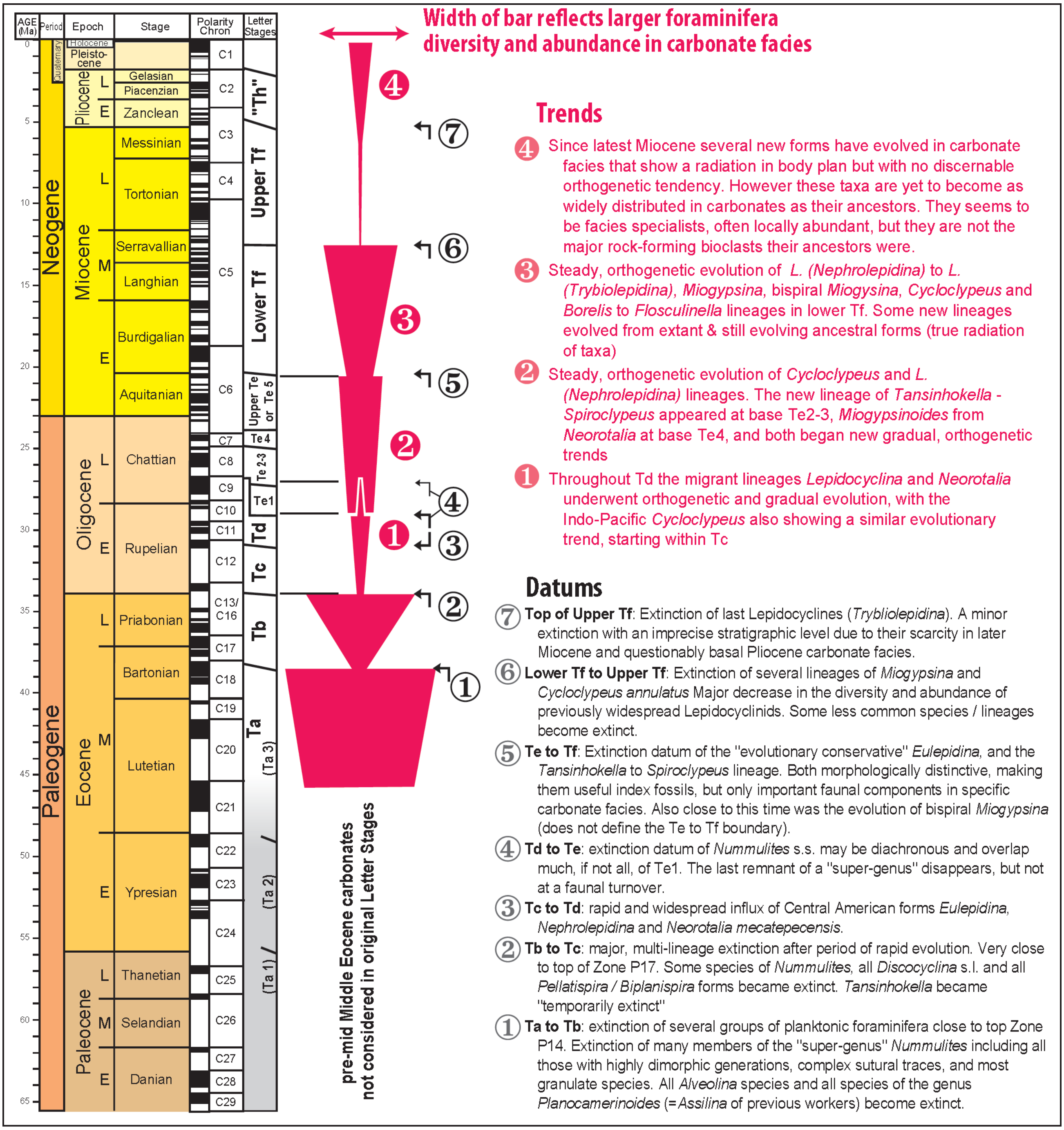

Figure 2: Summary of the Letter Stages set to the Standard Time scale (International Commission on Stratigraphy ICS at stratigraphy.org). There is much variation in published accounts of the Letter Stages, often derived from summaries which are not based on the original definitions, and often not calibrated to planktonic biostratigraphy or to Sr isotopic dating. Figure 3 shows a similar time scale as well as planktonic foraminifera and nannofossil zonations.

from Vahrenkamp (1998; Shell), who measured $^{87}Sr/^{86}Sr$ to only five decimal places. This has been corrected to the McArthur & Howarth correlation and time scale, but the combined measurement precision and sea-water calibration accuracy of these Sr ages is typically ±0.6 to 0.8 Ma. All cited planktonic foraminiferal ages are based on Wade *et al*. (2011) which is nearly identical to the GTS04 work but included far more secondary marker species, whilst the nannofossil datums are dated in Gradstein *et al*. (2012).

CORRELATION OF THE LETTER STAGES TO TIME SCALES

The correlation of the Letter Stages to an international time scale has taken decades. Eocene through Early

Oligocene sites are rare in SE Asia, but eventually sites with both planktonic foraminifera and nannofossils were located. The Early Oligocene has a low diversity of planktonic species which can be supplemented by strontium isotopic age dating (e.g. Lunt & Allan, 2004). However, this technique that cannot be applied to the Eocene due to there being no gradient on the strontium isotope sea-water reference curve at that time.

A very important area for calibrating the larger foram Letter Stages to planktonic biostratigraphy is the Tuban Plateau in NE Java. Here a palaeo-low area was located in front of a faulted high above which were Kujung Limestone reefs (also called Prupuh Limestone; which hosts many oil and gas fields such as the Pangkah Field, Figure 1). The palaeo-low area now outcropping across the Tuban Plateau contains common calciturbidites, rich in transported larger foraminifera interbedded with deep marine marls containing planktonic foraminifera and nannofossils. The elongate bounding fault inverted in Late Miocene times uplifting the palaeo-low to form the NE part of Java and Madura (Manur & Barraclough, 1994). This event exposed widespread outcrops, where seismic data shows gentle folding but remarkably little faulting. The oldest outcrops include one of the last records of *Nummulites* in mid Oligocene beds near the centre of the low relief anticline. The sequence then continues, unbroken, through to the Early Miocene where the type Prupuh Limestone Formation is a condensed deep marine carbonate, equivalent to the main Kujung Limestone biohermal reefs which are now located offshore Java. A few sections even traverse the start of the post reefal Tawun Claystones (which are softer, outcrop less, and have lower microfossil content). This area has been studied many times as a high quality and important biostratigraphic reference section, along many parallel river sections.

In 1957 Muhar sampled ten different traverses around this gentle anticline, of which four cross the Prupuh limestone into basal Tawun Formation. Then, in 1967, van der Vlerk & Postuma revisited the area and they studied the planktonic foraminifera applying modern taxonomy that was improved on Muhar's scheme, and they also recorded the biometric evolution of the *Lepidocyclina* (*Nephrolepidina*) larger foraminifera. In 2004 the area was revisited by one of the authors to collect samples for nannofossils, strontium dating and larger foraminifera. The results were presented in Lunt & Allan (2004) and Lunt & Renema (2014). This latter paper traced the iterative evolution of the *Heterostegina* (*Vlerkina*) lineage into *Tansinhokella* and then *Spiroclypeus* s.s (an evolutionary transition that had also been observed in the Late Eocene, before the end Eocene extinction of *Tansinhokella* and *Spiroclypeus*). One of the advantages of these sites is that the calciturbidites are usually slightly argillaceous and can be disaggregated, and as a result the individual larger foraminifera can be examined externally and then a thin section made to examine internal structure, instead of relying on the random sections observed in whole rock thin sections.

The NE Java area spans, in multiple parallel sections, just over ten million years; an exceptional reference location for about one quarter of the stratigraphic record encountered in the region. The ages of other boundaries found at smaller outcropst are discussed in more detail in the following text.

The Melinau Gorge and surrounding outcrops in Sarawak form another important reference section. The long cliff-face to the Gorge is clearly un-faulted, and the dominantly low energy micritic facies has no evidence of hiatuses due to karstification. The section begins in the top of Letter Stage Ta and continues into Upper Te, as an unbroken record lasting approximately 22 million years. Unfortunately no planktonic foraminifera or nannofossil data can be obtained from these hard rocks, but the section preserves a superb reference section that has been studied for biostratigraphy, and age related isotopic events, several times (Adams, 1965; Lunt, 2014; Cotton *et al*., 2014).

It is reference sections such as these that make Malaysia and Indonesia especially important for Cenozoic larger foraminifera biostratigraphy, compared to the highly faulted and discontinuous sections of the Philippines or the Mediterranean and Middle East (Hashimoto & Matsumaru, 1984; Jones & Racey, 1994).

FOUR KEY LETTER STAGE BOUNDARIES OFTEN MISUNDERSTOOD

The identity of some Letter Stage boundaries has become confused in the literature and in this review it is necessary to clarify four of these, as they have implications for regional geology.

The base of Tb

Since van der Vlerk & Umbgrove (1927), Leupold & van der Vlerk (1931) and van der Vlerk (1955) there were records of *Pellatispira* in Letter Stage Ta. These have been repeated in more recent reviews with illustrations, such as by Lunt & Allan (2004). The Ta to Tb boundary was marked by a multi-generic extinction event affecting all the *Alveolina* species (also known as *Flosculina* in old reports), the uncommon form *Assilina* (now considered *Planocamerinoides*, see Haynes, 1988), and the extinction of all thes trongly dimorphic *Nummulites* forms; i.e., forms where the smaller "A" generation has a very large protoconch and the "B" or microspheric generation are large, often to several centimetres diameter. In addition *Nummulites* with meandrine septal traces, and forms with granulate test ornament also became extinct at the same time.

However, in Malaysian Geological Survey work in Sabah and Sarawak, Adams (1965 and unpublished reports for the Geological survey) used the evolutionary appearance of *Pellatispira* to mark the base of his Letter Stage Tb. This seems to have an older origin that the studies of Adams, appearing in fieldwork reports of Sarawak Shell from at least Jordi & Bowen (1956, their Figure 13). This resulted in mis-correlation to the original sections that were used to establish the Letter Stages in what is now Indonesia. Sites assigned to Tb by Adams (e.g. basal Melinau Limestone, and thin limestones around the Tatau Horst also had Ta index larger foraminifera (Wolfenden, 1960; Adams, 1965), and these sites should therefore be re-assigned to the end of Letter Stage Ta.

The Lower to Upper Te boundary

The Lower to Upper Te boundary, also known as the Te4 to Te5 boundary, is defined on the evolution datum of *Miogypsina* (Leupold & van der Vlerk, 1931; Mohler, 1946; van der Vlerk, 1955; Muhar, 1957; Adams, 1970; 1984). However, the old reports of van der Vlerk & Umbgrove, 1927 and Rutten, 1947 (in van Bemmelen, 1949) did not differentiate the ranges of "*Miogypsina*" with and without lateral chambers (i.e. both *Miogypsina* and the ancestral *Miogypsinoides* were grouped together as "*Miogypsina*"). *Miogypsina* (*sensu stricto*) is the most ubiquitous marker at this Stage boundary. Other rare, facies dependent, forms such as *Flosculinella* are marked on shown by some authors to range from the base of Te5, but this is very much a secondary marker, and there is no evidence to suggest that this genus ranges as occur as old as the base of Upper Te.

BouDagher-Fadel & Price (2013) presented a range for the oldest *Miogypsina* to the base of Te4. This is a simple error in fact, deviating from all other known records, and the definitions of the Letter Stages, including those in BouDagher-Fadel (2008).

Allan *et al*. (2000) have their oldest record of *Miogypsina* with an $^{87}Sr/^{86}Sr$ ratio of 0.708280, or an age of 22.34 Ma (McArthur & Howarth, 2004). Similarly Lunt & Renema (2014), in the NE Java sections, found Te5 faunas with *Miogypsina* with the oldest ratios of $^{87}Sr/^{86}Sr$ = 0.708260 (22.67 Ma) and 0.708234 (23.12 Ma). Below this they recorded Te4 samples containing the ancestral *Miogypsinoides* but lacking descendant *Miogypsina,* with $^{87}Sr/^{86}Sr$ ratios of 0.708151 (24.16 Ma) and 0.708172 (24.31 Ma). The Te4 to Te5 datum is close to the evolution datums of both *Globigerinoides* and *Paragloborotalia kugleri* (van der Vlerk & Postuma, 1967), two biostratigraphic events dated as 24.3 Ma and 23.7 Ma (Wade *et al*., 2011). In the NE Java outcrops all these biostratigraphic markers are found very close to the base of the type Prupuh Limestone, and just above the extinction datum of *Sphenolithus ciperoensis* (24.43 Ma), and near the highest but inconsistent records of the nannofossil *Helicosphaera recta* (extinct at roughly 23-23½ Ma). All this data consistently indicates that the evolution of *Miogypsina* and hence the Lower to Upper Te boundary was between 23 and 24 Ma, i.e. very close to the Oligocene-Miocene boundary.

The value of the Miogypsina datum

The evolution datum of *Miogypsina* is a first-class biostratigraphic marker, comparable to the *Orbulina* datum of LeRoy (1948). Just as *Orbulina* was a significant and ubiquitous part of late Neogene tropical planktonic foraminiferal faunas, *Miogypsina* was, for about 12 million years, a ubiquitous component of SE Asian carbonate grainstones, packstones and wackestones.

LeRoy concluded that his *Orbulina* event, first described in Sumatra, was probably a reliable correlation datum in sections where the ancestral succession of *Globigerinoides sicanus* (also called *Globigerinoides bisphericus* or *Praeorbulina sicana*) into transitional "*Candeorbulina*" (an archaic name for what we now call *Praeorbulina* types) and finally *Orbulina universa.* This was a relatively rapid transition, with reasonably distinct morphological stages. Importantly, the presence of both the ancestral and subsequent descendant stages present in a section demonstrated that there was no hiatus or facies control on the biostratigraphic record. So under these conditions the preserved evolutionary appearance of *Orbulina* can be concluded to be a time-line, lacking diachroneity.

The *Miogypsina* lineage has the ancestral *Neorotalia mecatepecensis* developing into *Miogypsinoides*, and then *Miogypsinoides* evolving into *Miogypsina* in a similar fashion to the *Globigerinoides sicanus* to *Orbulina* succession. In many sites around SE Asia, including multiple NE Java sections, this succession of ancestor into descendant, each with distinct morphological criteria, indicates that the base Te5 *Miogypsina* datum is a reliable biostratigraphic marker in time. As long as sample sizes and recovered fauna are reasonable, then the presence of *Miogypsinoides* without the descendant *Miogypsina* indicates an age older than Upper Te or Te5.

A secondary test of this datum can be derived from the biometric evolution of the Miogypsinid lineage (Raju, 1974; Drooger, 1963; 1993). The gradual reduction of the juvenile stage in larger foraminifera (nepionic acceleration in evolution; van der Vlerk, 1955 and Haynes, 1981) has been observed by many workers, in many larger foraminiferal lineages. In *Miogypsina* it is measured as the angular rotation of the preserved juvenile (nepionic) whorl within the adult test (Amato & Drooger, 1969). The separation of *Miogypsina* from *Miogypsinoides* always occurs at the same stage of nepionic acceleration.

The term *Miogypsina primitiva* is the name applied when a specimen has the required degree of nepionic (juvenile stage) development but only exhibits a few, simple partings in the lateral walls; i.e. only a few lateral chamberlets. This is as expected, but very soon after these short-ranging *M. primitiva* forms appear in the record subsequent specimens, with multiple layers of lateral chambers, and a slightly lower degree of nepionic coiling developed. Unless sample spacing is very close the *M. primitiva* stage might not be encountered.

Just as the *Orbulina* datum has survived many dozens of tests in ocean drilling samples, the base of Letter Stage Upper Te (Te5) has also survived testing in a large number of well and outcrop samples. There is no evidence for diachroneity from well samples, seismic or other data, including strontium dating and planktonic biostratigraphy over long distances (Lunt & Luan, 2022). Relative to this base Upper Te datum the ancestral *Neorotalia mecatepecensis* fades rapidly into extinction at approximately the same time, and the genus *Miogypsinoides* (sometimes referred to as "*Miogypsina* without lateral chamberlets" in old reports) is greatly diminished in abundance, although it is found in small to moderate numbers in some carbonate facies throughout the Early Miocene.

The end of Te

The correlation of the end of Letter Stage Te to other time scales has been difficult because a regional unconformity across Sundaland at about this time saw the termination of the Kujung and Batu Raja Limestone across the Java Sea (Figure 1), the Subis and Gomantong Limestones of west and north Borneo and the Tabalar or Batu Hidup Limestones across north Kalimantan. Service companies, studying large numbers of wells around the Java reefs, especially sites off the reef crests, with little missing section over the end of the reef to the time of crestal onlap, indicated that the extinction of the genera *Eulepidina* and *Spiroclypeus* was within Zone N6 / NN3 (Robertson, 1986; an unpublished multi-client report based on several dozen wells) or about 18 to 19 Ma on modern time scales. This was based on the absence of *Globigerina binaiensis* and *Catapsydrax dissimilis* in the clays deposited off-reef, just after the end of carbonate deposition, and the presence of the nannofossil *Sphenolithus belemnos* in the same samples.

Lunt (2021a) published results from the Rebab-1 well offshore Sarawak (seismic through the well shown in Lunt (2021b). This was a rare example of a reef that continued through the mid Early Miocene and the well had large, slabbed cores that could be examined over a very big area for larger foraminifera in mixed grainstones and packstones. In addition there were many dozens of thin sections, in total giving an extensive record of larger foraminifera, as well as the results of strontium dating of multiple carbonate samples from the cores. The Sr ages were all in order up-hole at 19, 18.7 18.7, then a gap between cores and 15.7, 15.5 and 15.3 Ma; i.e. a coherent arrangement of ages. The young Sr ages of around 15 Ma were just below the *Orbulina* datum identified in a claystone (15.1 Ma, Wade *et al*., 2011). All samples lacked *Eulepidina* or *Spiroclypeus*, both of which can be identified from a single fragment in random section (either slabbed core or thin section). This extremely high quality negative evidence corroborates that the top of Te as slightly older than 19 Ma.

The composited Sr data of Allan *et al*. (2000) indicates the youngest records of *Eulepidina* and *Spiroclypeus* in Papua, where there was continuous carbonate deposition, have $^{87}Sr/^{86}Sr$ ratios of 0.708450, indicating an age for their extinction of about 20 Ma. This independently corroborates the work of Robertson Research using planktonic micro- and nannofossils, as well as the Rebab-1 well data.

Chaproniere (1981; also cited in Adams, 1984) suggested the top of Te was within basal planktonic foraminiferal Zone N6 in the Ashmore Reef-1 of NW Australia. In this well *Globigerina binaiensis* (extinct in basal N6) is found just above top Te. This species is the best proxy for base N6 in SE Asia because the defining zonal marker (evolution of *Globigerinatella* at 19.66 Ma) is a rare taxon in SE Asian sediments (Bolli & Saunders, 1985). Adams (1984) noted that the extinction level of *Spiroclypeus* was more difficult as the genus became rare in its upper age range, but it was common in strata that can be dated as N3 to N4. Djamas & Marks (1978) have reported it from the top of N5 in Borneo, although not in association with *Eulepidina*.

BouDagher-Fadel & Banner (1999) also suggested an age within N6 for this Letter Stage boundary, but without supporting data. In 2008 BouDagher-Fadel began drawing the top of Letter Stage Te at the top of N6 and very close to the Early to Middle Miocene boundary (see also BouDagher-Fadel & Price, 2013). However, the base of N6, as noted above, is the more likely age for top Te, and the base of this planktonic Zone is about 19.66 Ma (sensu stricto of *Globigerinatella* species) or close to 19.4 Ma if the proxy datum of *G. binaiensis* is used. This is approximately 1.8 Ma older than the line as drawn by BouDagher-Fadel (2008). The top of Zone N6 is at 17.62 Ma and the base Langhian is another million and half year younger at 15.97 Ma (and the base *Orbulina* proxy for base Middle Miocene in SE Asia is even younger, at 15.1 Ma). This long time span between top N6 and the Early to Middle Miocene boundary is not shown in the range charts of BouDagher-Fadel (2008), BouDagher-Fadel & Price (2013) and related papers, where this time span is drawn as condensed. The time scales of BouDagher-Fadel are not drawn based on a numerical time scale, and it is the same graphical template used in all their papers. If the base Aquitanian (base Miocene) is given a value of 23.03 Ma, and the base Langhian 15.97 Ma, then they draw their top Upper Te boundary at 76% of the way through the Early Miocene (about 17.6 Ma). In contrast, on Figure 2 herein, the well-constrained data set to a standard time scale, shows that the top of Upper Te is only about 35% of the way through the Early Miocene (at about 20 to 20.5 Ma).

This two and a half to three million year difference was the beginning of un-necessary "drift" in the dating of top Te, due mainly to simple, unscaled graphical summaries, which were continued as recently as BouDagher-Fadel (2018; the 2nd edition of the 2008 book on larger foraminifera).

The Lower to Upper Tf boundary

The Lower to Upper Tf boundary was originally based on a mass extinction of many larger foraminifera, see Leupold & van der Vlerk (1931) and Rutten (1947, in van Bemmelen, 1949). The age of this event was originally unclear, but it was thought to be close to the Miocene to Pliocene boundary, based on very poor independent age control at that time. Later work by Adams (1970, 1984) recognised that many species became extinct at an event within the Middle Miocene. However, the cosmopolitan genus *Lepidocyclina* (as the tryblioleidine *Lepidocyclina rutteni* forms) survived until about the end of the Miocene (Adams & Frame, 1979). This was confirmed in Lunt & Allan (2004) who determined strontium ages from Javanese samples with *L. rutteni* as young as about 5 to 6 Ma (several samples with strontium ages). Adams left this younger age as the top of his Letter Stage Tf, but the more obvious mass-extinction was an older event that he adopted as the top of his Lower Tf. The significance of this extinction event was not just in diversity of forms affected but also in their greatly reduced abundance. After this event the large, complex, so-called "Orbitoid" larger foraminifera were never an abundant part of the microfauna in tropical reefal grainstones and packstones, until new Plio-Pleistocene forms appeared.

The mass-extinction event was the top of the *Orbitoiden Kalk* (or OK Formation) across Java (Brouwer, 1966). Overlying this was the *Globigerinen formatie* (or Gl Formation), which still contains a few beds with very low diversity larger foraminifera (Brouwer, 1966; van Bemmelen, 1949). In the extensive limestones of Papua New Guinea there was biostratigraphic work carried out in the 1940's and 1950's, under the guidance of M.F. Glaessner, but this was unpublished until A.P.C. (1961). Workers in this area also recognised one dominant larger foraminifera extinction event that separated their Taurian Stage (rich in *Lepidocyclina, Cycloclypeus* including *C. annulatus* and *Miogypsina*) from their Ivorian Stage (which lacks diverse larger foraminifera assemblages). The outstanding magnitude of this extinction event has often been overlooked by different authors trying to subdivide Tf, usually into Tf1 to Tf3 sub-stages, but with each author having different definitions of what defines each sub-stage.

The carbonates of Luconia, offshore Sarawak, saw an increase in the rate of basement subsidence at this time; the Cycle IV "build out" carbonate platform changed to Cycle V "build-up" pinnacle reef stages. The extensively cored E11 pinnacle reef and adjacent F13 platform limestone have larger foraminifera data showing this extinction event as well as Sr dating in several wells and locally planktonic foraminiferal data. This data shows that the end Lower Tf mass-extinction of larger foraminifera was in the mid Middle Miocene, about 12 Ma, or near the top of the *Fohsella* lineage (top Zone N12), (see Lunt, 2021b, also Lunt & Allan, 2004, and Lunt & Luan, 2022).

IMPLICATIONS IN SARAWAK GEOLOGY

Clarifying the Ta to Tb boundary in Sarawak

As noted above, C.G. Adams, completing his PhD (with his 1965 paper) and then working in Malaysian Borneo, continued an idea already present in Sarawak Shell and Geological Survey files (e.g. Jordi & Bowen, 1956) that wrongly considered the Ta to Tb boundary to be based on the evolution of *Pellatispira*. In his Melinau Limestone section the lowest carbonates over the Mulu Formation siliciclastics contain the giant microspheric *Nummulites javanus* and small but megalospheric *Nummulites bagelensis* generation, as do the nearby basal few metres of the Batu Gading Limestone sites (Adams & Haak, 1962; Adams, 1965). Nearly all samples later studied by Adams were from sediments younger than this, so the mistake was not recognised for a long time. Using the better Indonesian Eocene sections for calibration, the onset of limestone deposition in Batu Gading and Melinau Limestones (above thick siliciclastics) is slightly older than the mass extinction of the Letter Stage Ta larger foraminifera, which we now correlate to the extinction of *Acarinina* and *Morozovella* planktonic foraminifera (see Lunt & Allan, 2004) at about 38 Ma. This extinction of planktonic forms is a proxy for the Middle to Late Eocene boundary (the base of the Priabonian Stage being fixed slightly younger than this at 37.71 Ma on the evolutionary appearance of the nannofossil *Chiasmolithus oamaruensis* that marks the base of Zone NP18 (Gradstein *et al*., 2020). This major change at the base of the Melinau and Batu Gading limestones, from siliciclastic to carbonate deposition across northern Sarawak, can therefore be dated as about 38 to 39 Ma.

In the Tatau area of central Sarawak an angular unconformity can be seen around the Tatau Horst where strongly folded Bawang Member of the Belaga Formation (type area) is overlain by the much less deformed Tatau Formation (type area). The micropalaeontology used by Wolfenden (1960; his Table 9) was based on analyses by Adams and this included a few samples with clearly Letter Stage Ta larger foraminifera (e.g. samples S5684, S5902, V1647, Vi648, dB24 and dB25 with giant and highly dimorphic *Nummulites* as well as *Assilina/ Planocamerinoides*). However, these were wrongly dated as Tb based on the presence of *Pellatispira*. This meant that for many years the unconformity, which was later named the Rajang Unconformity (Hall & Breitfeld, 2017), was stated to be within Letter Stage Tb, which in turn was correlated with the Late Eocene (e.g. Hutchison, 2005, p.96; Hennig-Breitfeld *et al*., 2019). However, this can can be dated around the Tatau area as occurring just before the extinction event at the top of Ta, i.e. before the end of the Middle Eocene, and slightly older than 38 Ma.

Such a minor change to the date of an unconformity (from "within about 34 to 37.7 Ma" to "slightly older than 38 Ma") may seem a small increase in precision, but new work on the Rajang Unconformity indicates that it was a much more complex and longer lasting transition (Lunt & Liaw, in prep), and so clarifying its age becomes an important part of any new studies. For example, the event between Bawang Member and Tatau Formation type locations can be correlated with confidence to the change from siliciclastic to carbonate sedimentation recognised in outcrops across the north Borneo region (including the Selidong and Keramit outcrops, Adams & Wilford, 1972), and also in the Engkabang-1 and West Engkabang-1 wells, where it is dated on planktonic foraminifera and nannofossils as just before the Middle to Late Eocene boundary (slightly older than 38 Ma). The next major unconformity in this transition is close to the end of Tb (end Eocene) or in basal Oligocene Tc; the onset of Sap / Penian Marls in the Tatau region and onset of a hiatus or highly condensed section in the Batu Gading, Melinau, Selidong and Keramat areas. By rigorously applying the Letter Stages these different unconformities can be separated, rather than all being lumped as "intra Letter Stage Tb unconformities".

Dating the Nyalau Formation in its type area

The Nyalau Formation of NW Borneo comprises high energy, coastal plain, lithofacies, yet it obviously has a complex stratigraphic history that needs to be understood in the dimension of time. In the SW around the town of Tatau it is clearly Oligocene in age, with *Nummulites* and isolepidine *Lepidocyclina* (Tc and Td), occurring in beds deposited during rare marine floods (Liechti, 1960), with the sedimentary transport direction then being from the SW (Mat-Zin, 1997, Figure 8 A; Hutchison, 2005, Figure 35 K; based on previously unpublished well studies by Shell). However, in NW Sarawak and even into Sabah the same lithofacies is clearly much younger. The Meligan Formation of SW Sabah was first called Nyalau Formation (e.g. Bowen & Wright, 1957), but it is not well dated in Sabah and was suggested to be within the Early Miocene (Wilson, 1964) based on the age of the underlying claystones. New fieldwork and analyses by one of the present authors (in prep.) suggests the Meligan Formation in its type area might be early Middle Miocene. Geological Survey samples from the north of Sarawak (detailed below) from a sandy coastal plain lithofacies were later Early Miocene, Zone N6 ("*Catapsydrax dissimilis* Zone" of early workers; Rahdon, 1971). The youngest beds of Nyalau Facies are lost through erosion, so a slightly younger age for the lithofacies here is possible. These beds have been mapped as either Nyalau Formation or belait formation (Liechti, 1960; Haile, 1962), see comments below. During the mid and later Early Miocene the sedimentary direction across Sarawak was from the SE (Mat-Zin, 1997, Figure 8 C; Hutchison, 2005, Figures 36 G & F), suggesting the Oligocene type Nyalau Formation was a different stratigraphic unit to the Early Miocene "Nyalau" coastal plain lithofacies.

Offshore a combination of seismic and well studies demonstrated marked changes in palaeogeography between Cycles I to III and there is no reason to think this stratigraphic pattern ended at the modern coastline. The onshore outcrops simply have not yet been assigned to Cycles that are equivalent to those mapped on seismic offshore. With such localised, folded and faulted beds in outcrop the primary way to do this would be to date the onshore lithofacies, but such work has not been attempted to date.

The type location for the Nyalau Formation was proposed to be in the Sabulong-Selungun area by Liechti (1960) and located just northeast of the town of Bintulu, where it had been studied by various members of the Geological Survey and found to contain rare marine floods containing a Lower Te fauna (see summary in Rahdon, 1971, especially his Appendix A1). In addition, Liechti (1960) notes that the Selungan-1 well on the northern coastal edge of the type area contained Lower Te fossils; *Spiroclypeus* sp. *Lepidocyclina* sp. *Heterostegina borneensis* and *Miogypsinoides ubaghsi*). Liechti noted that about 50 km to the east-northeast of the type area the marine floods in the Nyalau facies around the Ulu Suai Dome were of Upper Te age, containing *Miogypsina*. In this location the Geological Survey (Appendix A1 in Rahdon, 1971) recorded basal Miocene planktonic foraminifera from the *Globorotalia kugleri* to *Globigerina binaiensis* zones (N4/5 undifferentiated). Further northwest, field samples were dated as being from the *Catapsydrax dissimilis* Zone. In the Bakong area (Grabit and Ulu Bok Synclines) the same lithofacies was called Belait Formation (being closer to the Belait Syncline of Brunei than the Sabulong-Selungun type area) and the Nyalau-like facies here are from the N7/N8 or "*Globigerinatella insueta – Globigerinoides bisphericus* Zone". A review of Rahdon's core data and new field samples around the type is given in Lunt *et al*. (in press)

The above biostratigraphic deduction for the type area of a Lower Te and Late Oligocene age was unchallenged until Breitfeld *et al*. (2020), who reinterpreted the age as Early Miocene based on the historical records from the Geological Survey (but citing only Wolfenden, 1960, whose mapping did not even cover the type Nyalau area (his mapping area limit was about 25 km SW of the Sabulong Anticline). This revision of the outcrop age contained at least two objective errors in fact (in Section 5.1 of Breitfeld *et al*., 2020) "*The type species of Heterostegina (Vlerkina), H. (V.) borneensis van der Vlerk was initially described from the Early Miocene, N4-N6, in direct association with Miogypsina, Miogypsinoides, Eulepidina, Spiroclypeus, and the planktonic foraminifera Globigerinoides quadrilobatus, Catapsydrax dissimilis, Globoquadrina dehiscens (Eames et al., 1962).*" The planktonic foraminifera *Globigerinoides* and *Globoquadrina dehiscens* would indicate a Miocene age, if present. However, the type records of *H.* (*V.*) *borneensis* (van der Vlerk, 1929) assign this species to Lower Te ("Ondergedeelte Tertiair e"), and van der Vlerk's 1929 study records only larger foraminifera, with no mention of the planktonic foraminifera claimed by Breitfeld *et al*. (2020). Van der Vlerk's range chart shows that *Heterostegina* (*Vlerkina*) *borneensis* became extinct before the appearance of *Miogypsina* in his study area of the remote Bulungan Beds (spelt Boeloengan in the old Dutch orthography) of NE Kalimantan. In this area the older Mesalai Marls contain *H.* (*V.*) *borneensis* and the overlying Lower Naintupo Formation contains *Miogypsina* and *Tansinhokella/Spiroclypeus* (undifferentiated). In the Lexicons of Indonesian Stratigraphy (Marks, 1957; and Ratman & Sudijono, 2003) the only planktonic species mentioned in these formation is the Oligocene through basal Miocene species *Dentoglobigerina sellii*. There are almost no modern studies in this remote area. Secondly, Eames *et al*. (1962) do not mention *H*. (*V*.) *borneensis* at all, or any possible synonyms for this distinct involute form, and therefore they cite no association with the Miocene planktonic foraminifera as claimed by Breitfeld *et al*. (2020).

A third, slightly subjective, error in Section 5.1 of Breitfeld *et al*. (2020) cites Abdelghany (2002) as supporting evidence that *Heterostegina* (*Vlerkina*) *borneensis* occurs in the Early Miocene of Egypt. However, the images in Abdelghany's paper indicates that this is not the involute *H*. (*V*) *borneensis* type, but instead the related, but longer ranging, planispiral lineage *Planostegina* (see Banner & Hodgkinson, 1991, for a discussion of these lineages).

The papers that Breitfeld *et al*. cite supporting a proposed Miocene age for the type Nyalau Formation mention the species *Cycloclypeus eidae*, which has never been a precise age marker (see Tan Sin Hok, 1932 and Rutten 1947 in van Bemmelen 1949, through to Adams 1970 and 1984), as well as the extinction of of *H*. (*V*.) *borneensis*. Their new, extended, Oligo-Miocene age range for *H*. (*V*.) *borneensis* was based on false claims about the type occurrence, disproven above, as well as citing BouDagher-Fadel & Banner (1999), BouDagher-Fadel & Price (2013, 2014) BouDagher-Fadel (2018). However, all these papers can be traced to cite just one limestone site studied by this same academic group in central Sabah, in the Gomantong Limestone.

BouDagher-Fadel & Banner (1999) stated "*Heterostegina (Vlerkina) borneensis van der Vlerk may be restricted in Melanesia to the lower part of the Te interval, but evidence from Borneo has shown that it ranges throughout the Te interval in the eastern region as a whole*" and they cited a paper in press (BouDagher-Fadel, Banner, Lord & Noad in north Borneo, eventually published with a parallel paper by BouDagher-Fadel, Noad & Lord, both dated 2000). Neither of these papers, which are both focused on the Gomantong Limestone in central Sabah, mention any sample containing both *Miogypsina* and *H*. (*V*.) *borneensis*, and they record no planktonic species. BouDagher-Fadel *et al*. (2000) logged samples with *Miogypsina* (Te5) in the west near the type Gomantong limestone and its famous caves, but without *H*. (*V*.) *borneensis*, and samples in the east with *H*. (*Vlerkina*) and *Miogypsinoides* (Lower Te, and maybe from Labang Formation calciturbidites, see McMonagle *et al*., 2011). BouDagher-Fadel & Banner (1999) therefore could not justify their range of *H*. (*V*.) *borneensis* extending upwards into the Miocene based on their own cited data.

Ironically, in spite of this negative record of *H*. (*V*.) *borneensis* with *Miogypsina* in these two 2000 papers, this area was already known to be one of the few places in SE Asia where *H*. (*V*.) *borneensis* had actually been logged with *Miogypsina*. This was first observed by van der Vlerk (p.145 of the report by Reinhard & Wenk, 1951), and was confirmed by Adams (1964) who visited the western site, and stated "*A species believed to be H. borneensis has recently been found by me in the Gomantong Limestone in the midst of a typical Te5 fauna. Van der Vlerk has himself reported H. borneensis in association with Miogypsina sp. an undoubtedly Te5 marker in this area*". Adams (1964, p.162) then stated "*It [H. borneensis] is, nevertheless, most abundant in Te1-4 strata and its occurrence with large numbers of eulepidines and very few nephrolepidines may be taken as indicating Te1-4 beds in Sabah*." These older records were not cited by the BouDagher-Fadel *et al*. group.

In conclusion, there is no reason to suspect the extinction of *Heterostegina* (*Vlerkina*) *borneensis* was precisely coeval with the development of *Miogypsina* from the ancestral *Miogypsinoides*. The lineage of *Heterostegina* (*Vlerkina*) *borneensis* was in decline in late Te4 and a few examples appear to have survived into basal Te5, in very rare instances (Gomantong). However, it should be remembered that the *H*. (*V*.) *borneensis* form was preserved as the juvenile stage in the descendant *Tansinhokella*; following the same nepionic acceleration style of evolution (as seen in *Miogypsina*, mentioned above; for a description of this effect in heterosteginids see Banner & Hodgkinson, 1991). It is therefore possible that juvenile *Tansinhokella* specimens may look like a small *H*. (*V*.) *borneensis*. As *Tansinhokella* evolved into *Spiroclypeus*, the appearance of lateral chamberlets and cubiculae in the latter was progressively at such an early growth stage that even the juveniles of *Tansinhokella/Spiroclypeus* rapidly became very distinct from *H*. (*V*.) *borneensis*. This gradation of *H*. (*V*.) *borneensis* into *Tansinhokella* is one of the reasons why the extinction of *H*. (*V*.) *borneensis* is considered only a secondary biostratigraphic marker.

The very rare record of *H*. (*V*.) *borneensis* in the basal Gomantong Limestone does not justify its stratigraphic range being exaggerated as "*throughout the Te interval in the eastern region as a whole*". The very high number of geographically widespread outcrop samples in NE Java (38 km W to E and 10 km N-S; Muhar, 1957; and many workers after him), and the many dozens of exploration wells studying the oil and gas reservoir of the Prupuh/Kujung limestone just offshore NE Java, and the equivalent Batu Raja Limestone of west and central Java, have all failed to find any records of *H*. (*V*.) *borneensis* with *Miogypsina* (cf. Robertson Research 1986 study of East Java stratigraphy). The Subis Limestone of Sarawak is Te5/ Upper Te in outcrop, lacking *H*. (*V*.) *borneensis*, but the lower part of this limestone drilled by the well Subis-2 has *H*. (*V*.) *borneensis* with *Miogypsinoides*, but lacking *Miogypsina* (so Te4). The McMonagle *et al*. (2011) study of the Gomantong Limestone found only Te5 assemblages in the type area, with no samples containing *H*. (*V*.) *borneensis*. So, to repeat

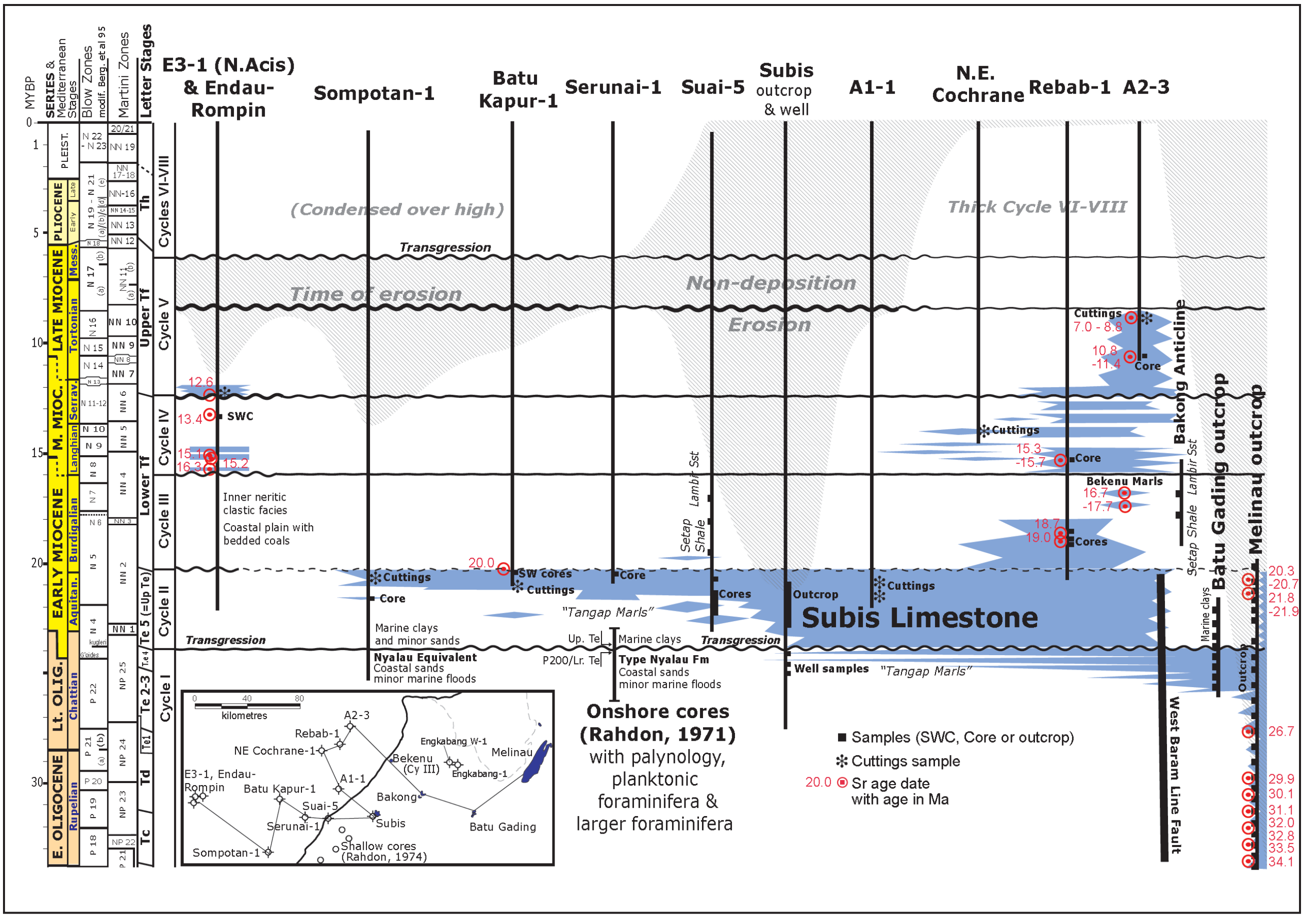

Figure 3: Summary of Late Oligocene and Miocene carbonates in Sarawak, updated from Figure 16 of Lunt & Madon, 2017a. The Cycle I-II boundary seems to correlate to the regional Base Miocene Unconformity (BMU), the Cycle II-III boundary close to the top of Upper Te is also a regional termination of carbonates, for example across the Java Sea (Lunt & Woodroof, 2021) and the Cycle IV to V event is exactly at the top of Lower Tf. Lunt & Luan (2022) have speculated on possible reasons between biostratigraphic events and regional geology. If Letter Stages are not picked properly these apparently important correlations in time will be missed or mis-understood. The time scale on this figure differs from Figure 2 as boundaries to the Early and Middle Miocene are shown with "standard" definitions tied to European Stratigraphic Stages and also the long-used SE Asian proxies of the *Globigerinoides* datum (base N4), *Orbulina* datum (base N9) and *Paragloborotalia mayeri* datum (base N15).

and emphasize, there is no data supporting the claim "*that it [H. (V.) borneensis] ranges throughout the Te interval in the eastern region as a whole*".

The significance of the *Miogypsina* datum as the base of Te5, and a common proxy for base Miocene, was overlooked by Breitfeld *et al.* (2020). The Geological Survey data compiled by Rahdon (1971, his Appendix A1) and the Selungan-1 well have over twenty sites yeilding larger foraminifera around the Sabulong – Selungun type Nyalau area, of which most contained a poor general Te fauna. The Selungun-1 well samples, seven field localities contained faunas of Lower Te not Upper Te age, having only ancestral *Miogypsinoides* without the descendant *Miogypsina*. These sediments were deposited before a major stratigraphic event that can be dated as the Base Miocene Unconformity, which can be correlated to coeval changes over a much wider area, as the local expression of a large scale geological change. Without good application of the Letter Stages this important correlation is lost.

The type Nyalau Formation is therefore equivalent to Cycle I (Figure 3), identified in wells and on seismic / dipmeter offshore (Ho Kiam Fui, 1978; Mat-Zin & Tucker, 1999; Lunt & Madon, 2017a). The Cycle I to II boundary is a tectonic episode expressed as the end of local folding (West Balingian Line) associated with subsidence and transgression. By dating this event as being very close to the Lower Te to Upper Te boundary (also near base planktonic Zone N4 and top Zone P200 on palynology) it correlates these local tectono-stratigraphic responses to other events at the Base Miocene Unconformity over a very wide area across the South China Sea, Borneo and even into the Java Sea (cf. Lunt & Woodroof, 2021). In Sarawak it explains why the Upper Te Subis Limestone is found transgressing onshore and in wells offshore (e.g. Batu Kapur-1 and Suai-5, see Figure 3). This was the only clean limestone deposited around Sarawak between the Early Oligocene and, except for rare reefs near the West Baram Line (Rebab-1 mentioned

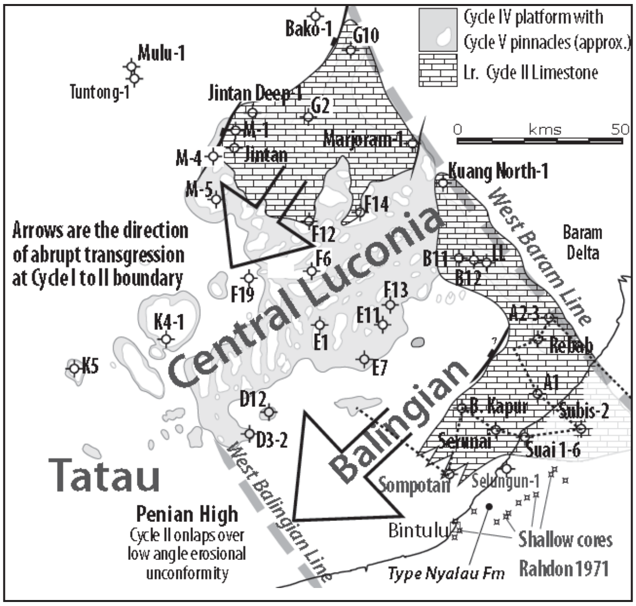

Figure 4: Map of carbonates across Sarawak, redrawn from Lunt (2021b). The main feature is the Cycle II or Subis and equivalent limestones. These were the only clean limestones deposited in 15 million years, as facies abruptly transgressed to the SW. This migration of facies is distinct in the Subis outcrops and wells (Subis-2) and Sompotan-1 to the west. Walther's Law states that this facies shift must be present onshore between Subis and Sompotan-1, where the shallow cores of Rahdon (1974) and adjacent outcrops have been studied by Rahdon (Sarawak Shell) and the Malaysian Geological Survey. This data set does identify a transgression at the correct biostratigraphic level, but student mapping of this area has failed to recognise this basic requirement of Walther's Law, and has mis-reported uninterrupted coastal plain facies as continuing to a much younger age. The black dotted line is the line of section in Figure 3.

above), the top Cycle III transgression (about 15 million years of sedimentation dominated by siliciclastics), indicating it was a transgression of major significance. Figure 4 is a map view of this Subis and equivalent limestones recognised by seismic offshore (and proven at Kuang North, G10 and G2 wells). The area of the later (Middle and early Late Miocene) Luconia limestones is also shown for comparison.

The unwarranted continuation of the type Nyalau coastal plain to paralic marine facies upwards well into the Early Miocene Upper Te suggested by Breitfeld *et al*. (2020), in a section without Upper Te *Miogypsina* and with Lower Te *H. borneensis,* raises questions that can be tested by Walther's Law. In many surrounding locations, such as the Subis area to the east and Sompotan-1 to the west (Figure 4) there was a step-like, abrupt marine transgression at the Cycle I to II boundary, as well as coeval transgression over the Penian High further west (Lunt & Madon, 2017a, their Figure 4; also Petronas, 1999, their Figure 12.7). Such an abrupt transgression, after many hundred of meters of stacked, monotonous, coastal plain sediments, and followed by equally thick shallow marine sediments, would also be expected in the area around the type Nyalau Formation cored by Rahdon (1974). Firstly, if the transgression was slow and diachronous the well records would not show a stepped shift in facies, but a gradually changing vertical record, however this is not the case (see Figure 6 in Lunt *et al.* in press). Secondly, this is not so much a relative sea-level rise but an abrupt migration of facies systems, constrained by Walther's Law. The facies migration must have proceeded, and been recorded in the stratigraphic record, in a coherent form. Therefore, with effects seen to the east and west, the 15 core holes of Rahdon and surrounding outcrops must also record this facies shift, as it cannot be absent in an uneroded stratigraphic record. It is therefore no surprise that such a facies movement is found in the youngest part of the core record, at exactly the same time, based on palynology, larger foraminifera and planktonic foraminifera in the overlying marine marls. Breitfeld *et al*. collected no new samples in this area on which to offer a contrary reconstruction.

The Lower to Upper Tf boundary in Sarawak

The E11 and F13 area of the Luconia Province (Figure 4) illustrates and dates an acceleration of subsidence using larger foraminifera, planktonic foraminifera and strontium dating (Figure 5). At this time the F13 reef failed to keep up with subsidence while the E11 reef changed from being a platform to become a high relief pinnacle reef.

The geological change is well-dated in these wells, including a record that shows it was at the same time as the Lower to Upper Tf Letter Stage boundary. This correlation of the Letter Stages with geological events is important as pointed out by Lunt (2021b) who showed that numerous wells through carbonates in SW Luconia, with only larger foraminifera for age dating, had previously mis-dated the Cycle IV to V boundary and consequently mid-identified the underlying Mid Miocene Unconformity (MMU; Cycle III-IV boundary) on seismic.

The correlation of the Letter Stages to planktonic biostratigraphy impacts regional geological reconstructions by clearly showing a suite of varied tectono-stratigraphic events across Sarawak which were clearly coeval. At the same time as the subsidence event in E11 and F13, well-dated on planktonic foraminifera (at the top of Zone N12), the western Luconia, non-reefal F19-1 location (Figure 4) had a condensed chalky marl (Cycle IV deep marine equivalent) terminated, possibly with subsidence, but more importantly this off-reef, low area began to receive a new siliciclastic sedimentary sequence (Lunt, 2021b, his Figure 7). Proper use of the Letter Stages in integrated biostratigraphy points to a complex geological transition at the Cycle IV to V boundary. This is much more precise than converting data to global chronostratigraphy and then estimating that the event was intra-Serravallian.

As pointed out by Luan & Lunt (2022) this was also the age of the abrupt subsidence at the Deep regional

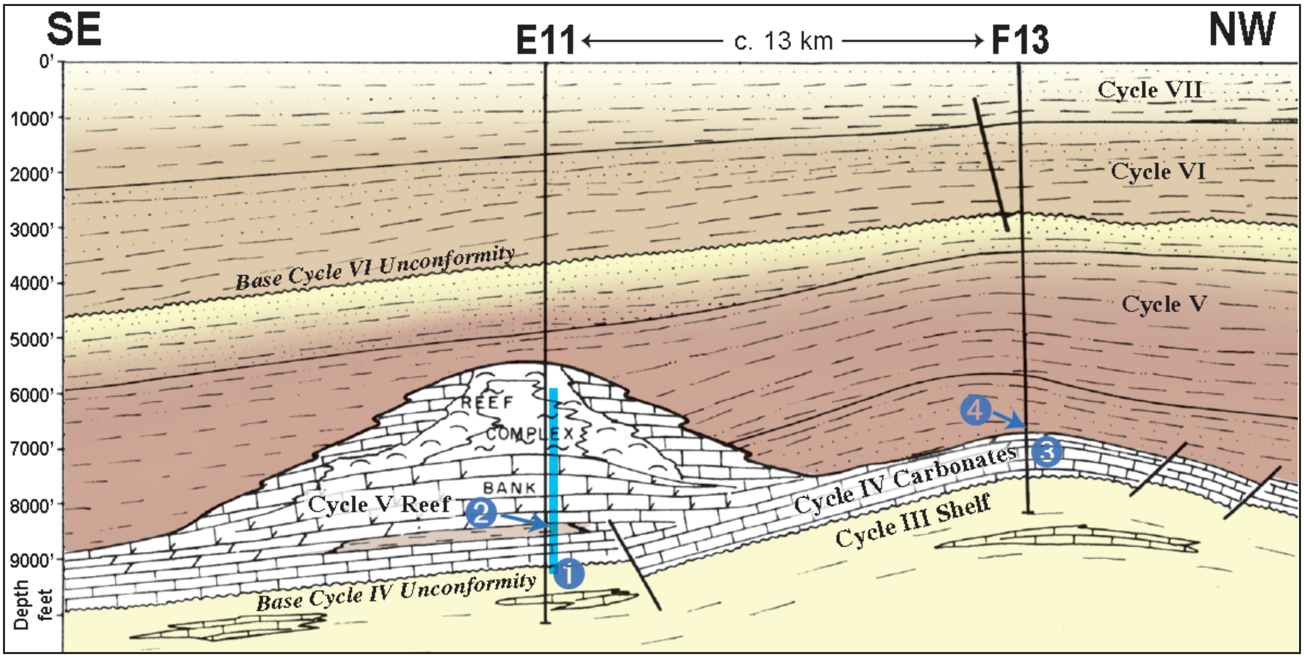

Figure 5: Depth cross-section over E11 and F13, Luconia. Yellow indicates shallow shelf facies with few planktonic foraminifera; brown are deep marine clays. Annotation number 1 marks the extent of continuous core in E11-2. Number 2 is a clay-rich marl with a small acme in planktonic foraminifera (nearshore marine, lacking age index forms) which is part of the base Cycle V flooding surface. Within this marl are the highest records of *Lepidocyclina* (*Nephrolepidina*), *Miogypsina* and *Austrotrillina* (all Lower Tf markers). The clean limestone over this marl has a Sr isotope age of 11.7 Ma, a limestone within the marl an age of 11.1 Ma and a limestone in the Cycle IV carbonate 12.1 Ma. Annotation number 3 is the top of the Cycle IV carbonate in F13 with *Miogypsina* and *Lepidocyclina* (*Nephrolepidina*). Sr dating at the top of the limestone is 12.4, 11.9 and 12.4 Ma. The base of the Cycle IV limestone is 14.3 Ma (2 analyses in E11-2), 14.8 Ma (in E13-2) and 15.4 Ma (F13-4). Nearby wells F1-1 and E7-1 have Zone N8 foraminifera below the base of Cycle IV. Annotation number 4 is the overlying deep marine clays with *Fohsella fohsi* (N12) in the basal sample directly over the carbonate (Lapre & Thornton, 1970) and then N13 marker *Globigerinoides subquadratus* (N13 marker) for about 900 feet of the claystones above. The top of N12 is dated globally at 11.7 Ma (Wade *et al*., 2011) which matches the Sr ages in both reefs for the top of Cycle IV.

Unconformity (DRU) in west Sabah and the "Red" Unconformity in south Palawan, as well as subsidence and drowning of multiple reefs in eastern Sabah (Lunt & Madon, 2017b). In the Terumbu area symmetrically across the Bunguran Trough (west) from Luconia there is an unconformity within the Terumbu Limestone that coincides with the Lower to Upper Tf boundary (Lunt, 2021b, Figure 11; modified from Franchino & Viotti, 1986). This event seems to correlate with many regional unconformities, from the Java Sea to the Luconia Province of Sarawak and the DRU in Sabah (Lunt & Madon, 2017a). Lunt & Woodroof (2021) proposed that all these unconformities might be coeval and related to a regional plate change, for which name of Duabelas Unconformity could be applied to this regional event.

The top of foraminifera Zone N12 and the global extinction of the *Fohsella* planktonic lineage seems be be slightly younger than this regional tectono-stratigraphic event, but the top of Letter Stage Lower Tf seems to be an exact correlation. This correlation has been discussed by Lunt (2021a) and Lunt & Luan (2022), and a hypothesis offered that it might have been related to a regional climate change when plate movement led to the Indonesian throughflow between the Pacific and Indian oceans becoming constricted. This hypothesis is as yet un-tested, but as described by Lunt (2021a), previous work on this topic (e.g. Wilson, 2011) was confused because of a mis-understanding of the age of larger foraminifera fauna changes, abandoning the Letter Stages for simple global Epoch age assignments (Wilson's Figure 6; with poorly-dated carbonate periods plotted against a high-resolution oxygen isotope curve) and the overlooked magnitude of the carbonate microfaunal turnover at the Lower to Upper Tf boundary.

CONCLUSIONS

The larger foraminifera-based biostratigraphy of the Letter Stages has fallen into disrepair through decades of small, but multiple and compound misunderstandings. These errors have crept into publications and then been re-cited without question. The original reports by the Indonesian and Malaysian Geological Societies, although often old work (some references date from almost a century ago), are based on highly detailed, thorough studies of excellent and unbroken sections, such as NE Java (Tuban Plateau) and the Melinau Gorge in north Sarawak. Biostratigraphic data from both these areas have since been complimented by modern strontium isotopic dating, and the former area was calibrated with detailed planktonic biostratigraphy by several independent groups.

Examples are given from multiple sites showing how we can be confident of dating many important geological events, and then correlating these events as coeval over a wide area. Often the nature of the geological event changes in character across the region, but occurs at the same time and therefore the data must describe a complex geological transition. As a result, without clarity and precision in dating, advances in interpretation of regional geology will be impossible.

Of the four Letter Stage boundaries discussed here in detail, the Ta to Tb boundary is an essential age datum during a complex and gradual geological transition that used to be over-simplified as the singular "Rajang Unconformity". The Cycle I to II boundary in Sarawak is clearly coeval with the Base Miocene Unconformity and has been recognised in many parts of Sundaland at the base of Upper Te. It is almost always a subsidence / transgression, but it must be dated correctly and both the magnitude of subsidence and direction of the transgression need to be estimated in order to describe a major regional tectono-stratigraphic transition. The fact that this regional Base Miocene Unconformity has not yet been placed in a plate tectonic framework is due to it having been mis-dated in several areas. The Cycle IV to V boundary of Sarawak appears to be part of the regional Duabelas Unconformity proposed by Lunt & Woodroof (2021), where many areas in Sundaland saw a strong and rapid tectonic readjustment precisely at the top of Letter Stage Lower Tf (roughly 12 Ma). Different areas have very different responses, and the driving cause of this geological event is currently unknown. Letter Stage biostratigraphy and facies analysis (e.g. geohistory plots) will be a key part of understanding new geologic and tectonic reconstructions.

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AUTHORS CONTRIBUTION

This study is part of an ongoing review of stratigraphic techniques in the tectonically active basins of SE Asia, especially around the South China Sea, by the current authors. XL contributes regional knowledge to the developing stratigraphic framework across the South China Sea, but has access only to published Malaysian data. The local stratigraphic review and biostratigraphy is by PL.

CONFLICT OF INTEREST

The authors know of no conflict of interest that impacts this paper.

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