When, how much, how fast, and why it matters. A quantitative view of stratigraphy and the emergence of a new paradigm

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Abstract

Our understanding of the regional geology of SE Asia appears to have stagnated and, to break out of this state, a new approach to stratigraphic studies is required. We must avoid the trap of deductive studies and boilerplate formats as these restrictive methods of investigation rely heavily on assumptions that are not valid in the tectonically active basins of the region. This review examines an alternative workflow that replaces model-based methods with evidence-based ones, and in particular uses stratigraphic properties in a quantitative way to test old concepts. Through this approach a tectono-stratigraphic framework is established, and new data is used to test and then build upon this interdisciplinary framework. It is argued that only this approach can accommodate and predict the unique and locally complex geology of the region. A key component of this approach is the now stable, cross-facies, biostratigraphy, and time scale for the later Eocene to Recent of SE Asia, as well as methods in estimating paleo-bathymetry. These can be used to evaluate the sedimentary history and structural evolution of the basins, using geohistory analysis.

The application of this quantitative approach, combined with a more open attitude to sub-surface data from government authorities, makes it highly probable that there will be a paradigm shift in our understanding of regional geology across SE Asia. Examples given here illustrate the use of the quantitative methods in rejecting long-established and widely cited old ideas, and the start of building of new concepts. We have not yet arrived at the new paradigm, but we can already observe that the attenuation of Sundaland, with two separate axes of extension, both with simultaneous episodes of movement, is not consistent with any current plate tectonic hypothesis, or even any known plate mechanism. The new framework is argued to be both innovative and predictive, replacing the largely descriptive and enervated role of geology in the past few decades. A new, evidence-based role will offer a better understanding of facies palaeogeography through time and exploration risks.

Keywords: *regional geology, geohistory analysis, SE Asia*

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INTRODUCTION

This is the third in a series of linked essay by the same authors. The first two (Lunt and Luan, 2023; 2024a) were opinion pieces discussing how geological studies have been conducted in SE Asia in the past decades, mostly using inappropriate methods imported from much simpler areas. These were argued to have failed to improve our knowledge of the dynamic geology of Sundaland. After naming conventions and the philosophy / process of investigation, this third review is a more standard-format paper, with data presented in support of a hypothesis; that by developing better methods for this tectonically active region we will see a paradigm shift in our understanding of the geological history of Sundaland.

This is a large task that cannot be accomplished in just one or two papers, and we are also preparing more detailed contributions in specific areas in the usual academic format, from the Pearl River Mouth Basin to the Lombok Basin. This paper contains new data shown in a quantitative way to informally present a large-scale, overview of possible new concepts to our peers in the region. Too often the local or specialist papers presented to international journals are mis-understood by outside reviewers who have only a limited appreciation of the complex geology, and contradictory histories found in SE Asian reports. For example, we describe here how there appear to be two axes of Eocene to Early Miocene extension across Sundaland, with simultaneous episodes of movement, and we can cite studies with data supporting this, but we are also aware of apparently contradictory material in other papers. We ask readers to consider the overview presented here, which appears to be balanced, while we write up more detailed local reviews of data for and against this concept. Such local papers must also consider the naming of formations or age index fossils, and the issues of precision, accuracy and trueness of observations discussed in the prior papers in this series. Most readers of *Berita Sedimentologi* are professional geologists who will probably know of archaic, mis-designated data in their research areas and therefore will hopefully be tolerant of statements in this paper perfunctorily rejecting contradictory opinions. While we are deconstructing local accounts, we want to offer for critical review a first pass outline of what may develop into the new regional paradigm.

Stratigraphy is a crucial discipline because an understanding of how the layers of sediment were deposited, how fast or slow, and how these parameters changed, as well as the content of the sediments, and their history of burial and then uplift, must all tie to structural geology, plate tectonics and even volcanic activity. Stratigraphy is constrained through Walther's Law and this, as well as cross-discipline validation of results, makes it a central discipline to link all of sedimentary geology and tectonic studies. Figure 1 shows the locations of this study.

INTRODUCTION TO QUANTITATIVE APPROACHES

A common form of presenting geological studies in SE Asia is the narrative, to which some new data is added through a new paper. There is an underlying assumption that scientific advance progresses through such small, modest steps. However, testing of the established paradigm is rarely carried out, and it is usually accepted as a fact.

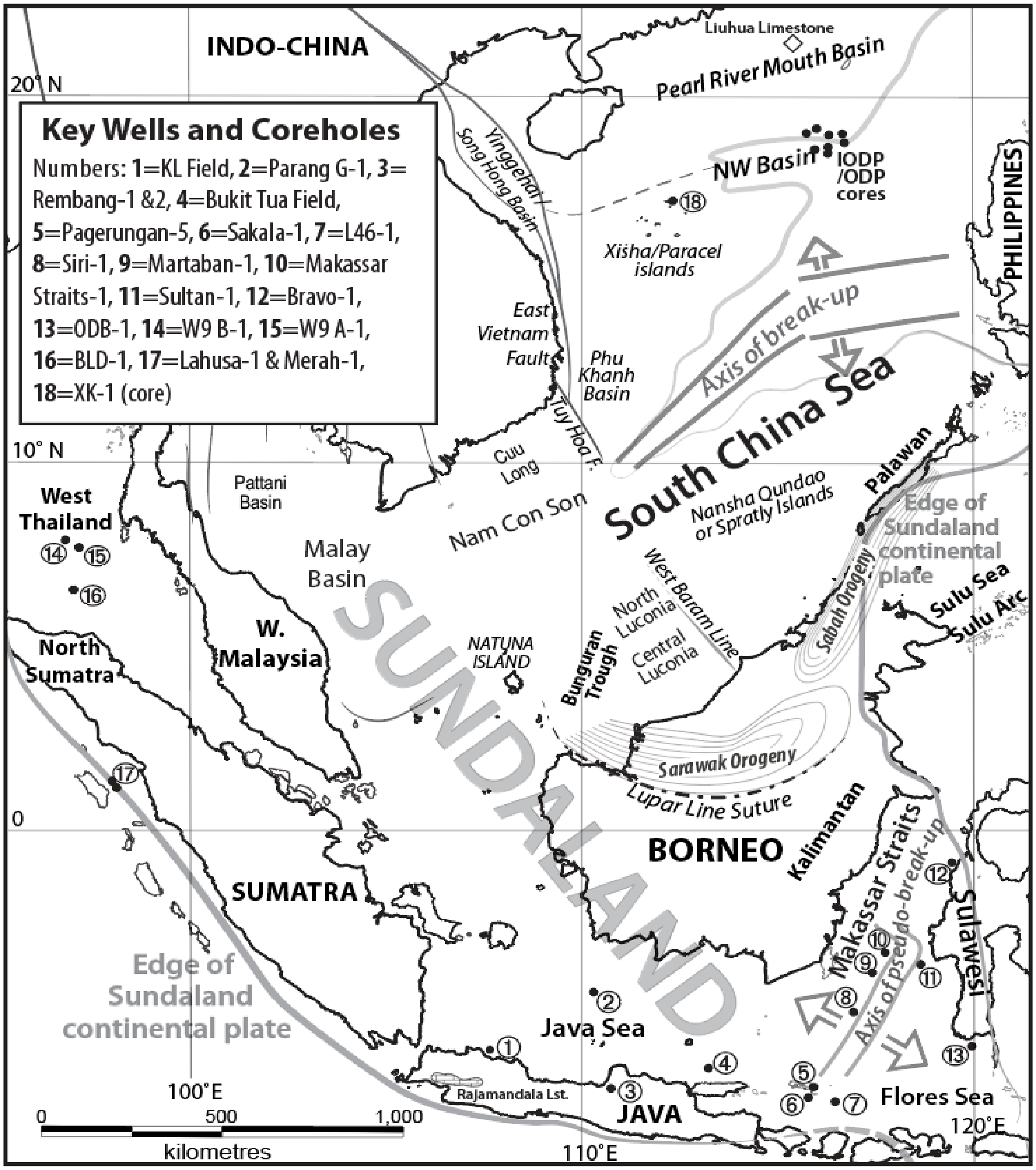

Figure 1: *Location map. Other locations are shown on Figure 11.*

Narratives are common in the humanities, where they can imitate hypotheses in social, political, and behavioural sciences. Good narratives are easy to listen to and memorise. In stratigraphy the narratives can be rich in jargon and thereby appear to be highly technical. However, the Nobel laureate Richard Feynman proposed "*Unless a thing can be defined by measurement, it has no place in a theory*" (Feynman, 1965). This review suggests that stratigraphy in tectonically active basins must move to a more quantitative approach to test, and then advance beyond, simple technical stories.

It can be argued that stratigraphy has stagnated because un-measured, imprecise narratives can too easily accommodate almost any new observation. The history can become more technically convoluted, with the excuse that SE Asia is known to be a complex area. However, it is an illogical correlation that an increasingly complex narrative must therefore be a true description of a complicated region. Furthermore, open-ended stories are hard to test and falsify, and therefore ideas tend to be selected based on the assumed authority of the writer, or if the sources that contain the foundations of the story are widely cited.

In the last sentence the term “selected” is used in its biological sense, meaning an evolutionary pressure that tends to preserve and promote over the un-selected variants (which are pushed towards extinction). Such evolutionary pressures occur every time a paper is published and cites a set of supporting references. Without Feynman’s requirement for measurement, a hypothesis can survive and even appear to develop without ever facing the prospect of falsification. This is why we must change to a quantitative approach in stratigraphy, scaled in the dimensions of time as well as facies palaeogeography, because such measurements lead to tests, and either falsification or survival of the theory, or at least an objective ranking of the alternative working hypotheses.

Note that the term quantitative stratigraphy does not refer to quantitative techniques, such as in biostratigraphy, where numerically identified peaks in facies-related taxa can be proposed to represent features like maximum floods or correlated climate shifts. Instead, the proposed approach quantitatively examines; (1) *when* – to link cause and then effect (never the other way around), (2) *how much* – to estimate by how much accommodation space changed and (3) *how fast*. This last point is important because it has long been assumed that tectonism is a slow and gradual change, upon which faster, glacio-eustatic changes have superimposed a distinct stratigraphic signature (Morrison and Wong, 2003). As will be demonstrated below this is not the case for many tectonic events across Southeast Asia.

An important derivative of measuring *how much* and *how fast* is that we gain the ability to map out variations in the magnitude of change. Sequence stratigraphy studies have invariably assumed an evenly expressed sea-level change across a basin (Posamentier et al., 1988, Posamentier and Allen, 1993; Haq, 2014). It is quite clear that basins in SE Asia have focal areas of change, with magnitude of change fading distally, and including not just abrupt alterations in basin shape, but often simultaneous variation in the hinterland location as well as sediment supply.

The concepts of modified eustatic sea-level, or relative sea-level changes tried hard to accommodate what are termed auto-cyclic sedimentary changes (e.g., lobe-switching of deltas, or of turbidite fans). However, the tectonically active basins of SE Asia are beyond such remedial approaches to a passive margin model, and they must be studied using methods based on measurement. As will be shown below, there is much to be gained from this quantitative approach to stratigraphy and geology. This contrasts with the recognition that no worker has yet to independently identify any eustatic controls on sedimentation in SE Asia (larger that possible parasequence-scale fluctuations), until the onset of the mid Pliocene M2 glacio-eustatic event in the northern hemisphere (Westerhold et al., 2020).

THE SIGNIFICANCE OF ACCOMMODATION SPACE

It has long been recognised that palaeoenvironment and accommodation space are critical characters in stratigraphy, and non-gradual or cyclical changes in these characters are important stratigraphic features. The term accommodation space was popularised by seismic stratigraphy, which sees sedimentary packages in a scaled vertical dimension (two-way time – TWT – directly proportion to depth), and changes in this dimension (=space in 3D) are the controls on the depositional units (systems tracts), and the lithofacies they contain.

The development of packages of sediment in a basin directly reflect its tectonic history. If the basin has a passive history, with only slow, gradual changes in subsidence (i.e., thermal subsidence, as envisaged by Posamentier et al., 1988), then there is little tectono-stratigraphic history to describe. Stratigraphy will also be nondescript (colloquially known as "layer-cake") and sedimentation is likely to be controlled by eustatic or broad epeirogeny changes in sea-level. Low stands will create small unconformities in the proximal sedimentary system and allow sediment to be pulled into the deep (distal) part of the basin, before a transgressive phase allows this small unconformity to be buried below new sediment. There are autogenic depositional movements of the sediment to complicate this simple proximal-distal stratigraphic model (such as lobe-switching), but a conceptual classification of parts of the sedimentary system has emerged, as summarised by Catuneanu et al. (2011). In such a system the accommodation space changes evenly across the basin because it is only affected by exogenous influences. Hence if sea-level changes by 30 metres, there is 30 metre change in accommodation space in all parts of the basin.

In SE Asia we see a second type of change in accommodation space, when the basin undergoes endogenous change (*endo-* Latin; within). This is when the basin rapidly changes its architecture, possibly including the depth and location of the depo-centre, as well as coeval changes in sediment supply. Such a complicating concept was anticipated by Posamentier et al. (1988) who set out specific conditions and assumptions that were required to apply their technique of eustatic sequence stratigraphy; namely:

1. Subsidence is primarily due to thermal cooling

2. Subsidence increases in a basin ward direction and this distal to proximal dimension in geography remain the same through time

3. Sediment supply remains about the same through time

4. Sea-level (accommodation space) changes in a curvilinear, approaching sinusoidal pattern

The paragraph after where these assumptions are described states "*the overprint of local factors must be considered in order to utilise them in a predictive mode for a particular basin.*" The geology of SE Asia repeatedly presents exceptions to all four of these assumptions.

The "*first principle conceptual model for tectonic successions*" presented by Matenco and Haq (2020) anticipated a need to combine regional and local tectonic effects with any eustatic changes to sea-level. In 2014 Haq had suggested the term eurybatic to describe local relative sea-level as a combination of all such effects. Both this and the 2020 paper with Matenco thought in terms of large controls such as epeirogenic change, now accommodated by theories on mantle-driven dynamic topography (Gurnis, 1993), compounded by local fault movement. This was a complete opening up of the parameters controlling stratigraphy, while at the same time abandoning the old idea of using a regional or eustatic sea-level curve to widely correlate and thereby date un-drilled sections. Matenco and Haq's conceptual scheme proposed a way to classify and count a combination of tectonic and eustatic changes, but it was open-ended and had no ability to be predictive or testable. It was a technique, or a model, for description. It recognised tectonic mega-sequence / succession boundaries, but offered no method to study these, unless they simply reinforced the previous passive, proximal to distal, sedimentary patterns with an additional cyclicity.

Examples across SE Asia show that unless analytical methods are applied, then seismic, which is the basis of the Matenco and Haq conceptual scheme, can miss major tectono-stratigraphic changes, or at least significantly underestimate their magnitude. Analytical methods are the only way to describe and predict these tectono-stratigraphic changes and build an evidence-based framework to guide seismic interpretation. An example of this is the mid-Oligocene subsidence across at least 50,000 square kilometres of west Thailand and north Sumatra (Lunt, 2019a) that was identified independently by four groups (the Indonesian Geological Survey, Mobil Oil field survey, Esso and Inpex Petroleum; between the 1970s and early 1990s) and described as a rapid "*catastrophic tectonic subsidence*" (Tsukada et al., 1996). This was estimated to be rapid displacement of many hundreds of meters (Mobil Oil) or many thousands of feet (Esso), reduced to a single log-break in para-conformable successions such as the W9 A-1 well, or very low angle bedding contacts in BLD-1 and W9 B-1. The low angle contacts have slight missing section during post-event onlap, but as a proportion of the thick and consistently paralic Agam (Sumatra) / Ranong (Thailand) Formation sediments below the unconformity, and the equally thick and consistent bathyal Pirak (Sumatra) or Yala (Thailand) Formation above, this missing section is very minor. The contrast in environment of deposition is still a step-like regional movement of entire sedimentary systems. This was the single largest Cenozoic tectono-stratigraphic event to have affected this region, but it was not noted as such on seismic and geophysical studies up to and even after Meckel et al. (2012), Meckel (2013) and Tampubolon et al. (2018). The extremely abrupt, step-like change in stratigraphy must reflect an abrupt, step-like shift in palaeogeography (Walther's Law) yet many reports reproduce the stratigraphic scheme of Ryacudu et al. (1992, redrawn as recently as Muchlis and Elders, 2020) where the boundary is shown as highly diachronous, and thereby a slow event, taking place over nearly the entire Early Oligocene (about four to five million years).

In East Java and the Makassar Straits, offshore Sarawak and around Sabah and the South China Sea there are many more instances of major changes like these, at many different ages (Hutchison, 2004; Morley, 2016). These might be recognised on seismic, but often they are not identified as exceptional and important events without the data from analytical geology. Seismically distinct stratigraphic boundaries such as breakup unconformities show episodic, staggered migration across the region (*cf*. Lunt and Woodroof, 2021) with each stage having similar seismic morphology (buried topography unconformities). These have previously been mis-correlated as coeval, or given different ages and considered gradually diachronous, instead of being of different ages in different places with an abrupt, episodic movement.

All this empirical data from many Southeast Asian basins indicates that the conceptual model of Matenco and Haq is inadequate for predictive, testable science in the extremely dynamic tectonism found in the region. Changes in accommodation space must be described in a quantitative fashion, especially; when, how much, and how fast.

Resistance in moving to a different method

There is a selection pressure to use deductive methods, especially through the application of in-vogue conceptual models such as Posamentier et al. (1988) or Matenco and Haq (2020), to carry out both commercial and academic studies. Both the workflow and the layout of such reports follow an approved, boilerplate, format consisting of (a) a statement of the problem/hypothesis, (b) the method used to investigate it (c) the results and then (d) the conclusions deduced from them. The boilerplate structure of deductive studies is usually selected for projects because it appears to have manageable steps, and predictable, easily counted deliverables that can be tied to contractual or performance milestones. The service provider is also subject to a different selection bias as the deductive format avoids any risky, innovative, research, from which it is impossible to predict the value of results due by a deadline that was set at the start of the study.

There is an additional bias pressuring workers to deduce from a popular concept or model. This is, that the assumptions in the adopted model are considered as being outside the peer review applied to a local study, i.e., it is "taken as given" that these are a close approximation to the truth. This was the case of the Vail / Haq eustatic sea-level changes, and the methods of Posamentier et al. (1988), which were forced onto SE Asian seismic studies for decades (e.g., Morrison and Wong, 2003). This is known as a halo-effect bias. Copying the renowned ExxonMobil approach insulates local projects from detailed criticism, despite the known dangers from adopting these assumptions (*cf*. Miall, 1992; Miall and Miall, 2022)

The alternative, evidence-based method is far harder to apply, from project design, through carrying out the work (maybe including outsourcing small, specialist jobs that were not anticipated at the start), and even in the closing documentation. In contrast to deductive studies, all data must be ranked for reliability; that is – the observation error bars that are obligatory in other sciences but overlooked in geology. Geology suffers from hubris to think its data does not need validating beyond collecting more and looking for a mean or modal value. In rare cases simple review work just on data precision and reliability can change the view of geology. This was the case with a review of NW Sabah and the eastern South China Sea (Lunt, 2022a) as discussed in a following section. Considering such uncertainty, how does a manager identify, budget and plan for such a suite of unknown variables? To quote an American statesman "*We know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know … it is the latter category that tends to be the difficult ones*" (D. Rumsfeld, 2002).

The motivation to carry out a more difficult project, with both a less certain schedule and unclear list of final deliverables, is that there is potential to discover truly new things, as stated in the colloquial idiom as "*thinking outside the box*". This contrasts with a deductive study that assumes SE Asia can be reconstructed from the same components that are found in the passive margin areas where the ideal guiding models were established. To emphasise this point, we can illustrate some simple examples that are now obsolete, and then move onto some work in progress with implications for future studies.

EXAMPLES OF OBSOLETE IDEAS

It is proposed that a quantitative approach to tectono-stratigraphy will lead to advances in regional geology, so here we will first examine some of the old concepts that the process appears to be making obsolete.

The Rift-Sag concept

Most geology papers in SE Asia that include any schematic cross-sections or annotated seismic invariably use the terms "rift" and "sag" (or post-rift) as technical jargon for a profile that is almost unavoidable as any extensional basins grows (a *tautology* is a vacuous statement containing self-proving logic). The terms have very little meaning and can sometimes be mis-leading. For example, many papers on North Sumatra cited above (e.g. Tsukada et al., 1996, their Figure 2) place both the fluvio-deltaic Agam/"Parapat" Fm. in the same early syn-rift phase as the fully bathyal "Bampo"/Pirak Formation, and in doing so miss the largest Cenozoic tectono-stratigraphic event to have affected the region, even though it was mentioned in their text as a "*catastrophic tectonic subsidence*".

The term rift-to-sag and the resulting "steer's head" basin geometry is tied to, and implied to reflect, a two-layer model of crustal extension (White and McKenzie, 1988). The first stage of extension was controlled by brittle failure of the upper crust (rifting). As faulting diminishes (e.g., after breakup), the lower lithosphere, which had been extended plastically over a wider area than the local rifts, became the dominant control on basin subsidence, with slower, broader sinking due to cooling and thermal contraction.

Many workers (Doust and Sumner, 2007; Doust and Noble, 2008) present classifications of SE Asian basins according to the rift-sag concept, but this is a poor deduction for three reasons. Firstly, using a criterion based primarily on analysis of shape, different workers see different things. Compare Longley (1997) with Doust and Sumner, (2007) and Doust and Noble (2008), who all studied similar lists of Asian basins but interpreted different classifications on their basin profiles. These last three cited papers contrast in their analysis of the North Sumatra Basin, and all miss the uniquely important mid-Oligocene subsidence event mentioned above.

Quantitative stratigraphic data directly challenges the old rift-sag ideas in several ways. Firstly, in many areas the "rift to sag" transition has been described as a breakup unconformity, but this is often not a unique crustal failure event, as anticipated by the ideal model of lithosphere breakup. In the south Makassar Straits area (=NE Java / Lombok of Doust and Sumner, 2007) some of the authors cited above place the "rift to sag" boundary at the Eocene – Oligocene boundary. The study of the Makassar Straits-1 and other wells by Lunt and van Gorsel (2013) describe this particular event as a marked reduction in sediment supply to the region as shown in Figure 2 with some subsidence (Martaban-1 in figure 10),

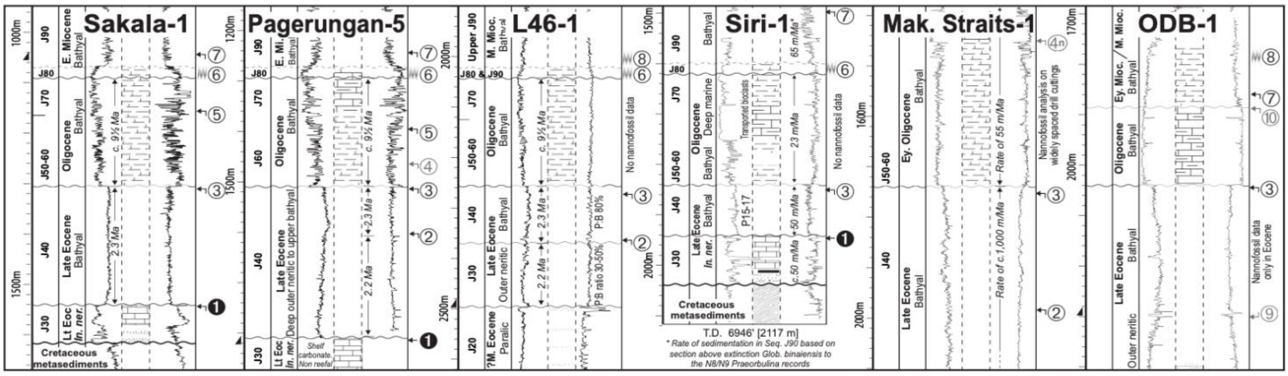

Figure 2: *Well sections over the Eocene – Oligocene boundary ("3") in the Makassar Straits showing a platform carbonate (below black 1) overlain by deep marine clays, then a major and abrupt change in lithofacies and rates of sedimentation coincident with the Eocene – Oligocene boundary. The end of the Oligocene ("6") is also marked by the onset of very condensed sedimentation, sometimes lasting into basal Sequence J90. The "J" sequences are based on the scheme of Lunt (2013).*

Key*: Black 1, top Tb (Lt. Eocene larger foraminifera), "2" highest Globigerinatheka semiinvoluta (E14; 35.8 Ma); "3" highest of the Turborotalia cerroazulensis, Hantkenina or Discoaster saipanesnis/ barbadiensis group – often in same sample; "4" top Sphenolithus pseudoradian (28.7 Ma); "4n" is the extinction of transported Nummulites at about 28.2 Ma; "5" top Sphenolithus distentus / predistentus (26.8 Ma); "6" Oligo-Miocene boundary, often very condensed basal Miocene indicated by various markers; "7" top Triquetrorhabdulus carinatus and nearby Globigerina binaiensis, extinctions both at about 18 or 19 Ma; "8" records of Praeorbulina and Globigerinoides sicanus indicative of an age near the base of the Middle Miocene or latest Early Miocene; "9" evolution of Sphenolithus pseudoradians a mid-Late Eocene datum (c. 37 Ma) near to casing point in ODB-1; "10" occurrence of Heterostegina (Vlerkina) borneensis indicates Oligocene.*

but prior to this, there were two older breakup-like extensional and subsidence accelerations; one near the end of the Middle Eocene, another within the Late Eocene (Makassar Straits-1, Figure 4 of Lunt and van Gorsel re-drawn as Figure 9 here), as well as a fourth event close to the Oligo-Miocene boundary (Sultan-1, Bravo-1 and other reefs; see Figure 4 here). Similar multiphase, breakup-like extension is also seen in the South China Sea (e.g., geo-history plot of North Luconia in Lunt and Luan, 2022; Figure 3 here) and elsewhere in that region.

This fourth, breakup-like event in the Makassar Straits was large, yet has been overlooked. It was the end Letter Stage Te4 subsidence and drowning of numerous pinnacle reefs in the Makassar Straits as well as in distal eastern Java basins (Luan and Lunt, 2022).

The magnitude of this event can be estimated from the geo-history plot in Figure 4. The highly condensed nature of subsequent Early Miocene sedimentation means that it was very unlikely that the reefs were terminated by eutrophic pollution from a new siliciclastic source, and this isolates subsidence as the main cause of multiple, simultaneous, reefal extinctions (red dots on Figure 11). This condensed sedimentation also means that there was insignificant overburden and isostatic loading of the area until the Late Miocene, so the reefs subsided to very deep settings during the Miocene due to tectonic activity alone. It is known that scleractinian reefs can temporarily survive very rapid but

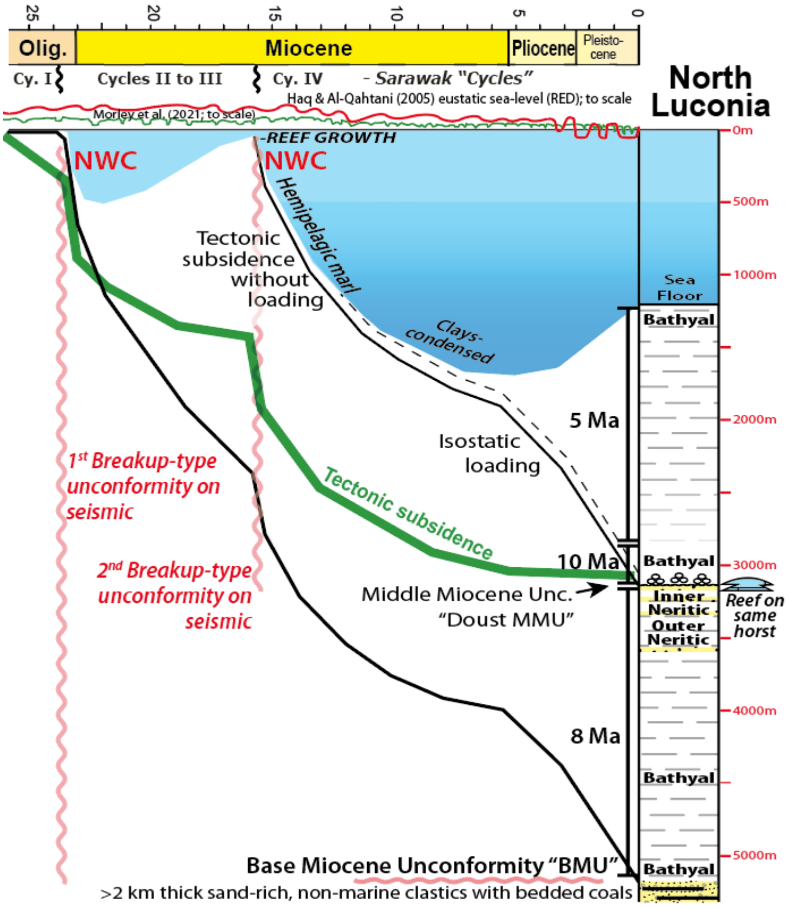

Figure 3: *North Luconia geohistory plot. This area was affected by two major breakup tectono-stratigraphic events. The event on the Oligo-Miocene boundary correlates to ridge jump in the South China Sea as well as subsidence of flanking areas such as XK-1 in the Xisha/Paracel Islands and G10-1 in the northeast Luconia area (Lunt, 2019c)*

small sea-level changes as high as 20 m over 500 years (Meltwater Pulse or MWP-1A at *ca.* 14.6 ka BP; Stanford et al., 2011), but if this is compounded on longer term and slower tectonic subsidence of about 2.5 to 6 m/ka, this is enough to drown reefs in such tectonically subsiding areas (Webster et al., 2009).

Model-driven interpretations tend towards arbitrary and subjective subdivisions such as Early and Late rift phases (see references cited above for common use of this terminology). In contrast, evidence-based approaches develop objectively through quantitative measurements. For example, it could be hypothesised that the last of the candidate breakup-like events in the Makassar Straits was crustal failure and the actual transition from lithospheric rift to sag. However, the high rate of subsidence, diminishing in magnitude laterally, can be traced over a very wide area across the flanking continental margin. This effect has been studied in the Gulf of Mexico by Pindell et al. (2014), who required an additional tectonic mechanism, called an outer margin detachment zone, to allow such rapid, broad and coeval subsidence. This rapidly acting mechanism replaced the slower, gradual onlap of the "horns" of the "steer's head" due to thermal cooling proposed by White and McKenzie. Adjacent to the Makassar Straits is the wide shelf now under the Java Sea, where the Kujung Unit I limestone rapidly transgressed over and replaced mixed siliciclastic and thin limestones, quite abruptly near the Lower to Upper Te, base N4, base NN1 zonal boundaries (Figure 5). Analysing this effect requires qualified age-dating to distinguish it from a diachronous transition, but also the observation that it was a step-like shift of facies, with none of the interdigitation expected from a slower, gradual shift. A combination of lithofacies and microfossil

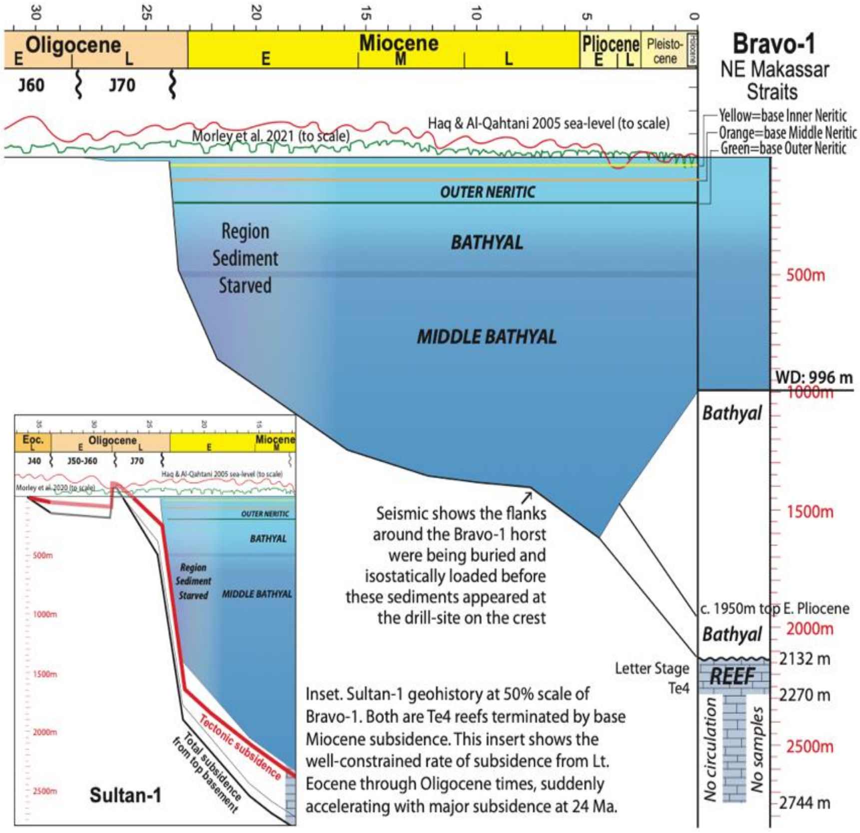

Figure 4: *Geohistory plot for Bravo-1 with inset a partial plot for Sultan-1 (both Makassar Straits) showing the large-scale subsidence of Letter Stage Te4 (latest Oligocene) reefs.*

data indicates a step-like change in all wells over the broad shelf. Walther's Law states that a step-like shift in the stratigraphic record, even if only of a few tens of metres in environment of deposition, indicates a step-like change in palaeogeography.

So now the stratigraphy has identified a coeval event over a very wide area with a distinct palaeogeography of magnitude having an axis of maximum subsidence, that structural geologists can consider in their models of plate evolution. This links stratigraphy with basin evolution in a predictive and testable framework, which is a significant advance from just labelling parts of a cross-section with tautological (and sometimes incorrect) terminology.

Bravo-1 did not reach basement, so no subsidence curve is calculated. The Sultan-1 shows the very much slower basement subsidence from about 36 Ma to 24 Ma, after which the basement, and the reef upon it, subsided to very deep marine conditions, but not due to sediment loading and isostasy. This extreme subsidence correlates to the less severe subsidence over the adjacent shelf (the modern Java Sea), ultimately to the very minor (no more that a few tens of meters), but long-term subsidence of the KL Field wells and Parang G-1 at the far side of the Java Sea some 600 km away (Figure 5).

The subduction of a Proto-South China Sea

Geological theories on the evolution of the South China Sea have been tested in a framework of time. Originally this was done by Silver and Rangin (1991), who reversed the north-westwards subduction model of Rangin (1989) around north Borneo and

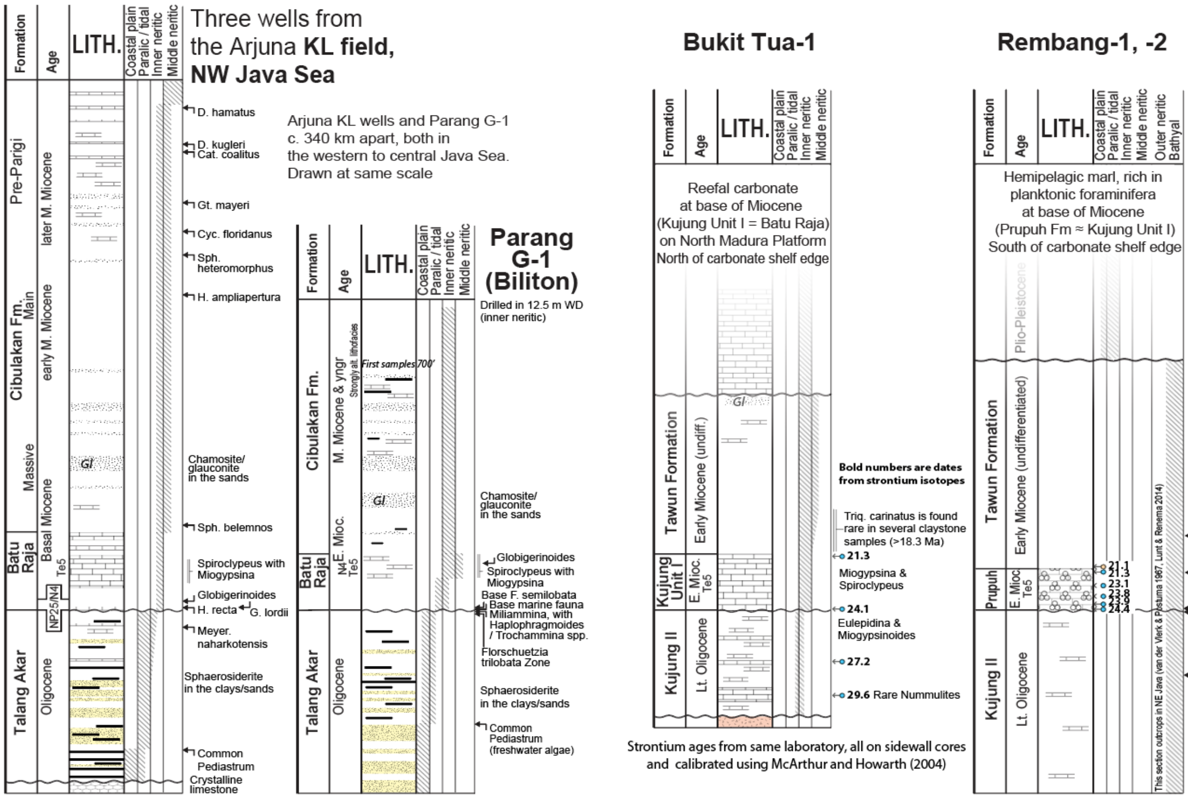

Figure 5: *Correlation across the modern Java Sea area, hung on the Oligo-Miocene boundary annotated with data supporting ages. Well locations shown on Figures 1 and 11.*

Palawan, to a model with southeast directed subduction of a lost Proto-South China Sea (PSCS). They did this because of three, clearly stated factors. First was the non-observation of any subduction zone imaged on seismic data around the Sulu Arc. The second and third reasons were based on the ages of tectono-stratigraphic features. The timing of the Cagayan Arc magmatism was thought to match the date of "*convergence along the north-west side of Palawan*". However, the references they cite – Hamilton (1979) Holloway (1982) and Hinz & Schlüter (1985) – were not of a high resolution on the topic of age dating, and have since been superseded, nullifying this argument. Thirdly, fieldwork on Zamboanga (Rangin & Muller; but published in Muller, 1991) at the northernmost end of the Sulu Ridge (see Figure 1), showed the earliest arc volcanics there were "*Zone NN5 in age, definitely younger than the age of the Sulu Sea oceanic basement or of ages from the Cagayan Ridge*". These relative ages suggested that the Cagayan Arc in the west was the arc associated with assumed back-arc spreading of the eastern Sulu Sea. While this made the Cagayan Arc distinct and a candidate subduction arc in front of spreading oceanic crust, it did not explain what the younger (mid Middle Miocene) Sulu Ridge arc was in a new plate tectonic model.

Gradually, data on the timing of events improved, coming from multiple disciplines (biostratigraphy, some strontium dating, and the dating of magnetic anomalies in the oceanic crust of the central SCS). It should have been noted early on that the model involving SE subduction of a PSCS was not tenable, but new data came in small increments, and rejecting a widely cited concept would require erection of a whole new regional tectono-stratigraphic framework. In contrast, inherited data, if left correlated to a very old-time scale, seemed to be consistent with the timing of compression and the formation of an accretionary wedge. This uncorrected data appeared to indicate that the Early Miocene was a time of spreading orthogonal to Sabah and south Palawan (roughly 25 to 20 Ma; Barckhausen et al., 2014; the northern green axis in Figure 11), and this seemed to correlate to the deformation observed in outcrops in north Borneo. The presence of accretionary wedge-like deformation, active while the postulated PSCS oceanic plate was subducted and lost, was essential for this tectono-stratigraphic model.

However, this was an incorrect age correlation, and the time of maximum plate drift in the SCS orthogonal to Sabah and south Palawan was during a period of quiescence in tectonic activity across north Borneo. The PSCS subduction model therefore fails because it can be shown that the deformation of north Borneo (the candidate accretionary wedge) <u>preceded</u> the "ridge jump" of seafloor spreading and drift that occurred at a time between 23.5 and 25 Ma (between anomalies 6c and 7; Barckhausen et al, 2014). The abrupt end of this compression (at the regional Base Miocene Unconformity; BMU) is dated as near the Te4 to Te5 boundary, *ca.* 24 Ma, after which there was about five million years of tectonic quiescence (Lunt, 2022a). This shows the importance of placing tectono-stratigraphic events in a qualified time scale (the "when" of this paper's title). In addition, the trend of deformation had a geographically restricted inverted "L" shape (see Lunt, 2022a, his Figure 6), not the required elongate, linear trend.

It is significant that the ridge-jump of seafloor spreading to face towards Sabah coincided with a regional subsidence event (at the BMU). This subsidence is locally of very high magnitude, such as in the area from the Kimanis Bay, Bunbury to Barton wells where deeply eroded Stage I/II sediments are thermally late mature (vitrinite reflectance Ro>1.2%) and are overlain by deep marine Stage III as old as the *Paragloborotalia kugleri* Zone (Zone M1) with a much lower burial maturity (Ro <0.6%). Furthermore, the latest Oligocene sediments of northwest Borneo are characterised by reworking of lithic fragments including basement, as well as Cretaceous to Eocene microfossils (noted by multiple workers from Bowen and Wright 1957 to Wannier 2009); an effect that stopped abruptly at the BMU. The rapid transition from erosion prior to the BMU, then to deep marine sedimentation (outer neritic to bathyal) Stage III Early Miocene indicates rapid basal Miocene subsidence. This was a higher magnitude of change than areas in east Sabah, where the latest Oligocene uplift had slightly eroded Labang Formation siliciclastics, which were then transgressed by the inner neritic Te5 Gomantong Limestone (McMonagle et al., 2011). These are the dimensions of "how much and how fast" of this paper's title, using quantitative properties stratigraphy to challenge geological ideas.

The rotation of Borneo

A narrative of the history of Sundaland often includes a counterclockwise rotation of Borneo, although there is debate about the reliability of the palaeomagnetic data (*cf.* Hutchison, 2005; Hall et al., 2008). This rotation appeared to match a model with subducting Proto-South China Sea under north Borneo, as the subducting plate roll-back could have been the motive force for such rotation, and it is reconstructed this

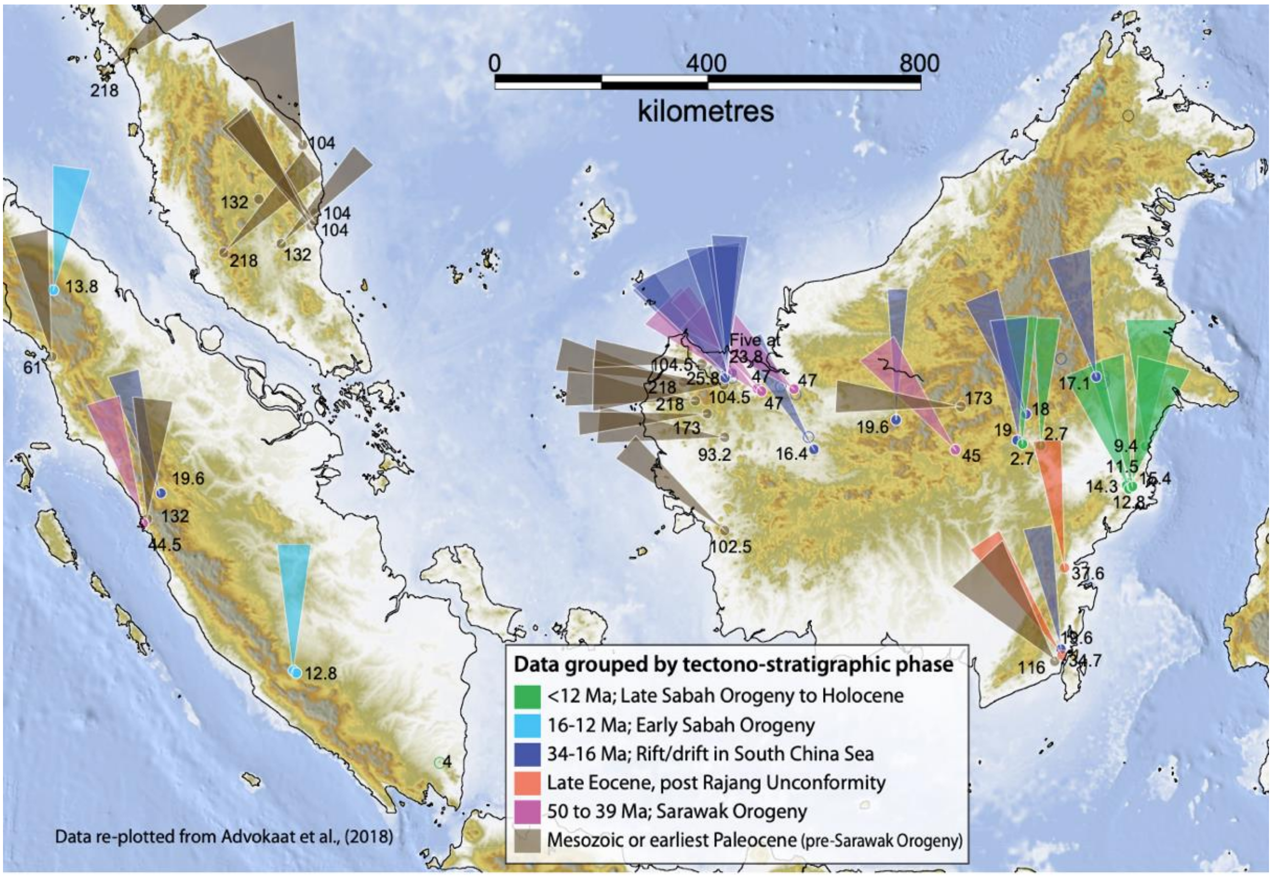

Figure 6: *Figure summarising the evidence previous used to support a concept of Miocene rotation of Borneo. Most of the dark blue magnetic vectors (34-16 Ma, Oligocene and Early Miocene) show no rotation, which appears to have been associated with the "Sarawak Orogeny" that ended at about 39 Ma (Rajang Unconformity; brown and pink vectors). Data re-plotted from Advokaat et al. (2018).*

way in the plate models of Robert Hall (e.g., Hall, 2011).

As with the phases of deformation and plate movement in north Borneo described above, a careful analysis of the "when" of geological properties yields a different story. A model associating this rotation with the postulated PSCS subduction would predict this rotation to have been active between about 24 and 20 Ma (or as young as 15 Ma if alternative ages for the end of SCS plate drift are believed, see notes below). Hutchison (2005) summarised: "*The Late Eocene Silantek Formation gives 41° of anti-clockwise rotation*" which he used to imply that these beds were rotated since the Late Eocene (post Rajang Unconformity). However, the Silantek Formation is dated to be within a broad age range of later Cretaceous through Early Eocene (Haile 1954, 1957). This Formation is stratigraphically below the non-marine Plateau Sandstone, which is dated from palynology by Morley (1998) as mostly Palaeocene, possibly late Maastrichtian at the base. Figure 6 colour codes the radiometric ages of igneous samples measured for palaeomagnetic vectors (Advokaat et al., 2018). Older beds from western Borneo (brown and pink) were subject to rotation that predated the younger samples in the east. These pink and brown vectors predate the Rajang Unconformity and would have been deformed by the tectonism that ended within the Late Eocene. The sparse data from the time of the plate spreading in the SCS (orange and blue vectors) indicates negligible rotation associated with the postulated subduction of a PSCS plate. Therefore, the rotation of west Borneo was due to the much older tectonic activity of the last phase of the Sarawak Orogeny (Sibu Compression) and not a hypothetical proto-South China Sea subduction and plate roll-back.

QUANTITATIVE METHODS OUTLINED

Analysis of inputs to the quantitative method

The post Middle Eocene timescale is summarised in van Gorsel et al. (2014) along with biostratigraphy schemes. Age is a critical part of any definition in a historical science, and from age the rate of deposition or fault movement can be derived. What is often omitted are the error bars to age determinations. These aspects of reliability vary in different parts of the time scale, with differences between fossils groups, or with strontium dating, and with data from different generations of workers as methods evolved. How an age is documented can greatly impact how different disciplines are fairly integrated, such as the use of Late Eocene for Silantek Formation above and also the Late Oligocene Kudat Formation of north Borneo that was for a long time classified, for understandable reasons, as Early Miocene (Lunt, 2022a, also the first essay in this series; Lunt and Luan, 2023).

Figure 7 summaries SE Asia stratigraphy with proxies. Since the Blow zones (P1-22 for the Palaeogene, N4 to N23 for the Neogene; Blow, 1969) simple zonal summaries have been very convenient and have been periodically modified. They usually follow similar formats such as Martini's (1971) NN zones, and Berggren et al. (1995) E, O, M and PL zones for Eocene through Pliocene foraminiferal zones. The fact that the original Neogene Zones N1-3 were found to be overlapping with the latest Palaeogene zones and therefore abandoned, is an illustration of the limited accuracy in the 1960s for determination of the Oligo-Miocene boundary.

Some sections are notoriously hard to date with precision, such as within the Early Miocene between roughly 21 and 16 Ma, on both planktonic and larger foraminifera, nannofossils and palynology. The reporting of dates of events, such as the base Cycle III unconformity across west Sarawak, within this period need qualification. In practical terms it may be better to abandon biostratigraphy and in shallow or non-marine facies, such as the ?Cycle III Begrih Formation onshore Sarawak, it may be better to use Sr dating of calcareous bioclasts in the rare marine floods.

A related contrast in precision and reliability comes through the simple choice of terms. Authors are encouraged to use the international "standard" Stage names such as Aquitanian or Burdigalian in higher-ranking journals, but these can only be applied through some form of translation via a standard time scale. There is obviously no observation of these Stages in samples or on seismic in SE Asia. The SE Asian Letter Stages were adopted specifically to replace European Epochs for this reason, but they have been ignored by the international community. Yet workers observe components of fauna that directly indicate the Letter Stages, so they are much more precise, especially concerning their boundaries, than the imprecise and assumption-based "standard" Stages.

This is all part of assessing observation precision, accuracy and trueness that

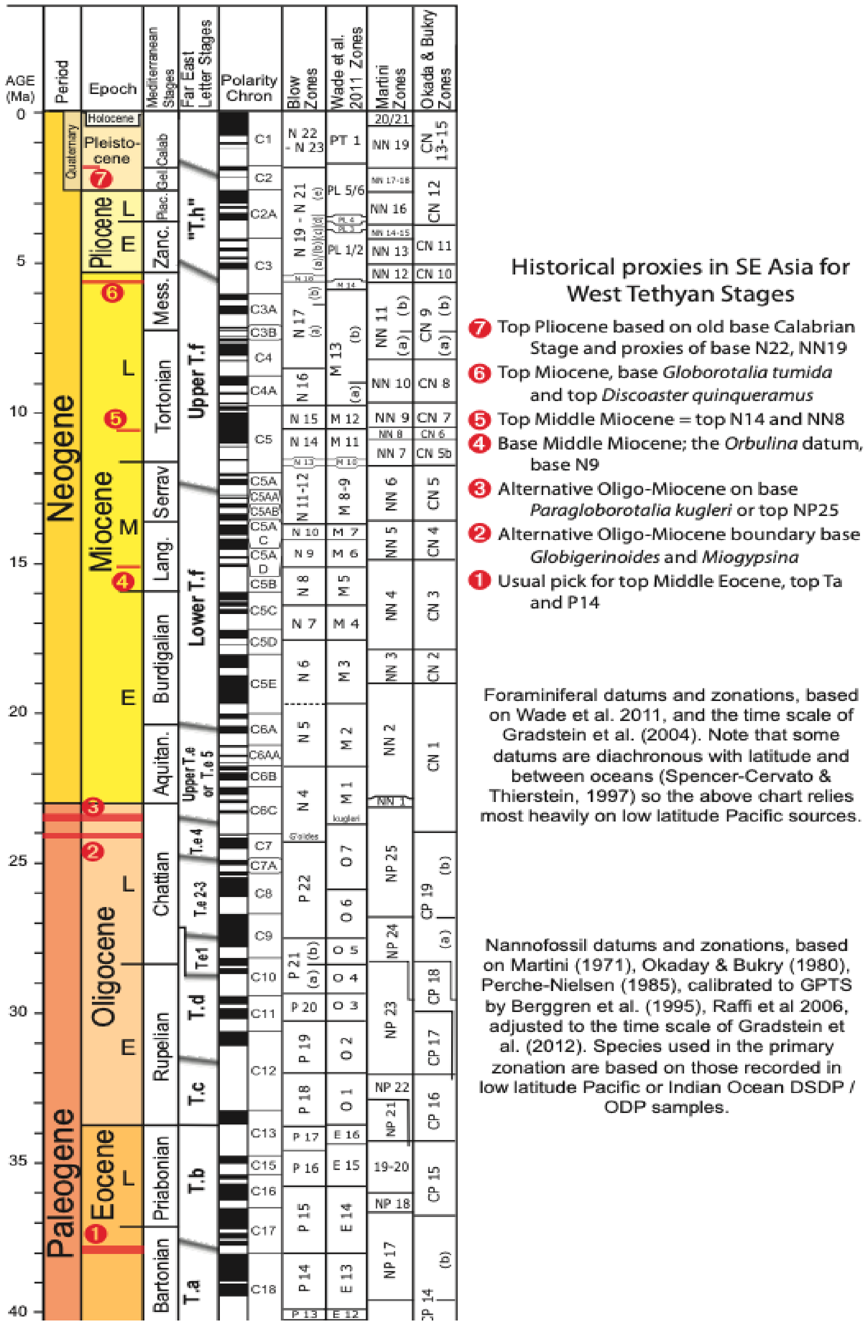

Figure 7: *Stratigraphic summary with proxies marked. Based on Gradstein et al. (2020) but the mid and later Cenozoic scheme has been fairly stable since Gradstein et al. (2004), which was also the same time that the modern Cenozoic strontium dating schemes became stable (McArthur and Howarth, 2004)*

begins with knowledge of drilling and casing history in a well, data that was not routinely supplied to service companies until within the 1980s and is still sometimes overlooked. There are also many instances of even modern wells drilling into a reef and logging only the easily processed but caved fauna from the open marine, even bathyal sealing clays (see previous essay; Lunt and Luan, 2024a). Luan and Lunt (in prep.) summarise the Kerendan limestone that had strontium dating giving a late Early Oligocene age (29.9 to 29.5 Ma; Saller et al., 1992) for the termination of the reef, which is widely re-cited to one decimal place, implying an age accuracy better than half a million years, even though the actual isotopic ratios and instrument calibration is not given in any of the well reports or papers, and the strontium ocean reference curve has evolved considerably since the time of the work. In contrast the sedimentologist's thin section descriptions from cores include images of *Tansinhokella* (evolved mid Late Oligocene, *ca*. 27 Ma Sr age and within P22/NP24; Lunt and Renema, 2014; and Lunt, 2014) found hundreds of metres below the top of the reef, so it is more likely the reef terminated near the end of the Oligocene. This is all part of cross-checking data for accuracy (=repeatability) and trueness (Sr dating is prone to diagenetic overprinting). This property of trueness is obtained from verification by independent observations, such as the nannofossils, planktonic foraminifera and Sr data all helping to fix the evolution of *Tansinhokella* from ancestral *Heterostegina* (*Vlerkina*) in NE Java (Lunt and Renema, 2014) that matched the independent planktonic foraminifera and larger foraminifera observed from the same sites by van der Vlerk and Postuma (1967).

A modern summary of environments of deposition and their associated microfauna, along with lithofacies characters, is needed, but it would be a difficult book to write due to the poorly organised taxonomy of the benthic foraminifera. Despite the inconsistent usage of names, multiple authors have arrived as the same basic scheme for determining environments of deposition and paleo bathymetry as consistently summarised by Brouwer (1966); Keij (1963, 1966), Biswas, (1976); Cater and Attewell (1976); James (1984); Wang et al. (1985); van Gorsel (1988), Kadar et al. (1996) and Szarek (2006, 2009). This scheme is verified as new wells are drilled next to each other and analysed, especially over a sloping area such as on the Mahakam Delta. This is an example of a technique with high trueness but low precision. It cannot precisely pick a depth where middle neritic changes to outer neritic, but a gradual environmental succession can be quickly, blindly, and repeatably identified, – as can an unconformity where there is a gap in this faunal grade. A summary was made based

FORAMINIFERAL ASSOCIATIONS IN CLASTIC MARINE ENVIRONMENTS

Environment	INNER NERITIC	MIDDLE NERITIC		OUTER NERITIC	UPPER BATHYAL	LOWER BATHYAL	ABYSSAL
Depth range	low tide – 20 m	shallow ± 20 – 50 m	deep 50 – 100 m	100 – 200 m	200 – 1000 m	1000 – 4000 m	4000 m — deeper
Faunal diversity	very low; 2 or 3 species may make up > 90% of fauna	moderate	high	very high	very high	high	low to moderate
Planktonic Foraminifera	absent or very rare	5 – 10% of fauna small specimens and very few species	up to 40% of fauna small to normal sized.	40 – 80% normal size, many species	± 60 – 95% very high species diversity	>90% solution prone species (*Orbulina spp., Globigerinoides spp.*) may be lacking in lower part)	Dissolved or only solution resistant species (thick-walled *Globorotalia spp, Pullentinnia Sphaeroidinellopsis*)
Composition of benthonic fauna and common species.	Small rotalids: *Ammonia* *Elphidium* *Cellanthus* Miliolids: *Quinqueloculina* *Triloculina* Larger foraminifera *Orbitoids* *Operculina* *Amphistegina* Small arenaceous forms: *Ammotium* *Trochammina* *Haplophragmoides, etc.*	* Most species as for inner shelf * In addition are *Pseudorotalia sp.* *Asterorotalia sp.* *Bolivina sp* *Florilus sp.* *Anomalinella rostrata (?)* *Lenticulina sp.*	* rare larger and arenaceous forams * small rotalids (as in inner-shelf) are still present, but rare * common forms are: *Heterolepa praecinctus* *Heterolepa margaritiferus* *Siphonina pulchra* *Bolivina spp.* *Uvigerina spp.* *Cibicides spp.* *Lenticulina spp.* *Miliolids* *Textularia sp., etc.*	* No larger foraminifera * Benthonic fauna mainly composed of calcareous benthonics: *Uvigerina spp.* *Lenticulina spp.* *Nodosaria spp.* *Bolivina group.* *Cassidulina spp.* *Gyroidina sp., etc* * Robust arenaceous species (*Cyclammina*) present, but very rare.	Benthonic fauna: * abundant small calcareous benthonic species Characteristic forms are: *Pullenia bulloides* *Chilostomella oolina* *Bulimina spp.* *Bolivina albatrossi* *Globocassidullina subglobosa* *Uvigerina auberiana* *Sphaeroidina bulloides* * Common robust arenaceous forms *Eggerella* *Cyclammina cancellata* *Martinotiella communis* *Textularia sp.,* *Karreriella bradyi, etc.*	* Foraminifera less common than in upper bathyal zone * Robust arenaceous species common and may dominate the benthonic fauna (same forms as in upper Bathyal) + *Bathysiphon* *Rhabdammina* *Ammodiscus* * Numerous calcareous benthonic species: *Planulina wuellerstorfi* *Oridorsalis umbonatus* *Melonis pompilioides* *Epistominella exigua* *Globocassidulina subglobosa*	* Foraminifera rare * Below Carbonate Compensation Depth (between 4000-5500 metres in presentday oceans) all calcareous foraminifera are dissolved. * Above C.C.D. some solution-resistant planktonic and calcareous benthonic species are present (as in lower Bathyal). * Faunas mainly or entirely composed of large, simple arenaceous forms *Bathysiphon* *Rhabdammina* *Ammodiscus* Agus - June, 19

Figure 8: *A summary of marine microfossils and environment of deposition, especially bathymetry, based on 1980s service company reports. Similar summaries exist for estuarine and coastal plain settings. Note the fine distinction of facies in these shallow settings, but once deep outer neritic and bathyal conditions are reached, faunal change has a much lower bathymetric resolution.*

on companies' reports and tabulated in Figure 8. The accommodation space and thereby palaeo-bathymetry profile on a geohistory plot must honour this micro-palaeontological data.

Geohistory analysis

The fundamentals of geohistory analyses were explained by van Hinte (1978). It is a valuable technique to cross-plot lithofacies, accommodation space / environment of deposition and a stratigraphic framework through time at one site. Not all geohistory plots are informative because some sections lack stratigraphic or facies contrast to measure, but in other cases they can be definitive descriptions of important tectono-stratigraphic events. The North Luconia plot updated and re-drawn here (Figure 3) has been included in several publications by the present authors because the well sections were drilled in water depths of 1000 metres yet have coastal plain, coal-bearing latest Oligocene beds and, in a few places, a base Middle Miocene photic reef. The conservatively de-compacted sediments measure the large-scale change of accommodation space that must have been generated by the first breakup-like subsidence (top Cycle I; Oligo-Miocene boundary), and the second such event near the end of the Early Miocene (top Cycle III, =Doust MMU). These are clear graphical presentations of the tectono-stratigraphic history, plotted with two published eustatic sea-level curves at the top at the same scale. Not only does this clearly demonstrate the dominance of tectonism in controlling sedimentation, but it contrasts with wells in the Central Luconia province where the events have much smaller magnitude, showing just a small-scale subsidence and the transgression by the Luconia Limestone (*cf*. Lunt, 2019a, Figure 12; Lunt, 2021, Figures 7 and 13), and further to the SE diminishing to having no noticeable effect (Lunt, 2022b). Simple mapping of this variable magnitude of tectonic displacement describes the location and style of tectonic activity, and thereby the endogenous controls on sedimentation from the changing basin architecture.

The geohistory plot for Makassar Straits-1 (Lunt and van Gorsel, 2013) is reproduced here in Figure 9 and shows the very large (*ca*. 2 km) accommodation space that must have been generated in just the later part of the Late Eocene (<2 Ma) before the very abrupt end Eocene starvation of sedimentation. This latter event on the Eocene-Oligocene boundary can be measured from the contrast in gradient of fill in the geohistory plot. Additional data from Martaban-1 (*ca*. 40 km away; Figure 10) can be used to analyse the end Eocene event as this well was a shallower setting, so the microfauna is able to reflect a shift from about middle neritic to a bathyal setting. This is event labelled "3" in Figure 2 with rates of sedimentation added. The end Eocene subsidence at Martaban-1, in the order of 15-200 m vertical displacement, is not resolved in the low-resolution paleo-environmental zones in the very deep marine Makassar Straits-1 site. In this way a network of wells can use geohistory evidence to measure the history of subsidence, and the evolution of both the basin and the sediment fill.

These simple methods to quantify stratigraphy have been recognised for decades (van Hinte, 1978), but all inputs have been gradually improved with better time scales and better facies descriptions, so it has only been in about the past two decades that geohistory plots became compelling evidence to describe and map stratigraphic change. There is tendency to assume such fundamental work has been

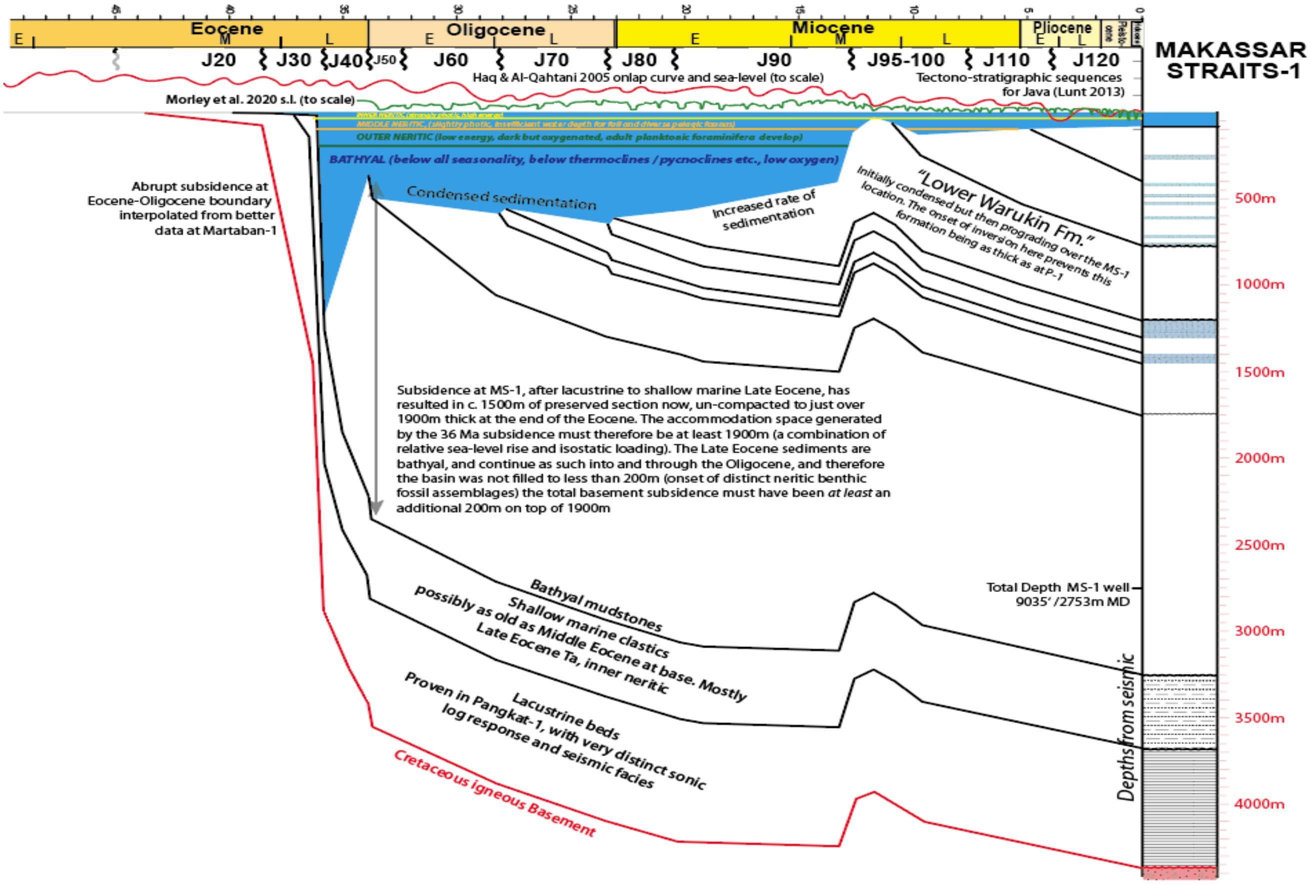

Figure 9: *Makassar Straits-1 geohistory modified from Lunt and van Gorsel (2013) and the new data from Martaban-1 (Figure 10)*

done, but in most cases it has not. As a result, we have long overlooked the speed of stratigraphic change in the region, as we needed better schemes to show that historically imprecise ages actually correlated, and with minimal diachroneity. The end Eocene event, described above, is a major extinction event that is clear in most marine and non-marine biostratigraphy. Over a very wide area a major tectono-stratigraphic change is seen in wireline logs precisely at this time, associated with abrupt changes in lithofacies and rates of deposition depicted in Figure 2. This is a well-dated example of what must have been a very rapid, regional geological change, but one that has still been overlooked in published accounts.

Outline of a new paradigm

The examples given above show how quantitative stratigraphy challenges and profoundly influences geological studies. This review presents a hypothesis that the neglect of stratigraphy for several decades, in an area where it should be a crucial component, inevitably means that a new phase of investigation will lead to the replacement of outdated concepts. Renewed studies will generate new, evidence-based, ideas that will help drive a paradigm shift in regional geology. We predict that this new paradigm will have certain content and features.

Firstly, there will be a shift in both our comprehension of stratigraphic expression

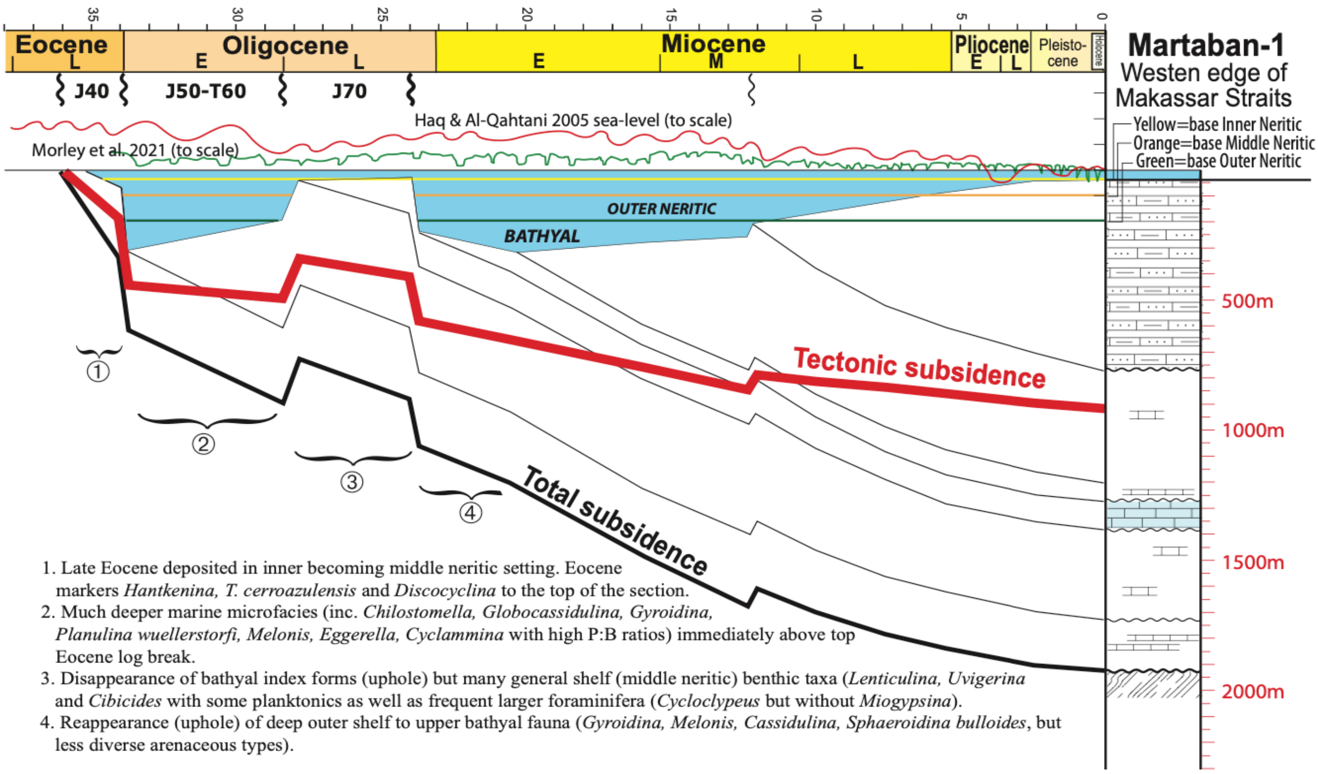

Figure 10: *Martaban-1 geohistory scheme.*

as well as its nomenclature. By this we mean that stratigraphic studies have long been mired in the naming of things, based on bookish discussions of multi-generational histories of studies, rather than being considered as a practical tool for basin analysis. A natural classification of sedimentary packages will emerge, and it is likely this will strongly resemble the evidence-based observation of the 70s and 80s (e.g. Cycles in Sarawak; Stages in Sabah; Cycles of Achmad and Samuel 1984 in NE Kalimantan; the Groups of the Malay Basin). The speed of tectonic change will be better understood, as well as how this integrates with broader epeirogenesis, or even eustatic, controls on accommodation space.

Secondly will be the emergence of a single geological model for all of Sundaland. This can fill the geographic gaps in our knowledge with testable predictions for under-explored regions. Nearly all regional summary maps, as recent as Doust (2017), identify SE Asian basins as static polygons when we know they are dynamic, shifting features with complex histories. The East Java Basin of many workers contains at least seven very different sub-basins (Lunt, 2019b), each with a unique stratigraphy but all forced to share one set of lithostratigraphic names. Many areas are excluded from the basin defining maps even though some, such as the Mangkalihat Peninsula and onshore West Java, have thousands of meters of Cenozoic sediments, as well as active oil seeps. Other basic basin concepts will change. The so-called fore-arc basin of west Sumatra was not a typical fore-arc basin until the Late Miocene. Wells such as Merah-1, Lahusa-1 and others found thick, Middle Miocene quartz sands that had been transported from the east under a very different type of basin configuration. A unified tectono-stratigraphic framework is required to explain and understand the evolution of these depocentres. Such an account must be a rigid, validated framework and not just a narrative; for example, the model-based narrative for fore-arc basins fails to predict the older Miocene sedimentary history of west Sumatra.

Thirdly, this regional model points to simultaneous extension focused along two axes: in the South China Sea and under the Makassar Straits (Luan and Lunt, 2022, their Figure 20, redrawn here as Figure 11), with coeval stages of movement. During the Eocene through to Early Miocene (20 million years; half the Cenozoic sedimentary history) rifting can be dated by the carbonates deposited on the flanks, and these axes of rifting can be seen to have migrated westwards in stages (Lunt and Woodroof, 2021).

The Early Miocene is a subject of active research being the period when the long-term attenuation of Sundaland came to an end, and there was the onset of the Sabah Orogeny, and probably related compression in west Sulawesi. Most publications associate compressional events in eastern Sundaland at this time with the approach of the Buton/Tukang Besi and Banggai-Sula microplates (Davies, 1990; Smith and Silver, 1991), but theories on why there is a Sabah Orogeny across western Borneo are lacking. As noted above, a correlation of the Sabah Orogeny with drift in the SCS is not valid. Li et al. (2014) tabulated different

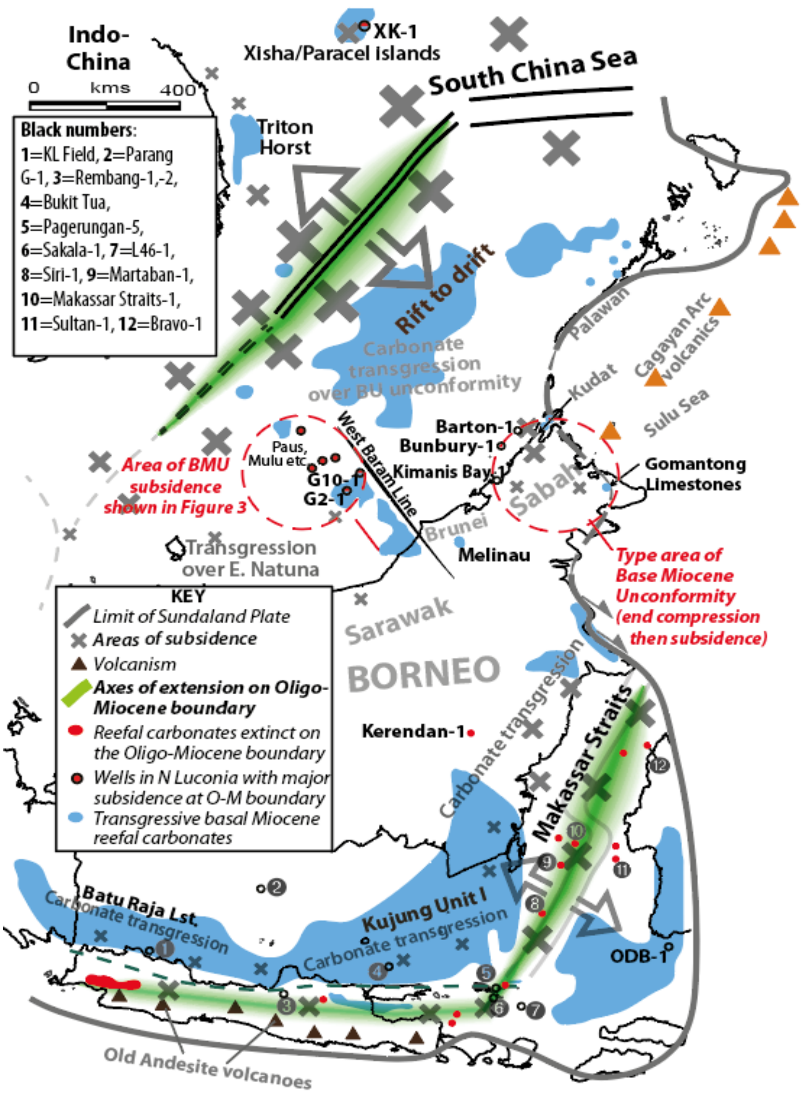

Figure 11: *Tectono-stratigraphic summary map of Sundaland at the Base Miocene Unconformity (BMU; modified from Luan and Lunt 2022, their Figure 20). The larger the grey cross, the larger the estimated subsidence. This was the time of plate spreading "ridge-jump" into the central South China Sea (green axis between Borneo and Indochina).*

workers accounts of when drift in the South China Sea ended, but as Barckhausen et al. (2015) point out, the youngest of these ages (15 or 16 Ma) include radiometric dates on extrusive basalts that may post-date the magnetic anomalies directly indicative of drift. The oldest fission track dating of cooling and uplift of the Western Cordillera created by the Sabah Orogeny are younger than this (14.5 ±1.9 Ma and 16.4 ±1.9 Ma; Hutchison, 2005, p. 266) which coincides with uplift, erosion and reworking of Paleocene and Cretaceous microfossils, and also slumped deposition visible as mass transport beds on seismic and pebbly mudstones in well samples (Lunt and Madon, 2017; Lunt, 2022a; Luan and Lunt, 2022). The Sabah Orogeny lasted at least 19 million years after this onset and is therefore clearly un-related to drift in the SCS.

Finally, any new tectono-stratigraphic framework will be based on evidence, rather than idealised models, and discussion of this evidence will have to include commentary on data reliability. In many areas we must examine new interpretations of seismic and the dynamic nature of stratigraphy, with times of apparently rapid change, pushing age-dating to its limits. In other areas studies will focus on the rate of change in sedimentation and contrasting the validity of multiple working hypotheses, for which each discipline will have to be considered with qualifications on likely trueness. We will have to abandon or overhaul badly defined concepts such as the Ngimbang Formation of Java, the Bampo Formation of North Sumatra and widely published deviations from the original Cycles and Stages concepts in west Borneo (among many examples). This kind of meticulous description and analysis is the opposite of fitting small amounts of new data to an old narrative.

CONCLUSIONS

A quantitative view of stratigraphy describes the formation of basins and the broad subsidence (and transgression) of Sundaland after the Middle Eocene, during a period when global sea-level fell by about 180 m (Haq et al., 1988) or 100 m (Snedden and Liu, 2010). The highly varied palaeogeography of this subsidence, the timing of stratigraphic events (now fixed to a reliable time scale), and the often-high rate of tectonic change, challenges many widely cited concepts on SE Asian geological history. A range of outdated concepts need replacing and the quantitative data from age and facies analysis will be a key contributor to building a new geological paradigm for the region.

It is hard to underestimate the magnitude of the changes that are likely. Both academia and industry have presented the same schematic geological summaries for twenty-five years or more. For example, the identical content of stratigraphic summary figures from Liechti (1960, their Figure 4) and Petronas (1999, their Figure 16.3) for Sarawak, and also James (1984, their Figure 16) and Osli (2021, their Figure 2) for Brunei, even though these can all be shown to be invalid or at least significantly incomplete, with neither matching the well-established Cycles stratigraphic scheme studied offshore west Borneo. Whether for hydrocarbon exploration or general geology we have fallen into a trap of thinking we understand Sundaland. The beginning of this review criticises our over-reliance on narrative as a familiar and comfortable account. Like any history, if it is re-written with different timing of events and a different emphasis of contributions, then the resulting account will be very different. Through a lack of testing, and inclusion of often contradictory data (and authors "agreeing to disagree"), geology became enervated, drained of vitality. A new paradigm requires rigorous testing of concepts, and it should offer not only new predictions on palaeogeography and petroleum systems elements, but all elements of geology up to basin evolution and a new understanding of the plate tectonic framework. This is the phase called *extraordinary research* by Kuhn (1962), and quantitative stratigraphic analysis is playing an important role in this research.

References

Achmad, Z., and Samuel, L., 1984. Stratigraphy and depositional cycles in the N.E. Kalimantan Basin. Proceedings from Proceedings Indonesian Petroleum Association Convention: 13, 109-120

Advokaat, E.L., Marshall, N.T., Li, S., Spakman, W., Krijgsman, W., and van Hinsbergen, D.J.J., 2018. Cenozoic Rotation History of Borneo and Sundaland, SE Asia Revealed by Paleomagnetism, Seismic Tomography, and Kinematic Reconstruction. Tectonics 37(8), 2486-2512.
DOI: 10.1029/2018TC005010

Barckhausen, U., Engels, M., Franke, D., Ladage, S., and Pubellier, M., 2015. Reply to Chang et al., 2014, Evolution of the South China Sea: Revised ages for breakup and seafloor spreading. Marine and Petroleum Geology 59, 679-681.
DOI: 10.1016/j.marpetgeo.2014.09.002

Barckhausen, U., Engels, M., Franke, D., Ladage, S., and Pubellier, M., 2015. Reply to Chang et al., 2014, Evolution of the South China Sea: Revised ages for breakup and seafloor spreading. Marine and Petroleum Geology 59, 679-681.
DOI: 10.1016/j.marpetgeo.2014.09.002

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: W. A. Berggren, D. V. Kent, M.-P. Aubry, & J. Hardenbol (Eds.), Geochronology Time Scales and Global Correlation (54), 129-212. SEPM Special Publication.

Biswas, B., 1976. Bathymetry of Holocene foraminifera and Quaternary sea-level changes on the Sunda Shelf. Journal of Foraminiferal Research 6, 107-133

Blow, W.H., 1969. Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. Proceedings from Proceeding First International Conference on Planktonic Microfossils: 1, 199-422

Bowen, J.M., and Wright, J.A., 1957. Geology of the Crocker Range and adjoining areas. Sabah Shell (unpublished)., 191 pp.

Brouwer, J., 1966. Stratigraphy of the younger Tertiary in north-east Java and Madura (report 1957, issued 1966)

Cater, M.C., and Attewell, R.A.K., 1976. Determination of palaeoenvironments in Southeast Asia. SEAPEX Proceedings 3, 1-7

Catuneanu, O., Galloway, W.E., Kendall, C.G.S., Miall, A.D., Posamentier, H.W., Strasser, A., and Tucker, M.E., 2011. Sequence Stratigraphy: Methodology and Nomenclature. Newsletters on Stratigraphy 44/3, 173-245

Davies, I.C., 1990. Geological and exploration review of the Tomori PSC, Eastern Indonesia. Proceedings Indonesian Petroleum Association Convention 19, 41-67

Doust, H., 2017. Petroleum Systems in Southeast Asian Tertiary basins. Geological Society Malaysia Bulletin 64, 1-16

Doust, H., and Sumner, H.S., 2007. Petroleum systems in rift basins – a collective approach in Southeast Asian basins. Petroleum Geoscience 13, 127-144

Doust, H., and Noble, R.A., 2008. Petroleum systems of Indonesia. Marine and Petroleum Geology 25, 103-129

Feynman, R. 1965. The Feynman Lectures on Physics (ed. Addison Wesley Publishing Company

van Gorsel, J.T., 1988. Biostratigraphy in Indonesia: methods, pitfalls and new directions. Proceedings from Proceedings Indonesian Petroleum Association Convention: 17, 275-300

van Gorsel, J.T., Lunt, P., and Morley, R.J., 2014. Introduction to Cenozoic biostratigraphy of Indonesia- SE Asia. Berita Sedimentologi 29, 4-40

Gradstein, F.M., Ogg, J.G., and Smith, A.G., 2004. A Geologic Time Scale 2004. Cambridge: Cambridge University Press., 500

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M., 2020. Geologic Time Scale 2020. Elsevier., 1390

Gurnis, M., 1993. Phanerozoic marine inundation of continents driven by dynamic topography above subducting slabs. Nature 364, 589

Haile, N.S., 1954. The geology and mineral resources of the Strap and Sadong valleys, West Sarawak, including the Klingkang Range coal. Geological Survey Department, British Territories in Borneo, Memoir 1.

Haile, N.S., 1957. The geology and mineral resources of the Lupar and Saribas valleys. West Sarawak. Geological Survey Department British Territories in Borneo, Memoir 7.

Hall, R., van Hattum, M.W.A., and Spakman, W., 2008. Impact of India–Asia collision on SE Asia: The record in Borneo. Tectonophysics 451, 366-389

Hall, R., 2011. Australia-SE Asia collision: plate tectonics and crustal flow. In R. Hall, M. A. Cottam, & M. E. J. Wilson (Eds.), The SE Asian gateway: History and tectonics of the Australia-Asia collision, Special Publication, 75-109. London: Geological Society of London.

Hamilton, W., 1979. Tectonics of the Indonesian region. U.S. Geological Survey Professional Paper 1078, 345

Haq, B.U., 2014. Cretaceous eustasy revisited. Global and Planetary Change 113, 44-58.
DOI: 10.1016/j.gloplacha.2013.12.007

Haq, B.U., Hardenbol, J., and Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and eustatic cycles. Sea-level changes; An integrated approach SEPM Special Publication 42, 71-10

Haq, B.U., and Al-Qahtani, A.M., 2005. Phanerozoic cycles of sea-level change on the Arabian Platform. GeoArabia 10, 127-160

van Hinte, J.E., 1978. Geohistory Analysis - Application of Micropaleontology in Exploration Geology. AAPG Bulletin 62(2), 201-222

Hinz, K., and Schlüter, H.U., 1985. Geology of the Dangerous Grounds, South China Sea and the continental margin off southwest Palawan: results of Sonne Cruises SO-23 and SO-27. Energy 10(3/4), 297-315

Holloway, N.R., 1982. North Palawan Block, Philippines - its relation to Asian mainland and role in evolution of South China Sea. AAPG Bulletin, 1355-1383

Hutchison, C.S., 2004. Marginal basin evolution: the southern South China Sea. Marine and Petroleum Geology 21, 1129-1148

Hutchison, C.S., 2005. Geology of North-West Borneo: Sarawak, Brunei, and Sabah. Elsevier Science., 421

James, D.M.D., 1984. The Geology and Hydrocarbon Resources of Negara Brunei Darussalam. Muzium Brunei., 164

Kadar, A.P., Paterson, D.W., and Hudianto, 1996. Successful techniques and pitfalls in utilizing biostratigraphic data in structurally complex terrain: VICO Indonesia's Kutei Basin experience. Proceedings Indonesian Petroleum Association Convention 25, 313-331

Kuhn, T.S., 1962. The structure of scientific revolutions. Chicago & London: Phoenix Books, The University of Chicago Press., 196 pp

Li, C.-F., Xu, X., Lin, J., Sun, Z., Zhu, J., Yao, Y., Zhao, X., Liu, Q., Kulhanek, D., Wang, J. et al., 2014. Ages and magnetic structures of the South China Sea constrained by deep tow magnetic surveys and IODP Expedition 349. Geochemistry Geophysics Geosystems 15, 4958-4983 *DOI: 10.1002/2014GC005567*

Longley, I.M., 1997. The tectonostratigraphic evolution of SE Asia. In: A. J. Fraser, S. J. Matthews, & R. W. Murphy, Petroleum Geology of Southeast Asia, 311-339. Geological Society Special Publication No. 126.

Luan, X., and Lunt, P., 2022. Controls on Early Miocene carbonate and siliciclastic deposition in eastern Java and south Makassar Straits, Indonesia. Journal of Asian Earth Sciences 227, 105091. *DOI: 10.1016/j.jseaes.2022.105091*

Luan and Lunt (in prep.). Stratigraphic analysis of SE Asia gives a new view of basin development during prolonged extension.

Lunt, P., 2013. The sedimentary geology of Java. Jakarta: Indonesian Petroleum Association, 346 pp.

Lunt, P., 2014. A review of the foraminiferal biostratigraphy of the Melinau Limestone, Sarawak. Berita Sedimentologi 29, 41-52

Lunt, P., 2019a. Partitioned transtensional Cenozoic stratigraphic development of North Sumatra. Marine and Petroleum Geology 106, 1-16

Lunt, P., 2019b. The origin of the East Java Sea basins deduced from sequence stratigraphy. Marine and Petroleum Geology 105, 17-31

Lunt, P., 2019c. A new view of integrating stratigraphic and tectonic analysis in South China Sea and north Borneo basins. Journal of Asian Earth Sciences 177, 220-239

Lunt, P., 2021. Tectono-stratigraphic framework of Luconia carbonates. SEPM Special publication, Cenozoic Isolated Carbonate Platforms – Focus Southeast Asia 114.
DOI: 10.2110/sepmsp.114.08

Lunt, P., 2022a. Re-examination of the Base Miocene Unconformity in West Sabah and stratigraphic evidence against a slab-pull subduction model. Journal of Asian Earth Sciences 230, 105193.
DOI: 10.1016/j.jseaes.2022.105193

Lunt, P., 2022b. Field and well evidence for large unconformities in north Sarawak, compared to south Sabah, Malaysia. Bulletin of the Geological Society of Malaysia 74, 69-84

Lunt, P., and van Gorsel, J.T., 2013. Geohistory analysis of South Makassar. Berita Sedimentologi 28, 14-52

Lunt, P., and Renema, W., 2014. On the Heterostegina– Tansinhokella–Spiroclypeus lineages in SE Asia. Berita Sedimentologi 30, 6-31

Lunt, P., and Madon, M.B.H., 2017. Onshore to offshore correlation of northern Borneo; a regional perspective. Geological Society Malaysia Bulletin 64, 101-122

Lunt, P., and Woodroof, P., 2021. Tectono-stratigraphic controls on Cenozoic SE Asian carbonates. SEPM Special publication, Cenozoic Isolated Carbonate Platforms – Focus Southeast Asia 114, *DOI: 10.2110/sepmsp.114.06*

Lunt, P., and Luan, X., 2022. Choosing between a dichotomy of methods in stratigraphy. Geology Today 38(2), 69-74

Lunt, P. and Luan, X., 2023. Giving names to features in geology; the choice between subjective listing or researching objective natural divisions. Berita Sedimentologi, 49 (2), 28 – 55.

Lunt, P. and Luan, X., 2024a. The importance of process in modern tectonostratigraphy and regional geology. Berita Sedimentologi, 49 (3), 1 – 17.

Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. Proceedings from Proceedings II Planktonic Conference: 739-785

Matenco, L.C., and Haq, B.U., 2020. Multi-scale depositional successions in tectonic settings. Earth-Science Reviews 200, 102991
DOI: 10.1016/j.earscirev.2019.102991

McArthur, J.M., and Howarth, R.J., 2004. Strontium Isotope Stratigraphy. In: F. M. Gradstein, J. G. Ogg, & A. G. Smith (Eds.), A Geologic Time Scale 2004, 96-105. Cambridge: Cambridge University Press.

McMonagle, L.B., Lunt, P., Wilson, M.E.J., Johnson, K.G., Manning, C., and Young, J., 2011. A re-assessment of age dating of fossiliferous limestones in eastern Sabah, Borneo: Implications for understanding the origins of the Indo-Pacific marine biodiversity hotspot. Palaeogeography, Palaeoclimatology, Palaeoecology 305, 28-42

Meckel, L.D., 2013. Exploring a 19th Century Basin in the 21st Century: Seeing the North Sumatra Basin with New Eyes. Search and Discovery Article #10464,

Meckel, L.D., Gidding, M., Sompie, M., Banukarso, M., Setoputri, A., Gunarto, M., Citajaya, N., Abimanyu, A., and Sim, D.,

2012. Hydrocarbon systems of the offshore North Sumatra basin, Indonesia. Proceedings from Indonesian Petroleum Association: 36, 1-11.

Miall, A.D., 1992. Exxon global cycle chart: An event for every occasion. Geology 20, 787-790.

Miall, C.E., and Miall, A.D., 2002. The Exxon factor: The Roles of Corporate and Academic Science in the Emergence and Legitimation of a New Global Model of Sequence stratigraphy. The Sociological Quarterly 43(2), 307-334.

Morley, C.K., 2016. Major unconformities/termination of extension events and associated surfaces in the South China Seas: Review and implications for tectonic development. Journal of Asian Earth Sciences 120, 62-86
DOI: 10.1016/j.jseaes.2016.01.013

Morley, R.J., 1998. Palynological evidence for Tertiary plant dispersals in the SE Asian region in relation to plate tectonics and climate. In: R. Hall & J. D. Holloway (Eds.), Biogeography and geological evolution of SE Asia, 211-234. Leiden, The Netherlands: Backhuys Publishers.

Morley, R.J., Hasan, S.S., Morley, H.P., Jais, J.H.M., Mansor, A., Aripin, M.R., Nordin, M.H., and Rohaizar, M.H., 2021. Sequence biostratigraphic framework for the Oligocene to Pliocene of Malaysia: High-frequency depositional cycles driven by polar glaciation. Palaeogeography, Palaeoclimatology, Palaeoecology 561, 110058
DOI: 10.1016/j.palaeo.2020.110058

Morrison, K., and Wong, C.L., 2003. Sequence stratigraphic framework of Northwest Borneo. Geological Society Malaysia Bulletin 47, 127-138

Muchlis, and Elders, C., 2020. Structural style of the North Sumatra basin, offshore Aceh. Proceedings from IOP Conf. Ser.: Mater. Sci. Eng. 796 012038: 1-7

Müller, C., 1991. Biostratigraphy and geological evolution of the Sulu Sea and surrounding area. In: E. Silver, C. Rangin, & M. T. von Breymann (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, Vol 124, 121-131. College Station, Texas: (ODP Program).

Osli, L.N., Shalaby, M.R., and Islam, M.A., 2021. Source rock characteristics and hydrocarbon generation potential in Brunei-Muara district, Brunei Darussalam: a comparative case study from selected Miocene-Quaternary formations. Journal of Petroleum Exploration and Production 11, 1679-1703

Pindell, J., Graham, R., and Horn, B., 2014. Rapid outer marginal collapse at the rift to drift transition of passive margin evolution, with a Gulf of Mexico case study. Basin Research 26(6), 701-725 *DOI: 10.1111/bre.12059*

Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988. Eustatic controls on clastic deposition; I-conceptual framework. Sea-level changes; An integrated approach SEPM Special Publication 42, 109-124 *DOI: 10.2110/pec.88.01.0109*

Posamentier, H., W., and Allen, G., P., 1993. Variability of the sequence stratigraphic model: effects of local basin factors. Sedimentary Geology 86, 91-109

Rangin, C., 1989. The Sulu Sea, a back arc basin setting within a Neogene collision zone. Tectonophysics 161, 119-141.

Rumsfeld, D., 2002. DoD News Briefing – Secretary Rumsfeld and Gen. Myers. United States Department of Defense. http://archive.defense.gov/Transcripts/Transcript.aspx?TranscriptID=2636

Ryacudu, R., Djaafar, R., and Gutomo, A., 1992. Wrench fauting and its implications for hydrocarbon accumulation in the Kuala Simpang area - North Sumatra. Proceedings Indonesian Petroleum Association Convention 21, 1-24.

Saller, A., Armin, R., Ichram, L.O., and Glenn-Sullivan, C., 1992. Sequence stratigraphy of Upper Eocene and Oligocene limestones, Teweh area, Central Kalimantan. Proceedings from Proceedings Indonesian Petroleum Association Convention: 21, 69-92.

Silver, E.A., and Rangin, C., 1991. Leg 124 Tectonic synthesis. In: Proceedings of the Ocean Drilling Program, Scientific Results Vol 124, 3-9.

Smith, R.B., and Silver, E.A., 1991. Geology of a Miocene collision complex, Buton, eastern Indonesia. Geological Society of America Bulletin 103(5), 660-678
DOI: 10.1130/0016-7606(1991)

Snedden, J.W., and Liu, C., 2010. A compilation of Phanerozoic sea-level change, coastal onlaps and recommended sequence designations. Search and Discovery Article #40594,

Stanford, J.D., Hemingway, R., Rohling, E.J., Challenor, P.G., Medina-Elizalde, M., and Lester, A.J., 2011. Sea-level probability for the last deglaciation: A statistical analysis of far-field records. Global and Planetary Change. Rapid climate change: lessons from the recent geological past 79(3), 193-203
DOI: 10.1016/j.gloplacha.2010.11.002

Szarek, R., Kuhnt, W., Kawamura, H., and Kitazato, H., 2006. Distribution of recent benthic foraminifera on the Sunda Shelf (South China Sea). Marine Micropaleontology 61, 171-195

Szarek, R., Kuhnt, W., Kawamura, H., and Nishi, H., 2009. Distribution of recent benthic foraminifera along continental slope of the Sunda Shelf (South China Sea). Marine Micropaleontology 71, 41-59

Tampubolon, R.A.T., Purba, H., Diria, S.A., Jaya, I., Setyowaty, T.P., Nusantara, Y.P., Wicaksono, A.B., Hidayatillah, A.S., Basundara, A.H., Darman, H., and Trivanty, J., 2018. Reassesment of the tectonic, paleogeography and geochemistry in Mergui and North Sumatra Basin. Proceedings Indonesian Petroleum Association Convention 42, 20.

Tsukada, K., Fuse, A., Kato, W., Honda, H., Abdullah, M., Wamsteeker, L., Sulaeman, A., and Bon, J., 1996. Sequence stratigraphy of the North Aceh offshore area, North Sumatra, Indonesia. Proceedings from Proceedings Indonesian Petroleum Association Convention: 25, 29-41.

van der Vlerk, I.M., and Postuma, J.A., 1967. Oligo-Miocene Lepidocyclinas and planktonic foraminifera from East Java and Madura. Proceedings of the Koninklijke Nederlandse Academie van Wetenschappen 70(B), 392-399.

Wang, P., Min Qiubao, and Bian Yunhun., 1985. Foraminiferal biofacies in the northern continental shelf of South China Sea. In Wang Pinzin (Ed.), Marine Micropaleontology of China, 151-175. Guangdong: Guangdong Science and Technology Publishing House.

Wannier, M., 2009. Carbonate platforms in wedge-top basins: An example from the Gunung Mulu National Park, Northern Sarawak (Malaysia). Marine and Petroleum Geology 26, 177-207.

Webster, J.M., Braga, J.C., Clague, D.A., Gallup, C., Hein, J.R., Potts, D.C., Renema, W., Riding, R., Riker-Coleman, K., Silver, E.A., and Wallace, L.M., 2009. Coral reef evolution on rapidly subsiding margins. Global and Planetary Change 66, 129-148.

Westerhold, T., Marwan, N., Drury, A.J., Liebrand, D., Agnini, C., Anagnostou, E., Barnet, J.S.K., Bohaty, S.M., De Vleeschouwer, D., Florindo, F. et al., 2020. An astronomically dated record of Earth's climate and its predictability over the last 66 million years. Science 369(6509), 1383-1387.
DOI: 10.1126/science.aba6853

White, N., and McKenzie, D., 1988. Formation of the "steer's head" geometry of sedimentary basins by differential stretching of the crust and mantle. Geology 16, 250-253.