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Indonesian Journal of Sedimentary Geology

A scientific Journal published by Indonesian Sedimentologists Forum (FOSI), a commission of the Indonesian Association of Geologist (IAGI)

Berita Sedimentologi was first published in February 1996 as a newsletter for the members of the Indonesia Sedimentologists Forum (Forum Sedimentologiwan Indonesia or FOSI) only. In its first year, Berita Sedimentologi was published in Indonesian language, then from 1997 onward this publication uses English as the language of communication.

Frequency of publication is 3 issues per year, usually published in April, August and December of each year.

Topics cover sedimentology and stratigraphy of both siliciclastic and carbonate rocks, depositional processes, but also cover biostratigraphy, geochemistry, basin analysis, geodynamics, petroleum geology and structural geology.

From the Editor

Dear Readers,

This is going to be my last "*From the Editor*" column for **Berita Sedimentologi** as I'm stepping down from Editor-in-Chief role beginning in early 2024. Having served Berita Sedimentologi since around 2011, I finally can pass the Chief Editor role on to **Dr. A.M. Surya Nugraha**, one of our young research geoscientists of international caliber. Dr. Nugraha has served Berita Sedimentologi as an Associate Editor for several years so I'm sure that our journal will be in a safe hand. His strong research background will be of benefit to improve the quality of our publications.

On this occasion I also want to inform you that **Dr. Tom Reijers** has decided to retire from serving Berita Sedimentologi as one of our External Reviewers. Over the years, Dr. Reijers has been instrumental in helping us to review manuscripts particularly those related to carbonate rocks. On behalf of Berita Sedimentologi Editorial Team and FOSI, I would like to thank Dr. Reijers for his time and support. We are really grateful to have him as a reviewer and would like to wish him well during this retirement.

Last but not least, as always, I would like to invite all readers to share their research through publication in Berita Sedimentologi. We accept manuscripts of quite wide topic ranges, from sedimentary geology to basin study and petroleum geosciences. We welcome research articles, review articles, short communication notes and field trip reports. Expected manuscripts can be in the form of an extended abstract with a minimum of 4 pages including figures, or a full manuscript. Please contact one of our editors to express your interest in submitting your work to Berita Sedimentologi. Bye for now and take care!

Minarwan
Editor-in-Chief

Cover Photograph:

Highly folded deep sea slope deposit of Pulaubalang Fm. Kutei Basin, consisting of alternating very fine-grained sands, silts and shales. The straight ripple suggests water depth of ca. 600-700m (photo by courtesy of Erlangga Septama).

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About FOSI

The forum was founded in 1995 as the Indonesian Sedimentologists Forum (FOSI). This organization is a communication and discussion forum for geologists, especially for those dealing with sedimentology and sedimentary geology in Indonesia.

The forum was accepted as the sedimentological commission of the Indonesian Association of Geologists (IAGI) in 1996. About 300 members were registered in 1999, including industrial and academic fellows, as well as students.

FOSI has close international relations with the Society of Sedimentary Geology (SEPM) and the International Association of Sedimentologists (IAS).

Fellowship is open to those holding a recognized degree in geology or a cognate subject and non-graduates who have at least two years relevant experience.

FOSI has organized three international conferences in 1999, 2001 and the most recently in 2018.

Most of FOSI administrative work will be handled by the editorial team. IAGI office in Jakarta will help if necessary.

The official website of FOSI is:
http://www.iagi.or.id/fosi/

FOSI Membership

Any person who has a background in geoscience and/or is engaged in the practising or teaching of geoscience or its related business may apply for general membership. As the organization has just been restarted, we use **LinkedIn** (**www.linkedin.com**) as the main data base platform. We realize that it is not the ideal solution, and we may look for other alternative in the near future. Having said that, for the current situation, LinkedIn is fit for purpose. International members and students are welcome to join the organization.

FOSI - Indonesian Sedimentologists Forum

ABOUT THIS GROUP

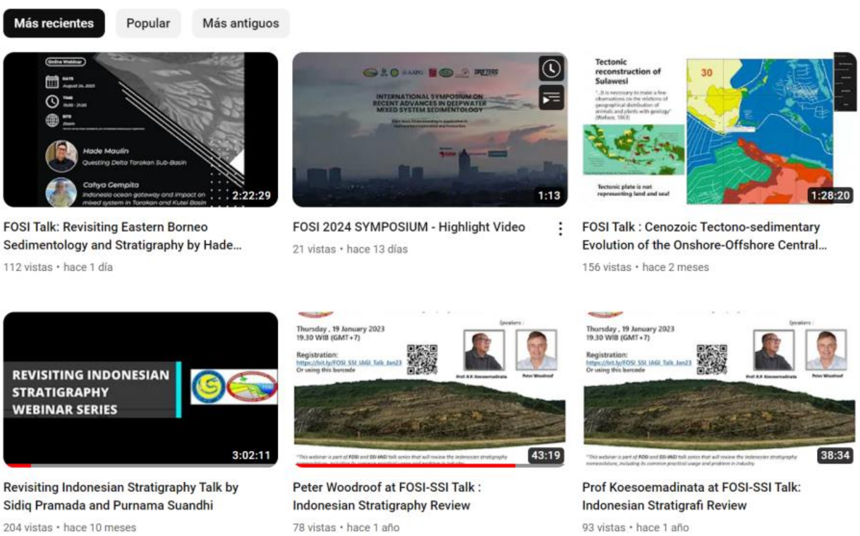
FOSI was established in 1995 and became a commission of IAGI (Ikatan Ahli Geologi Indonesia/Indonesian Geologists Association) few years later. The association is aimed as a discussion forum for Sedimentologists in Indonesia, to share experience and knowledge amongst the members. Through the network with international organizations, such as SEPM and IAS, FOSI tries to put Indonesian sedimentary geology into broader perspective.

FOSI Group Member as of February 2024:

1,029 members

Including Yudistira Effendi and 221 other connections

Visit FOSI's youtube channel at https://www.youtube.com/@fosiiagi1954 to watch recording of recent online webinar!



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The importance of process in modern tectonostratigraphy and regional geology

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ABSTRACT

In its simplest form geology is a history, which appears to only require the compilation of a chronicle. However, our data is fragmentary, and aspects such as the dimension of time and the depositional setting of sediments are obscured, especially the correlation of time over wide areas and determining rates of change. As a result, geology cannot advance just by accumulating observations, expecting that a credible narrative will inevitably emerge. There must be reality checks on the proposed history to avoid confirmation bias towards over-simple expectations. In a region suspected to be complicated and, in many ways, unique we require an abductive investigative technique to reconstruct its history. This means to force testing through cross-checking independent but related data types. Such inter-disciplinary testing can produce a rigorous framework, even to reconstruct special situations not accommodated by ideas models. This essay examines three topics necessary for such evidence-based investigation. The first is to investigate and document the reliability of observations (like the "error-bars" required in hard-sciences). Secondly is the shift from model-based to evidence-based processes (from deductive to abductive reasoning). Thirdly is the need to consider if conclusions are "significant" - i.e., is there confidence that an interpretation would be repeatable by independent workers, as well as being distinct from background variability in data. It is proposed that we must acknowledge the replication crisis highlighted in the past two decades in other sciences by considering how we work in the complex geology of SE Asia, to prevent a similar validation crisis undermining the value of the science here.

Keywords: *tectonostratigraphy, regional geology, abductive investigative technique*

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INTRODUCTION

This is the second in a series of related essays on the general properties of geological studies in the dynamic setting of SE Asia. The first examined the application of names in a science rich in nouns and jargon (Lunt and Luan, 2023).

There seems to be an unstated assumption that as more data is gathered it will inevitably trend towards better conclusions. However, other sciences have raised an alarm on this topic, so here we attempt to outline concerns on the possible misuse of process in Asian geology. The work of Ioannidis (2005) led to recognition of the so-called "replication crisis" in experimental sciences, as documented by Baker (2016) and discussed in general magazines (e.g., New Scientist, 6 April 2022). The term p-hacking came out of this reflection on mostly accidental misuse of processes, as did the related term HARKing (Hypothesizing After Results are Known; Kerr, 1998), which highlights a combination of confirmation bias and cherry-picking to match a new model or hypothesis on the assumption that the new hypothesis (or technology) must be right. A form of HARKing is sometimes relevant in exploration geology when new technology presents visually impressive, often expensive results, and data is then arranged to support a positive interpretation. Instead, it might have been better asking if the whole process might have been a waste of resources to reach nothing outside a null-hypothesis, or beyond a simple tautology.

Previous examples of the examination of process in stratigraphic geology include the discussion of the hermeneutic cycle by Miall and Miall (2004), which were attempts to balance the empirical (inductive) stages of reasoning with deductive stages from a theoretical model or a current paradigm/framework. As both approaches can be flawed, the hermeneutic cycle is a process of repeatedly moving between the two contrasting ways of reasoning to bring about meaningful, self-checking application and advance. What is proposed here is an adaptation of this approach for tectonically active areas, which exploits the excellent biostratigraphy in SE Asia from tropical Cenozoic micropalaeontology. As noted by Miall and Miall "*But if there is any lesson that two centuries of geological investigation since the days of William Smith have taught us, it is that* ***biostratigraphy is the ultimate arbiter of chronostratigraphic correlations****. The literature is full of lithostratigraphic correlation schemes that have failed because of insufficient attention to biostratigraphy. … Blindly correlating stratigraphic events to the outdated onlap-offlap curve of Haq et al. (1987, 1988) without determining whether biostratigraphic data support their correlations, continues the trend of poor science.*" (their emphasis). In SE Asia the excellent micropalaeontology means we can also add tests from examining facies shifts and Walther's Law, an application that greatly extends the usual tools of biostratigraphic correlation and age dating.

It is proposed that SE Asia requires a repeatedly inductive hermeneutic cycle. That is, the excellent facies and age data is used along with lithostratigraphy, seismic and other data, to induce new concepts, but this is followed by a stage of extending induction into related disciplines. This is a deliberate search for tests of concepts in the adjacent data sets, also known as abduction; or the forcing of resolution through tests (abducere means to lead or force through). Abductive reasoning is strictly a ranking of plausibility between what geologists would call multiple working hypotheses (the latter being an idea developed by the 19th century geologist T. C. Chamberlin). Once a single hypothesis stands out as the most reasonable, it becomes the updated geological framework (a multi-disciplinary hypothesis; distinct from a conceptual model) and this framework can be temporarily used for deduction. However, the cycle of investigation is then repeated by deliberately obtaining new data that is designed to test, and not just confirm, the framework. This process of deliberately forcing integration of related disciplines will both test existing concepts as well as potentially highlight any anomalies that can lead to paradigm shifts.

An example from the region of an entrenched "fact", presented as an ideal model, that is being overturned by considering related fields of investigation is from the top of the Belaga Formation, outcropping widely across onshore Sarawak. This is considered to be almost phyllitic basement (Liechti, 1960; Petronas, 1999) and is dated as Palaeocene to Late Eocene in age, terminated by the regional Rajang Unconformity; the primary stratigraphic division of the Cenozoic stratigraphic record across western Borneo. Searching out the few old wells offshore Sarawak that drilled into equivalent marine claystone finds data from independent discipline that challenges the concept of metasedimentary basement capped by a major scale break in the geological record. The clays in these wells have sonic log values of around 80µsecs/ft (only moderate compaction), and thermal maturity indicators (spore colour and vitrinite reflectance) that were the same as the overlying Oligocene Cycle I sediments. In 2023 geologists working for Petroleum Sarawak Berhad (Petros) decided that the sonic log and thermal maturity data were reliable and carried out new fieldwork onshore, confirming that the concept of the Rajang Unconformity is a massive over-simplification of a much longer lasting and complex transition, which no longer includes the upper Belaga Formation as economic basement for hydrocarbon exploration. The results of this fieldwork are not yet published, but the key point here is that independent data from non-stratigraphic analyses forced a "*back to the drawing board*" re-examination of a long accepted, idealised concept. Such an advance in science is outside the scope of model-based deductive studies.

The abductive approach is therefore an evidence and test-rich process, which specifically anticipates that the complex and unique history of a tectonically active basin cannot be reliably predicted by an ideal, tectonically passive model. For sedimentary geology there is a fundamental difference in that in tectonically active basins the relative sea-level, and hence sediment accommodation space and sediment supply, do not change in a geographically even fashion, as would be expected from eustatic or epeirogenic sea-level changes (e.g., Matenco and Haq, 2020). Instead, the rapid tilting and movement of both depocenters and hinterland architecture can change in ways that could not be predicted from passive margin type models. Many times, in SE Asia such changes were very rapid and they became the primary tectono-stratigraphic divisions, but they require a specific mode of study.

In contrast to Matenco and Haq (2020) the method proposed here does not seek to define a "*first-principle conceptual model*" but instead it seeks a way to study the predictable properties of the possibly unique tectono-stratigraphic framework. For this the role of Walther's Law is important, and the derivative that at major unconformities the palaeogeography of the tectonic movement will be related to the contrast in facies across the unconformity.

COMPONENTS OF THE NEW METHOD

There are three parts to the application of the new method (it is the traditional approach of geologists, slightly updated). The first is quality control on inputs, and the second is the actual shift from model-based to evidence-based processes, and thirdly is the application of a null hypothesis test. This third part does not necessarily come at the end and should also be applied to intermediate interpretations of individual disciplines. In the following paragraphs the reliability of data is discussed, with examples that challenge simple model-based thinking.

The shift in emphasis from model to evidence highlights the importance of questioning input data, current paradigms and the need to repeatedly test ideas. This high level of scepticism contrasts with the deductive, model-based approaches, where it is assumed that both the guiding model is established and trustworthy, and also that a new study will give a result that resembles the ideal model. In such studies it is common practise to accumulate data with some redundancy so that a modal value will appear, and bad data (e.g., biostratigraphy from caved fossils in drill cuttings samples etc.) be deviants on the edge of the bell-curve predicted by the ideal model. The workflow is designed only to deduce from the model, and so if reality deviates from such expectations, it is unlikely to be recognised. For example, biostratigraphy analysis looking for cyclicity reflecting high and low stands in sea-level has a simple format seeking to spot acmes of transgression that are candidates for maximum flooding surfaces. In North Luconia, however, the wells encounter a hemipelagic, globigerina marl up to a hundred metres thick that has the regional Doust MMU at its base. This is a singular flooding event an order of magnitude greater than the anticipated smaller and repeated eustatic events. Not only is this stratigraphic unit then outside the model considered by sequence stratigraphers, but its presence impacts the workflow applied to the thick section below the marl. This abundantly micro-fossiliferous marl facies caves into cuttings samples from the poorly fossiliferous siliciclastic section below, drowning out the very different in-situ fauna. As a result, expensive sidewall core samples are required to carry out palaeontology below the unconformity, and one such sidewall core in this deeper section is more valuable (much higher ranking of reliability) than multiple drill cutting samples from a similar depth. Such ranking of samples for quality is part of the evidence-based method, but it deviates from the deductive workflow that assumes eustasy and passive basin conditions. It can be argued that good workers following eustatic-based workflows can accommodate such local anomalies. However, in doing so they are already moving from simple deduction to abduction, and the best approach is to continue an examination of this major stratigraphic event (Doust MMU) that dwarfs any smaller cycles that the model assumed had controlled stratigraphy. The eustatic model did not predict this major stratigraphic event, so what else might it have missed? To reduce this to a single sentence; model-based deduction is naturally prone to confirmation bias, but abduction is necessarily sceptical and wants to test the empirical framework.

The danger of confirmation bias in using a stratigraphic model with a simple binary polarity (such as accommodation space either increasing or decreasing), and which specifically assumes a constant location for the hinterland and the depocenter (see Posamentier et al., 1988), has already been highlighted by Miall (1992) and Miall and Miall (2002). The conditions found in an area such as North Luconia indicate that this is a tectonically active basin and calls out for both scepticism and a different approach, using different reasoning, to answer new questions and avoid confirmation bias.

PRECISION, ACCURACY, AND TRUENESS FROM EXAMPLES

Observations in geology must be ranked for what other sciences present as measurement error bars. However, in geology these are usually two or three independent dimensions of precision, accuracy and trueness (see below). That such basic quality controls are overlooked may surprise other scientists reading geology, but while a so called "hard-science" paper would be rejected for not including observation error-bars, this type of documentation is invariably absent from geology reports. Error bars and precision in naming conventions are discussed in the first essay in this series (Lunt and Luan, 2023), but here some more applied examples are given.

Figure 1 is from a well report in SE Asia just over ten years old and is quite typical. This well drilled a reefal objective, originally deposited close to sea level. Perhaps the most important information from the well samples is the contrast between the reef (mainly its age), and the age of the overlying siliciclastic that contain outer neritic to bathyal microfossils (right-hand columns on Figure 1). There is assumed to be missing stratigraphic section after the termination of the reef, while the reef flanks were being onlapped. Yet the technical report containing the original of Figure 1 misses this, and logs deep marine conditions to total depth as well as the same nannofossil zone. Note that Zone (NN9) lasted almost exactly 1 million years (Gradstein et al., 2012), so a very rapid transition from shallow to deep marine (in less than a million years) is directly implied if the marker fossils in drill cuttings below the top of the limestone are in situ. Clearly there is much clarification needed on the reliability of the analyses that went into this commercial report.

We propose that this lack of scientific discipline and analytical rigour is a product of our over-reliance on models, rather than data, to guide our thinking. The real well example in Figure 1 can be correlated to outcrops onshore and other wells in this play, and the reefal limestone should contain a diverse suit of carbonate facies, larger foraminifera that became extinct at the top of Letter Stage Lower Tf (older than about 12 Ma). No larger foraminifera were looked for in the limestone drilled by the well (three drill cuttings samples examined). Confirmation of a Lower Tf age for this high relief pinnacle, perhaps refined by strontium dating, would have greatly improved our understanding that a reef subsided to deep marine conditions a little before 12 Ma, and then the flanks were onlapped up to the crest all before a time between 10.5 to 9.5 Ma when the NN9 clays covered this location. A simple change to workflow would have resulted in a better description of both very rapid and high magnitude (many hundreds of meters subsidence) tectono-stratigraphic change. Reporting aspects of reliability in this case would consist of highlighting the type of sample examined, and cross-referencing the appropriate, facies-related biostratigraphy and strontium dating, matching correlatable instances nearby, as well as citing the reliability of fauna indicating outer neritic to bathyal conditions as well as a geohistory plot that would also indicate limits for the magnitude of new accommodation space that had been generated by the reefal subsidence. This mid Middle Miocene reef crest is currently over two kilometres below modern sea-level. Geohistory analysis would begin to quantify how much of this was isostatic response to later sediment loading, and analysis of the siliciclastic fill would help identify if the tectonic component of subsidence was mostly active at the termination of the reefal facies.

Munging data

In addition to the evaluation of sample quality, geological context, and general quality control on analytical methods, there is a need to be aware of a related but opposite effect when reading reports. This has the slang name of "munging", also known as data wrangling. This is the process of converting data into another format, often as a precursor to data integration (originating in computer sciences). This is often a desirable and necessary step, such as converting the depths of fossil datums from biostratigraphy in a well to a time scale for use in geohistory or basin modelling. There is a long-recognised risk which reflects the

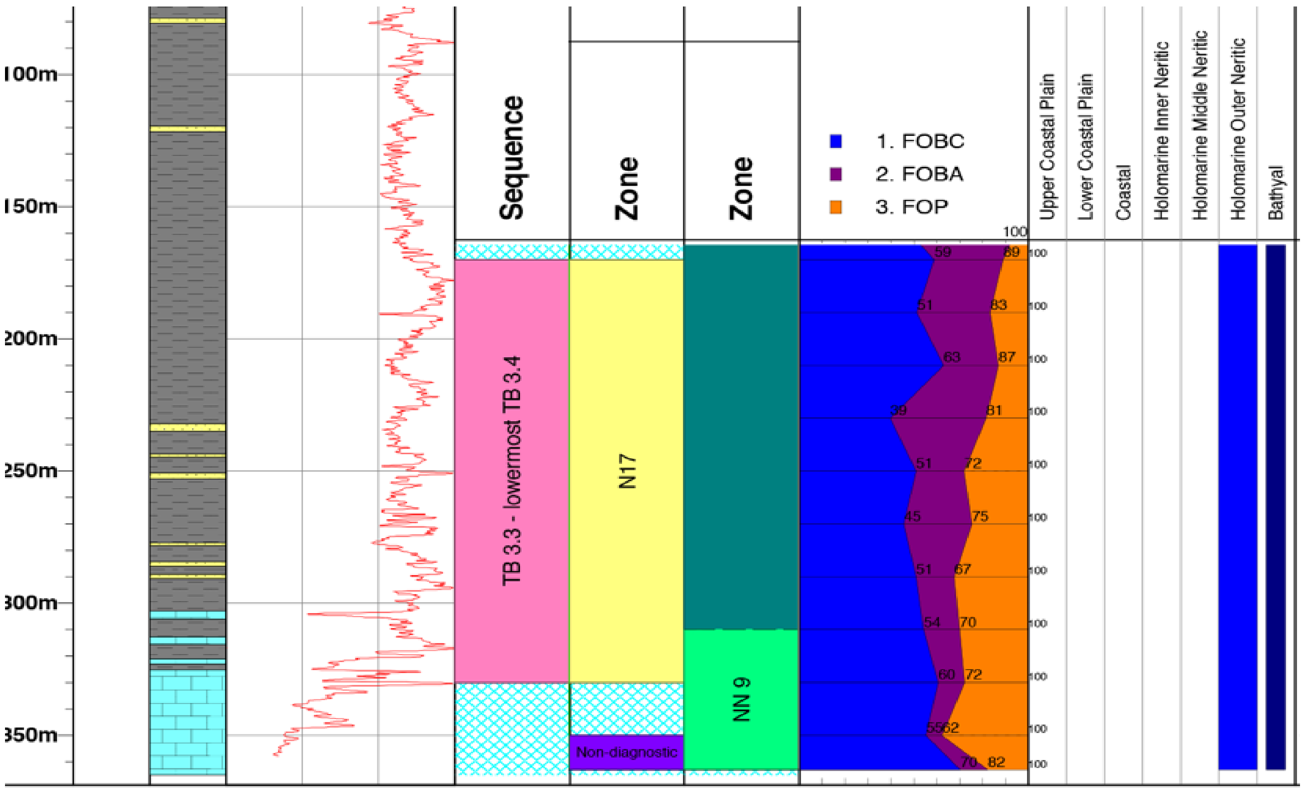

Figure 1: *A 2008 well (actual report data but cropped to disguise source) showing complete lack of consideration of data reliability. This type of example in is not unique, or even rare. No larger foraminifera were looked for in the limestone. A well a few tens of kilometres away and outcrops onshore have an assumed equivalent limestone with Lower Tf foraminiferal faunas, and these are overlain by only very slightly younger siliciclastic with deep marine microfossils.*

supposed origin of the term; that the name is derived from acronym "Mash Until No Good". Hence munging is a colloquial term used to flag data that may have been "corrected" prior to input into a database, but in changing it is rendered useless or misleading.

Figure 2 is from a real well in SE Asia. On the right is the column from the final well report with lithostratigraphy and the operator's report of the environment of deposition in words. On the left is the analysis report, flagging that the work was based on sidewall cores. Examples like this are not uncommon, but this one was chosen because analyses were based on sidewall cores. The operator's column on the right side first "munges" the uppermost sands into a shallower environment of deposition, just below the modern seafloor of about 60 m water depth, even though these sands are not sub-Recent but below a regional unconformity. That is, the text on the right side contradicts the SWC analyses that directly indicated bathyal "upper slope" or "lower slope" in the middle part of the diagram. The sands in the middle of the well are marked by a question mark, which is still munged data as quite clearly there is no evidence for anything other than very deep marine conditions. As with the example given in previous paragraphs, such poor-quality control is common in both commercial and academic reports, and such misrepresentations are then re-cited and become accepted. This is symptomatic of a migration away from analytical data. It can only be assumed that such workers assume that some larger model will guide interpretation, as they are certainly not looking to the evidence to test geological ideas.

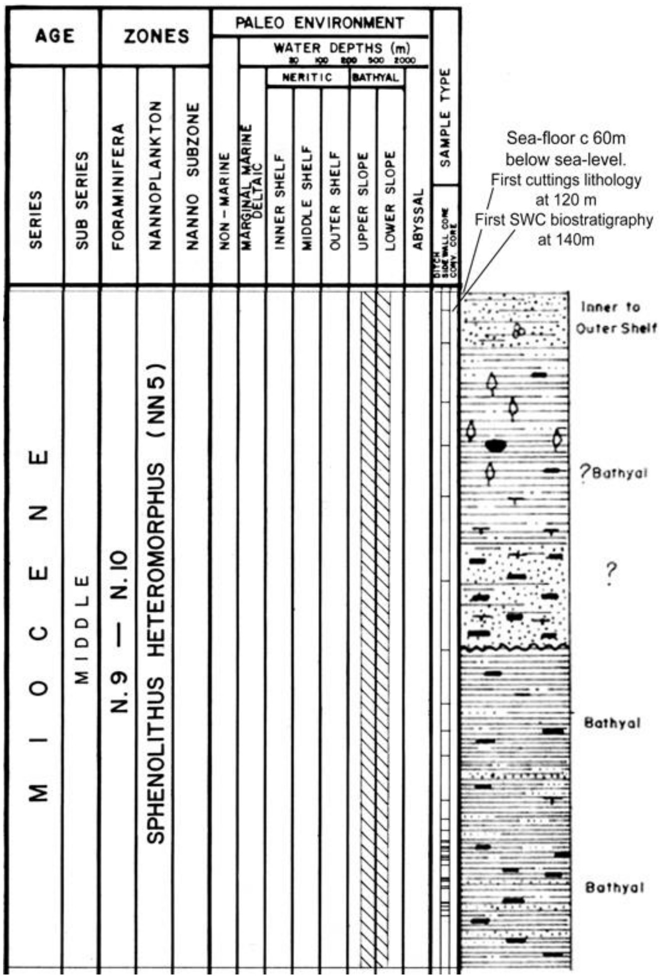

Figure 2: *A disguised real well, with final well report summary column on the right, and the micropalaeontology summary on the left, with a column indicating that analyses were from sidewall cores. The top of the lithology column shown is 60 metres below the modern sea floor.*

WHEN OLD SCHOOL ANALYSES TRUMP HIGH TECH METHODS

Depending on the type of analysis, the dimensions of precision and accuracy may overlap. However, the following is an example that has measurement precision, distinct from accuracy, as well as trueness. Figure 3 is updated from Luan and Lunt (2022) for strontium isotopic dating in the north Madura area off eastern Java, constrained by biostratigraphy, including the mass extinction of forms at the Eocene-Oligocene boundary that is well recognised and well dated (33.9 Ma Premoli-Silva & Jenkins, 2006). This could be used as an example of HARKing (Kerr, 1998) as the apparently precise data yielded by the new, and expensive, high-tech method of strontium isotopic dating was inadvertently assumed to be "better" than old-school biostratigraphy, and a new regional stratigraphic correlation was

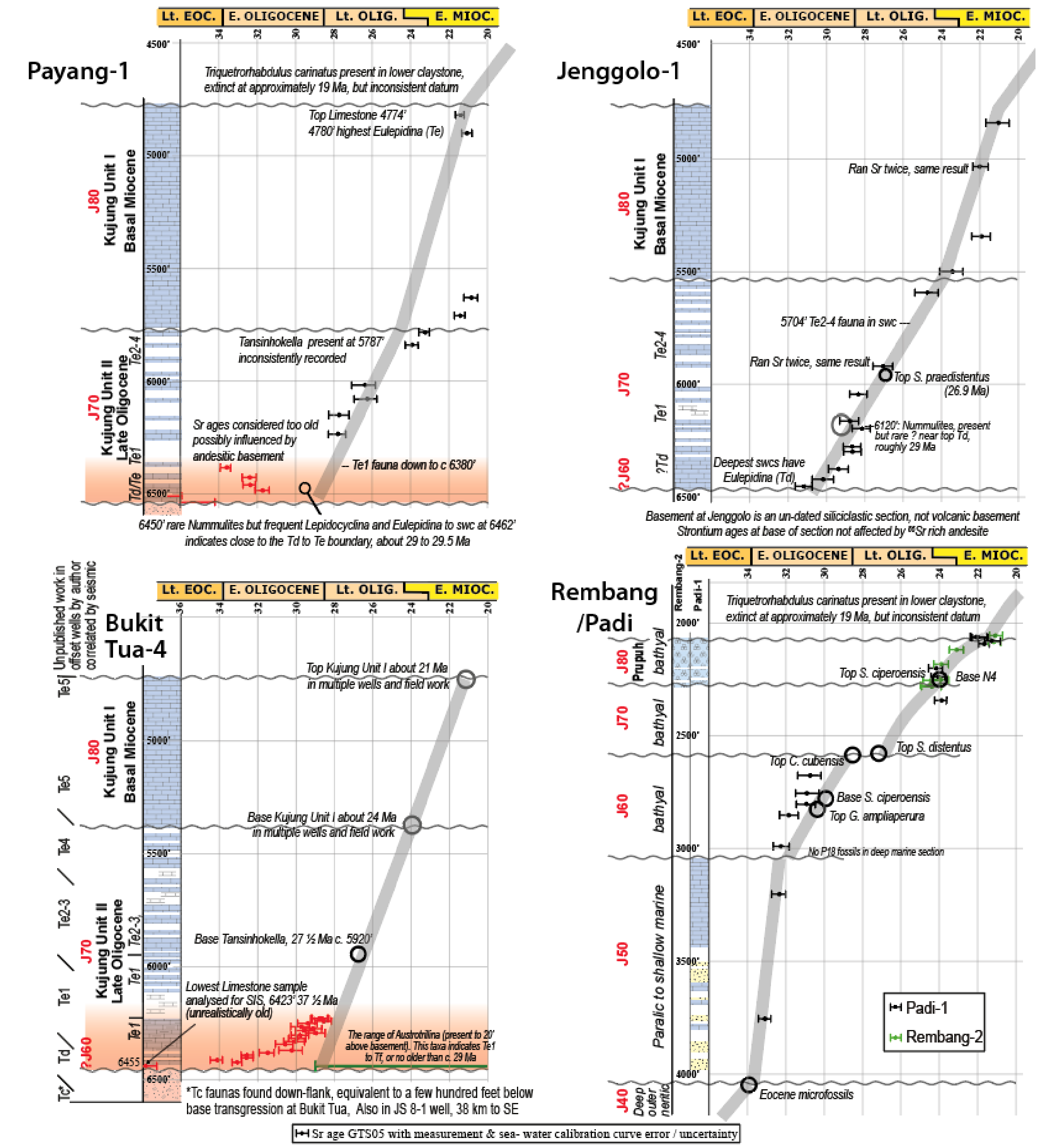

Figure 3: *Summary of strontium dating in North Madura wells (modified from Luan and Lunt 2022). This summary of strontium dating shows the independent dimensions of precision (usually high), accuracy (repeatability; also, apparently high) but low trueness in the wells drilled over andesitic volcanics, indicated by the orange shading. The error bars on the data points are the mass-spectrometer measurement precision.*

integrated to reflect this (Maynard and Morgan, 2005).

Sidewall core and core samples to within a few metres of the basement unconformity contain mid Oligocene foraminifera and lack the Eocene foraminifera predicted by strontium dating in some wells. Bukit Tua-4 has a coherent trend of many Sr ages through the entire Early Oligocene and well into the Eocene that have good machine measurement precision, and both the trend and close spacing of adjacent samples suggests good accuracy. However, from biostratigraphy we know this cannot be true. No other record in the world has species that became extinct at the end-Eocene "Grand Coupure" paleontological event, surviving in some niches for several millions of years into the Oligocene. The Jenggolo-1 shown on the upper right is also from north Madura but located over metasedimentary basement, and this well has a combination of strontium and biostratigraphy data that match each other (and seismic correlation to the palaeontology in the other wells). Lower right is a reference curve for tectono-stratigraphy through the entire Oligocene in eastern Java, where strontium and biostratigraphy again closely agree, although the machine precision of the strontium data is scattered (lower accuracy) and locally outside the measurement range. The biostratigraphy datums marked are biassed to the best age datums.

The reason for failure in this test of trueness in the basal sections in Payang-1 and numerous Bukit Tua wells is thought to be the andesitic basement that is probably a source of ^{86}Sr. This seems to have permeated a few tens of metres into the overlying sedimentary section, reducing in its effect with distance from the source, and this has artificially changed the ^{87}Sr/^{86}Sr ratio to give a falsely old age.

THE NULL-HYPOTHESIS TEST

The definition in experimental sciences for statistical significance is the arbitrary P<0.5 (Fisher, 1925), or a that a result has less than a 1 in 20 chance of being a null value: where null means indistinguishable from just normal, random variation and "back-ground noise". Failure to consider a null-hypothesis test in non-experimental sciences is the equivalent of p-hacking in the experimental sciences (Simonsohn et al., 2013), or HARKing (Kerr, 1998), as all of these are the proposal of an arbitrary result or model, with selected facts being presented as a tested conclusion, when in fact no independent test occurred.

In the non-experimental sciences, which lack both controlled experiments and numerical data for statistics, the null-hypothesis test simply asks if an interpretation would stand out significantly from natural variation in data. This is usually a judgment call, such as agreement that if different workers, faced with the same data and same methods (training in sedimentology, geochemistry etc.), would almost always recognise a similar result. For example, the gamma ray log has long been used to distinguish clays (high gamma ray values) from sands, limestone, and the metal casing in a drill-hole (all low gamma). Before logging-while-drilling was used, the wireline gamma log was run multiple times in a hole section, first as a complete scan, but later as a tool on other logging runs to pick a depth-control point (a casing point or a distinct marker bed) so that all wireline logs were calibrated in depth. Such multiple gamma log runs are often slightly different from each other. This might be from the tool facing different parts of the hole on each run, as well as some background noise and variability. Patterns on one logging run, such as modest fining or coarsening trends of sediment, or individual gamma peaks as candidate flooding surfaces, might appear to be different on another run over the same section (often the case for small gamma log peaks). What passes the null hypothesis test is the lithostratigraphic pattern that an independent observer can agree as being distinctly outside this range of known observation variability.

This is the reverse of an appeal to authority. That is, once trained, a student would, for the most part, replicate the work of his tutor. In other words, no technique should require the trusted eye of the inventor to see the desired result. The schemes of biostratigraphy, for example, have been successfully transferred to multiple new generations. It is possible that poor training (such as lack of expertise in the specialised larger foraminifera) may produce some variation and degradation, but the evolutionary history of morphotypes considered species has been tested and documented, including the ranking of easier and more difficult to identify markers. This becomes peer review of an analytical method, after which, if an exceptional observation is encountered – such as a gap in ages at a suspected unconformity – it is more likely to be a stratigraphic feature than a null-type error in observation.

Concerns regarding distinction from a null hypothesis occur more in subjects that lack tested frameworks or cross-linking with related analyses (examples of cross-linked analyses include vitrinite reflectance with spore colour and logs measuring compaction or density; foraminiferal zones with nannofossils and Sr dating etc.). For example, while chemostratigraphy has had many successful applications, it rarely has such a unique signature that correlation between sites is incontrovertibly significant. Similarly, interpretation of gravity and magnetic anomalies are non-unique because multiple theoretical solutions are always possible, and distinction from a null interpretation usually relies on integration with geological data.

Without deliberately asking for faith based on authority, there is often subliminal pleading for confidence towards a favoured conclusion because it is “high-tech” or a new, ideal model from a reputable source. For example, the Exxon Cycles scheme was still a new technology when Miall (1992) warned of this potential failure in his paper “*Exxon global cycle chart: An event for every occasion*”, which showed how a simple binary character had a low likelihood of passing a null-hypothesis test. This was further elaborated with an example in Miall and Miall (2004) in a criticism of a correlation between Late Cretaceous sections in the Anglo-Paris Basin and in southeast India. The criticised work specifically set out to demonstrate that sea-level changes are globally synchronous and therefore must be eustatically controlled. The critique by Miall and Miall included the quote by Kuhn (1962) “*Results which confirm already accepted theories are paid attention to, while disconfirming results are ignored. Knowing what results should be expected from research, scientists may be able to devise techniques that obtain them.*”

This last sentence succinctly summarises the null hypothesis as a test to counter confirmation bias. Put another way, it might be possible to see the desired result in your data, and the more famous the expert the greater the confidence in such an interpretation, but if a peer with similar experience can interpret different results that are no less plausible, then the test has been failed. This is supposed to be one of the pillars of the peer review system, but selection pressures often means that data is presented in such a way as to make a single outcome the most obvious, or simply not mentioning that other equally viable interpretations are possible.

The experimental sciences developed a method to circumvent HARKing, by preregistering hypotheses to be tested prior to the experiment being carried out (see Kupferschmidt, 2018). This kind of rigour is usually not possible in the non-experimental sciences, although the third essay in this series (Lunt and Luan, 2024b), promoting the reformational idea of a paradigm shift, contains such an initial estimate of a new hypothesis for peer review. More often however, the test-rich and evidence-based abductive method enforces a similar rigour to eliminate unwarranted confidence in apparently attractive ideas.

USING WALTHER'S LAW AS A TEST

The excellent range of depositional facies present, and the tropical microfauna they contain, gives SE Asia an additional test of stratigraphic validity through Walther's Law. Perhaps the simplest example of this are the multiple breakup-like subsidence unconformities found at various times around SE Asia. In the sedimentary record there is a fundamental relationship we can exploit. For basins with thick, continuous deposition of a single facies or closely related facies groups (e.g. lower coastal plain to occasionally inner neritic), and then a step-like change to a much deeper – but often also rapidly deposited – bathyal claystone, such as the Agam or Ranong Formations abruptly overlain by Pirak or Yala Formations across north Sumatra and West Thailand area, then this vertical, step-like sedimentary record must reflect a step-like, sudden shift in sedimentary palaeogeography. This is Walther's Law, and the step-like facies shift has been named a non-Waltherian contact (NWC; Lunt, 2019a, b). At the event the entire sedimentary system withdrew, and it cannot leave a portion of a delta behind on some more slowly subsiding, isolated, submarine high. Similarly, any clays within the underlying Agam Formation, deposited before this event, cannot be classified as belonging to the Pirak Formation, and thereby drawn as an interdigitation of the two named lithofacies. Yet both in this basin and elsewhere such misinterpretations are frequently found in reports and publications. The presence of such a non-Waltherian contact in the four dimensions of space and time is a test of correlations, stratigraphic models and basin history. Such tests are significant in that if the facies data is correct, then biostratigraphic or seismic correlation cannot cross an NWC. Being based on a Law and not a theory, this is not an issue of interpretation where workers can agree to disagree.

THE ABDUCTIVE METHOD SUMMARISED

Abduction is the process of taking different inductively derived hypotheses, applying the data quality controls described above, then testing these hypotheses against each other and any existing geological framework. Continuing the example of the previous paragraph, a non-Waltherian contact can be dated with foraminiferal data, cross-checked by nannofossil and strontium data with the knowledge that no biostratigraphic correlation datum can cross the NWC, and that the NWC must have a facies shift reflected both in micropalaeontology and lithofacies (and be geographically variable in a mappable, meaningful pattern). All these independent disciplines, plus timing of fault activity, can be combined into a single historical framework. This, of course, was an established method of investigation until the key science of stratigraphy (which links facies in space and time) moved towards an inappropriate ideal model, and for many basins around SE Asia we lost track of the role of tectonic activity and its geographic variability.

The power of abduction is that it can study unique geological scenarios that are well outside ideal models. This might include drilling a feature that was predicted to be a reef but was then found to be a buried volcano. Simple induction changes from "*all pinnacle highs are reefs*" by adding the caveat *"… and some are volcanos*". That is, there is a numerical probability based on ratios of known data that any future well would find either a reef or a volcano. In contrast, abduction proposes hypotheses that volcanos should perhaps have a geographic trend, be of a certain age, be associated with feldspar-rich or tuffaceous sands of a certain age, that uplift during intrusion created shallowing around the flanks (associated with increased feldspar / tuffaceous sands). Abduction is the active leading or forcing of alternative hypotheses through a process of investigation from multiple independent disciplines.

In the case above, it is of course expected that researchers would naturally begin to ask about igneous activity after the first volcano was drilled, in order to prevent another commercial failure, and not just rely on an over-simple percentage risk. But in stratigraphy, with poor quality-controlled data such as in Figure 1 (a real well from an area with volcanic activity just older than the reefs), such critical questions are often not asked. In this example why, within a very short period of time, did such a series of reefs subside to very deep marine conditions? Deductive methods such as eustatic sea-level models cannot begin to tackle such unique questions. As pointed out by Lunt and Luan (2022) simply changing from a eustatic sea-level curve to a local relative sea-level curve fails to honour the scientific principles of both a model-based deduction and an evidence-based local "model". There are many widely cited papers that attempt to carry out such a compromise (e.g. Wong, 1993, Figure 22). Instead, workers must keep separate the model-based concepts while an evidence-based framework is established. The model-based concepts have assumptions that should not be accidentally applied to the empirical framework, such as geographically eustatic sea-level changes does not mean that tectono-stratigraphic changes to sedimentary siliciclastic are also evenly expressed across the basin (e.g. Wong, 1993, Figure 22). It is arguable that the geographic variability of tectono-stratigraphic sequence boundaries is their most important property. Continuing the example shown in Figure 1, mapping out this variability in the event that terminated a series of reefs would include a study of the outcrops located onshore from this well, which have not been visited by professional geologists since the mid 1960s. There it can be seen that reefs grew above sub-aerial volcanic beds, and the carbonates first slowly subsided to form pinnacle reefs, then rapidly subsided and drowned. The age of this rapid subsidence of multiple reefs appears to correlate with a regional subsidence event that is observed a few hundred kilometres further west, which was dated from biostratigraphy in the 1980s. However, in recent years a different age was mistakenly assigned to that western subsidence after miscorrelation with a eustatic sea-level event. That is, a failure to keep model-based assumptions separate from empirical data. The abductive process demands clarification of many geological topics, and ideally confirmatory new analyses. In contrast, the model-based deductive process survives, and even thrives, with less geological investigation.

This example of buried volcanos near reefs could be argued to be an exception (it was used here only as it followed on from the example chosen to illustrate the point in Figure 1), but the present authors have multiple papers across SE Asia with other exceptions to accepted, over-simplified, but regularly re-cited geology. Each is unique, as SE Asia is highly varied and complex, but all such examples have roots in data quality control and a paucity of independent tests. Rather than give multiple different examples of abduction it might be more beneficial to highlight two roles of abduction in geological studies in tectonically active basins; the first is more obvious and of less value, the second is harder to explain to non-geologists but it is where the greatest values lie.

First, abduction forces a greater degree of resolution and precision on the geological framework. Lunt (2021) demonstrated that an unconformity long considered base Cycle V in offshore west Sarawak was, in fact, overlain by Cycle IV limestones in several wells and therefore the unconformity was the base of Cycle IV (the Doust MMU), and this matched a simpler regional tectono-stratigraphic model. How important is that correction for the seismic pick for base Cycle V to base Cycle IV? A blunt answer is that nobody changes their opinion of an exploration prospect because of a revision and improvement to the regional geological framework. Seismic-dominated studies can be argued to satisfy the Pareto Principle of economics that implies roughly 80% of consequences come from 20% of causes, and that 80% of subsurface understanding can come from the single discipline of seismic interpretation, with the more abstract field of stratigraphic geology adding relatively minor commercial value. (This simple logic is slightly undermined by the relative costs of expensive seismic acquisition and processing, versus cheap well analytical studies.)

The second effect of abduction is the reverse of the 80:20 rule; that by forcing resolution of the geological framework an unanticipated divergence may appear, and we are forced to re-invent the geology. In such settings the low cost, abductive, analytical geology delivers 80% of the value, in an innovative paradigm shift that can lead to whole new geological concepts or exploration plays. Of course, this does not happen very often, but it is most likely after a prolonged period of stagnation. Details of some new concepts in SE Asian geology are presented in other essays in this series (Lunt and Luan, 2023; 2024b) as they are best discussed along with comments on data reliability. A short example of the principle is the mid Oligocene tectono-stratigraphic event in eastern Java, noted by Matthews and Bransden (1995) to have both localised uplift and subsidence visible on seismic. This movement was focused along a narrow geographic trend in the zone south of the Rembang Line, along almost all of Java to the Madura Straits (Luan and Lunt, 2021) where entire proto-petroleum systems were locally uplifted, slightly eroded and the tops of the structural highs then developed reefs during Late Oligocene through Early Miocene subsidence. Seismic data below this carbonate is poor but later Neogene burial led to source rock maturation, and sub-Kujung Limestone structural traps with sands are possible but have only once been deliberately drilled. This is the reverse of the established concept of Kujung reefs growing on ancient basement highs. It is also inconsistent with the concept of the trough under Java being an extensional back-arc basin.

Such changes to basic geology are not always going to yield new hydrocarbon prospects but they can radically change key exploration risks. For example, the Stage III (Early Miocene to early Middle Miocene) of west Sabah is on record as being deformed economic basement (Petronas, 1999), as is the Belaga Formation of Sarawak (see introductory section), but both these sedimentary sections are misunderstood due to over-simple descriptions of their bounding unconformities. Both have organic rich facies, locally oil seeps (in mis-dated outcrops), and in certain areas they retained low levels of thermal maturity until later Miocene burial.

Only evidence-based, abductive, geology can reconstruct such unique problems, and by definition this will lead to either new or strongly re-risked plays that are "*off the creaming curve*". This is oil industry slang for novel discoveries with potential for high value, as distinct from ever-smaller replicas of known hydrocarbon plays. In 1982 Michael Halbouty edited an AAPG memoir which outlined the importance of developing new concepts to find the next generation of hydrocarbons. However, if we cannot study, measure and predict the tectono-stratigraphic complexity of SE Asia sedimentary basins we cannot begin such a deliberate search. Modern seismic data is excellent, but in the decades taken to develop the acquisition, processing and display tools for this data we have neglected the natural geological framework in favour of a pastiche of science based on passive margin models that simply fail (do not match observed data) in many areas with oil seeps and unexplored sediments.

As noted above, this is not a wholly new method but rather a return to classical methods. The prose of van Bemmelen (1949) is rich in abductive thinking. It weighs up primitive sets of gravity and volcanic data with rudimentary stratigraphy and structural ideas (precision, accuracy and trueness of each observation). The Geological Survey in Malaysia was equally active until the mid 1970s with work such as Liechti (1960) through to Leong (1974), the latter author going into detail on why the Ayer and Kuamut Mélanges of east Sabah are extensional and not compressional deposits. However, since then an aggregation mentality has dominated geology – which assumes as more data is gathered, possibly in small increments, it will inevitably trend towards better conclusions. This is not the case as the process requires that specific hypothesis must be constructed, tested and re-formulated in a deliberate fashion. To compound this problem, academia and industry have moved towards the simpler, cheaper, deductive processes. For example, for thirty years the industry assumed it could deduce stratigraphy from a eustatic, or modified eustatic model, even though the largest candidate events such as the mid-Oligocene sea-level fall and near base Late Miocene sea-level fall have never been identified in the region (Saller et al., 1993, Matthews and Bransden 1995; Lunt, 2014; Morley et al., 2021).

Such prolonged stagnation in critical thinking (lacking repeated, independent testing of different observations), while old concepts are re-cited and become entrenched in our mental models, forms a barrier to the adoption of new processes. This is because a return to abductive critical thinking will first break-down familiar old concepts before re-building a new framework. To take only small steps along this path is a destructive process that will probably meet resistance in peer review, until it is widely recognised that a paradigm shift is in process. A following paper examines several features around

Sundaland to illustrate that that not only is a paradigm shift possible but that it well underway.

Conclusions

There is no reason to expect that the replication crisis in the experimental sciences does not also affect geology, where it might be better termed a validation crisis. In the non-experimental sciences the model-based approach mostly escapes testing because the source of deduction is an ideal model, which is assumed to be correct. In the earth sciences, especially in tectonically active basins where each area has a unique stratigraphic history, the only way to avoid a validation crisis is to define a framework (a documented geological account, not a conceptual model) and then seek to test it. What appears to be happening in SE Asia, both from onshore geological surveys, and offshore from oil companies, is that fewer and fewer analyses or studies capable of testing a geological history are being carried out. Such analyses, quality controlled and documented accordingly, are essential for independent tests of models and interpretations. Miall (1992) showed the great difficulty of refuting an ideal model even with good age data for the events. So the trend to decreasing the amount of independent age, and facies data exponentially reduces our ability to test basic assumptions, and the science stagnates. We must also move documentation away from simple narratives to carefully constructed technical accounts that includes notes on the reliability of input data, the tests applied, and distinction of results from a null hypothesis.

This review emphasises that ideal models are very poor analogues from which to develop an understanding of complex and unique geological scenarios. They may be an unavoidable starting point where there is no other data, but the acquisition of diverse data is paramount, and an abductive approach, of developing several methods of investigation and cross-checking each of these, to refute some of the alternative working hypotheses, is the only way to progress. Where tests have been carried out, several long-established and widely cited models in SE Asian geology have been found to fail (e.g. Lunt, 2022 on subduction of a proto-South China Sea plate), yet we lack an objective process to construct the replacement. This review discusses some ideas to develop a replacement process.

References

Baker, M., 2016. "1,500 scientists lift the lid on reproducibility". Nature (News Feature). Springer Nature. 533 (7604): 452–454. *DOI: 10.1038/533452a*

van Bemmelen, R.W., 1949. The Geology of Indonesia. The Hague, Netherlands: Government Printing Office., 997

Fisher, R.A. 1925. Statistical Methods for Research Workers. Oliver and Boyd, Edinburgh, 237 pp.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M., 2012. The Geological Time Scale 2012 (1). Elsevier, Amsterdam., 1144

Halbouty, M.T., 1982. The Deliberate Search for the Subtle Trap., DOI: 10.1306/M32427

Haq, B.U., Hardenbol, P.R., and Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. Science 235, 1156-1167

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, 71-108

Ioannidis, J.P.A., 2005. Why most published research findings are false. PloS Med 2(8),

Kerr, N. L., 1998. "HARKing: Hypothesizing after the results are known". Personality and Social Psychology Review. 2 (3): 196–217.
DOI:10.1207/s15327957pspr0203_4

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

Kupferschmidt, K., 2018. More and more scientists are preregistering their studies. Should you? Science (News), 18 Sept. 2018.
DOI: 10.1126/science.aav4786
https://www.science.org/content/article/more-and-more-scientists-are-preregistering-their-studies-should-you

Leong K.M., 1974. The Geology and Mineral Resources of Upper Segama Valley and Darvel Bay, Sabah (4). Malaysia Geological Survey, Borneo Region., 354

Liechti, P., 1960. The geology of Sarawak, Brunei and the western part of North Borneo (Bulletin 3). Kuching Sarawak: Geological Survey Department British Territories in Borneo.

Luan, X., and Lunt, P., 2021. Latest Eocene and Oligocene tectonic controls on carbonate deposition in eastern Java and the south Makassar Straits, Indonesia. Journal of Asian Earth Sciences 220, 104900
DOI: 10.1016/j.jseaes.2021.104900

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

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

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

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., 2022. 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. 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., 2024b. When, how much, how fast, and why it matters. A quantitative view of stratigraphy and the emergence of a new paradigm. Berita Sedimentologi, 49 (3), 18 - 46.

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

Matthews, S.J., and Bransden, P.J.E., 1995. Late Cretaceous and Cenozoic tectono-stratigraphic developments of the East Java Sea Basin, Indonesia. Marine and Petroleum Geology 12(5), 499-510.

Maynard, K., and Morgan, W.A., 2005. Appraisal of a complex, platform carbonate, Bukit Tua discovery, Ketapang PSC, East Java Basin, Indonesia. Proceedings from Proceedings Indonesian Petroleum Association Convention: 30, 317-330.

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

Miall, A.D., 2004. Empiricism and model building in stratigraphy: The historical roots of present-day practices. Stratigraphy 1(1), 3-25.

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.

Miall, A.D., and Miall, C.E., 2004. Empiricism and model-building in stratigraphy: Around the hermeneutic circle in the pursuit of stratigraphic correlation. Stratigraphy 1(1), 22-46.

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

Petronas., 1999. The petroleum geology and resources of Malaysia. Kuala Lumpur: Petroliam Nasional Berhad (Petronas)., 665 pp.

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

Premoli-Silva, I., and Jenkins, D.G., 2001. Decision on the Eocene-Oligocene boundary stratotype. Episodes 16(3), 379-382.

Saller, A., Armin, R., Ichram, L.O., and Glenn-Sullivan, C., 1993. Sequence stratigraphy of aggrading and backstepping carbonate shelves, Oligocene, Central Kalimantan, Indonesia. In: R. G. Loucks & J. F. Sarg (Eds.), Carbonate sequence stratigraphy: recent developments and applications. AAPG Memoir 57, 267-290.

Simonsohn, U., Nelson, L.D., and Simmons, J.P., 2013. P-Curve: A Key to the File Drawer. Journal of Experimental Psychology: General, Forthcoming, 14 p.

Wong, R.H.F., 1993. Sequence stratigraphy of the Middle Miocene–Pliocene southern offshore Sandakan, East Sabah. Geological Society Malaysia Bulletin 33, 129-142.

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.

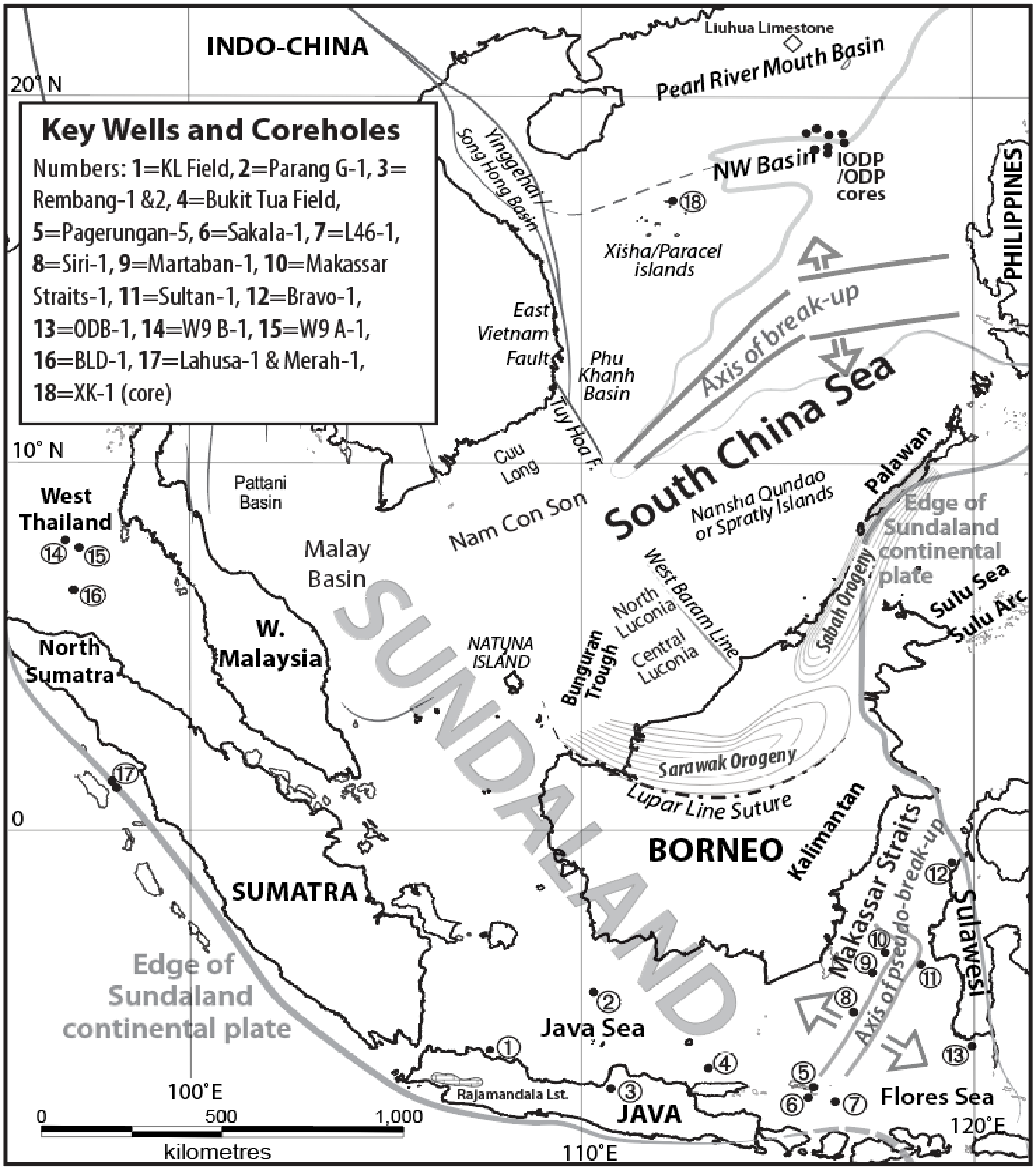


Figure 1: *Location map. Other locations are shown on Figure 11.*

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),

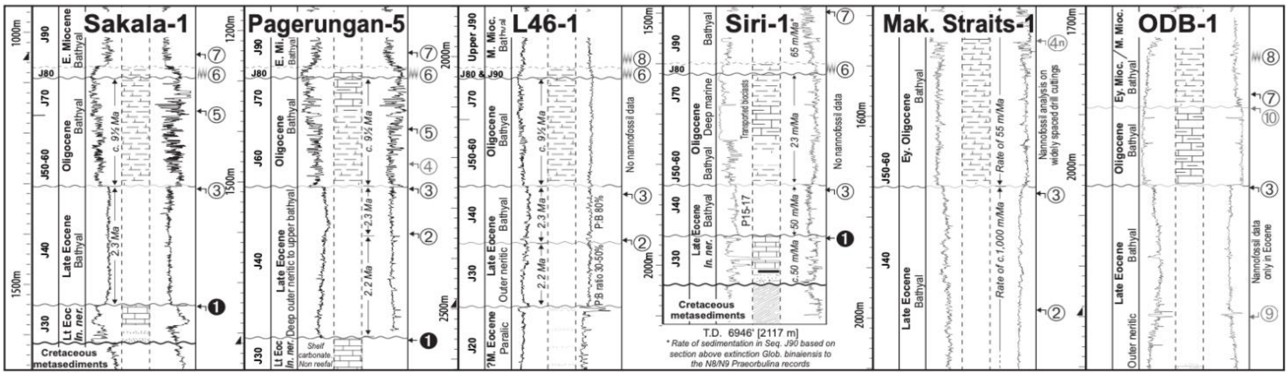


Figure 2: *Well sections over the Eocene – Oligocene boundary ("3") in the Makassar Straits showing a platform carbonate (below black 1) overlain by deep marine clays, then a major and abrupt change in lithofacies and rates of sedimentation coincident with the Eocene – Oligocene boundary. The end of 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

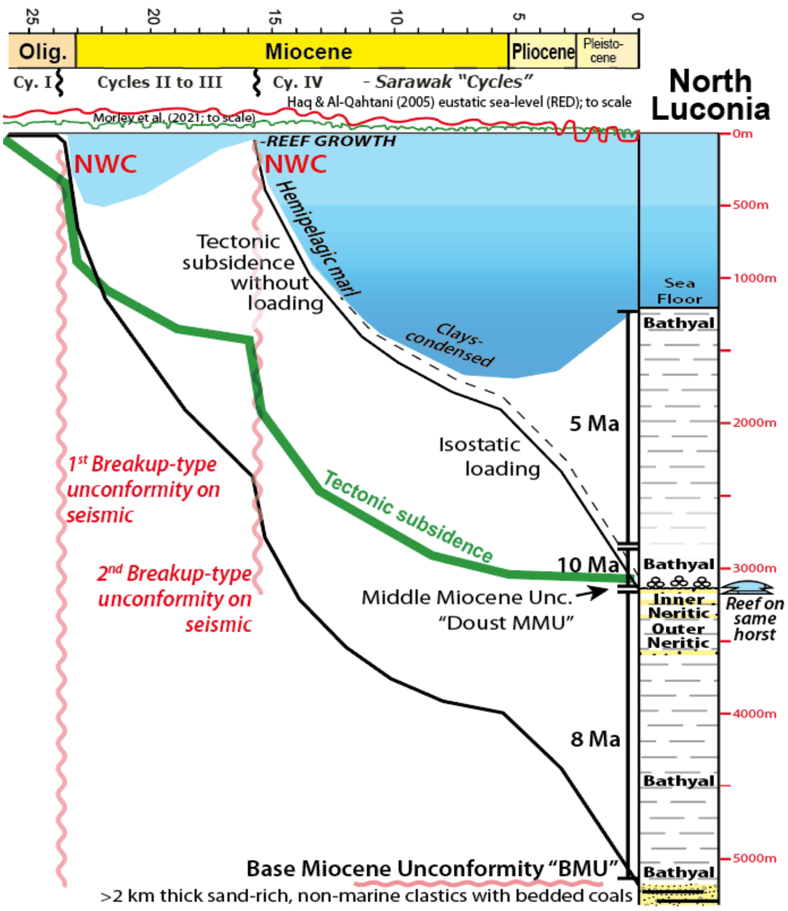


Figure 3: *North Luconia geohistory plot. This area was affected by two major breakup tectono-stratigraphic events. The event on the Oligo-Miocene boundary correlates to ridge jump in the South China Sea as well as subsidence of flanking areas such as XK-1 in the Xisha/Paracel Islands and G10-1 in the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

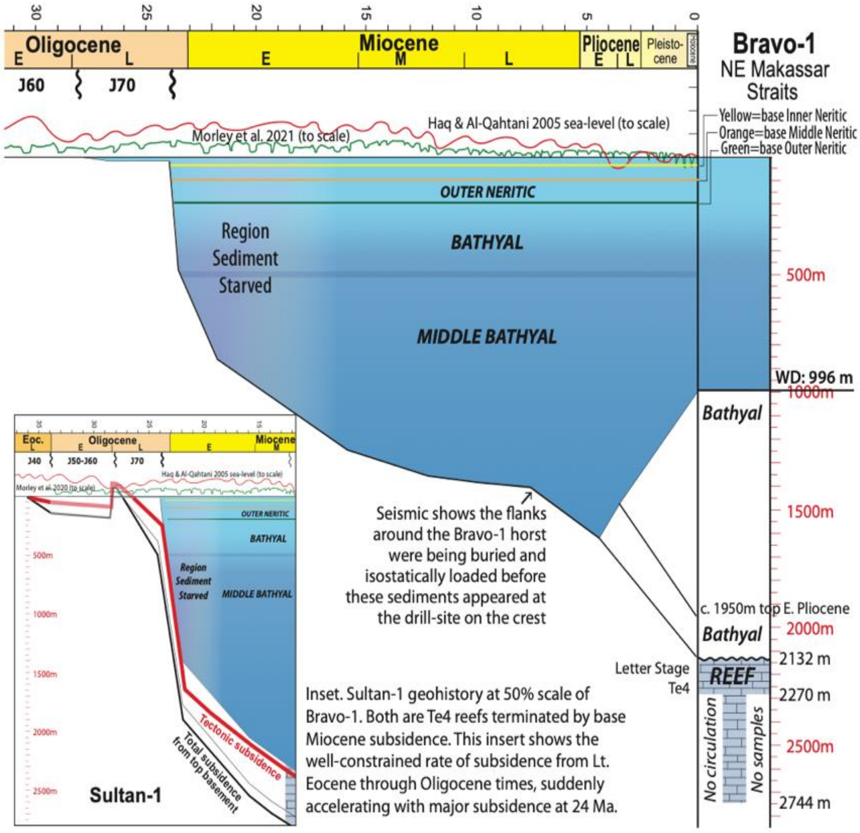


Figure 4: Geohistory plot for Bravo-1 with inset a partial plot for Sultan-1 (both Makassar Straits) showing the large-scale subsidence of Letter Stage Te4 (latest Oligocene) reefs.

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

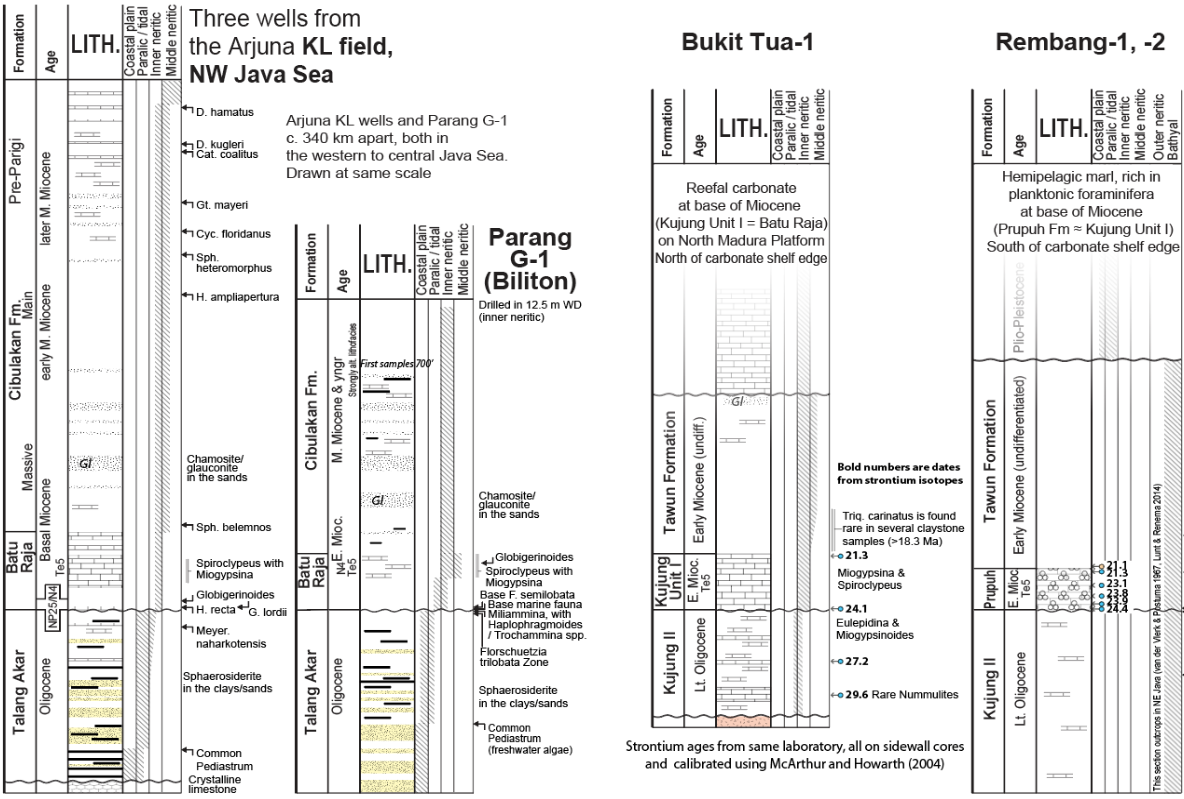


Figure 5: *Correlation across the modern Java Sea area, hung on the Oligo-Miocene boundary annotated with data supporting ages. Well locations shown on Figures 1 and 11.*

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.

<u>The rotation of Borneo</u>

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

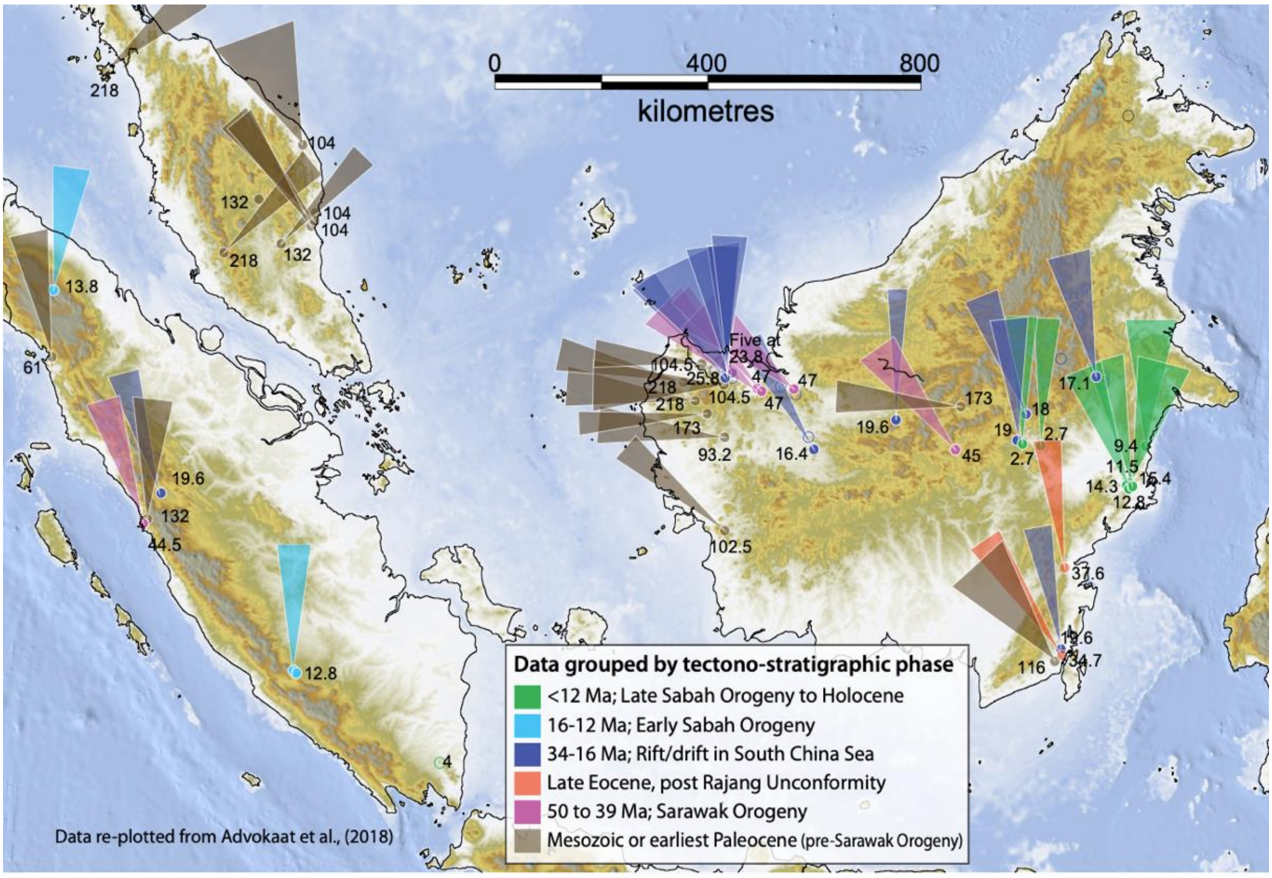


Figure 6: *Figure summarising the evidence previous used to support a concept of Miocene rotation of Borneo. Most of the dark blue magnetic vectors (34-16 Ma, Oligocene and Early Miocene) show no rotation, which appears to have been associated with the "Sarawak Orogeny" that ended at about 39 Ma (Rajang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

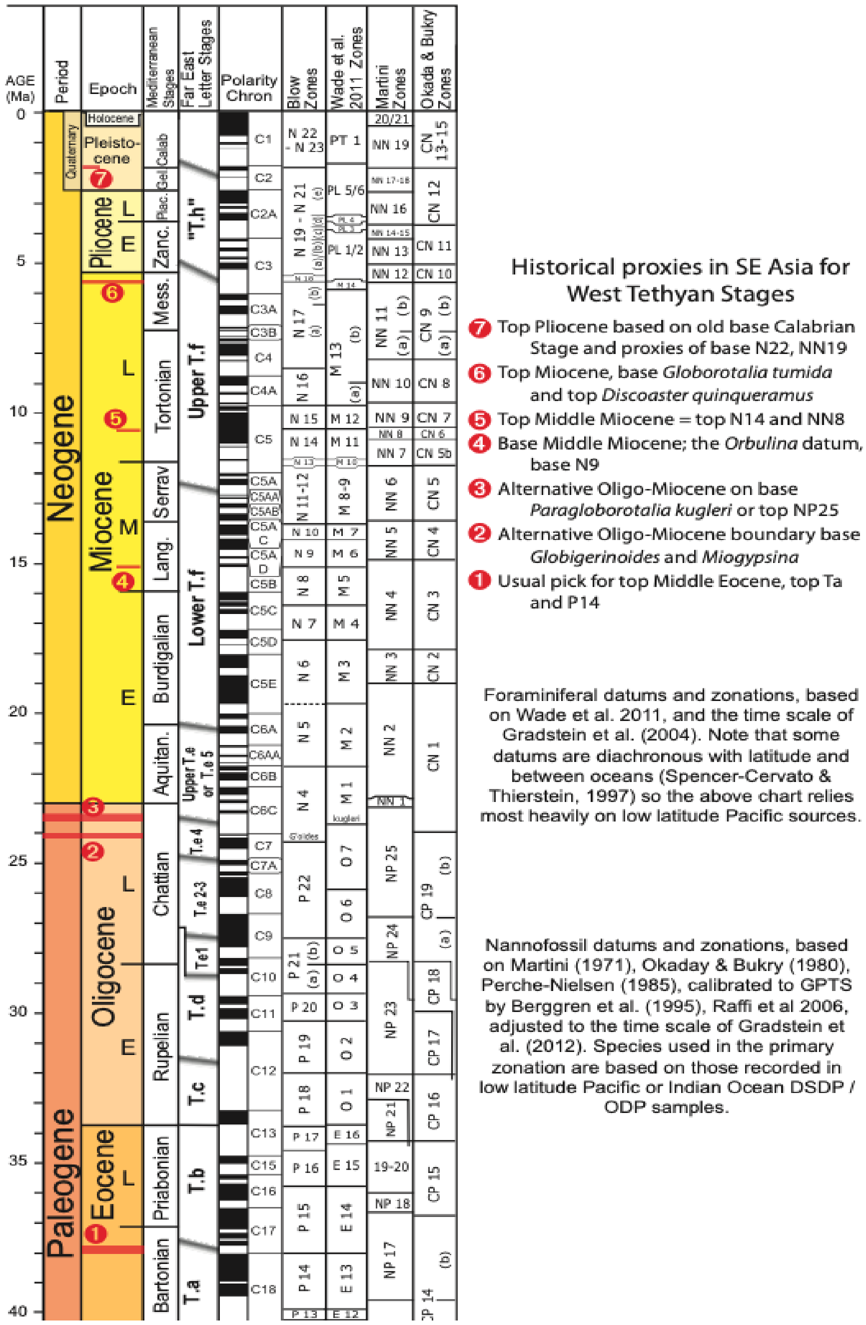
Figure 7 summaries SE Asia stratigraphy with proxies. Since the Blow zones (P1-22 for the Palaeogene, N4 to N23 for the Neogene; Blow, 1969) simple zonal summaries have been very convenient and have been periodically modified. They usually follow similar formats such as Martini's (1971) NN zones, and 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* *Globocassidulina 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

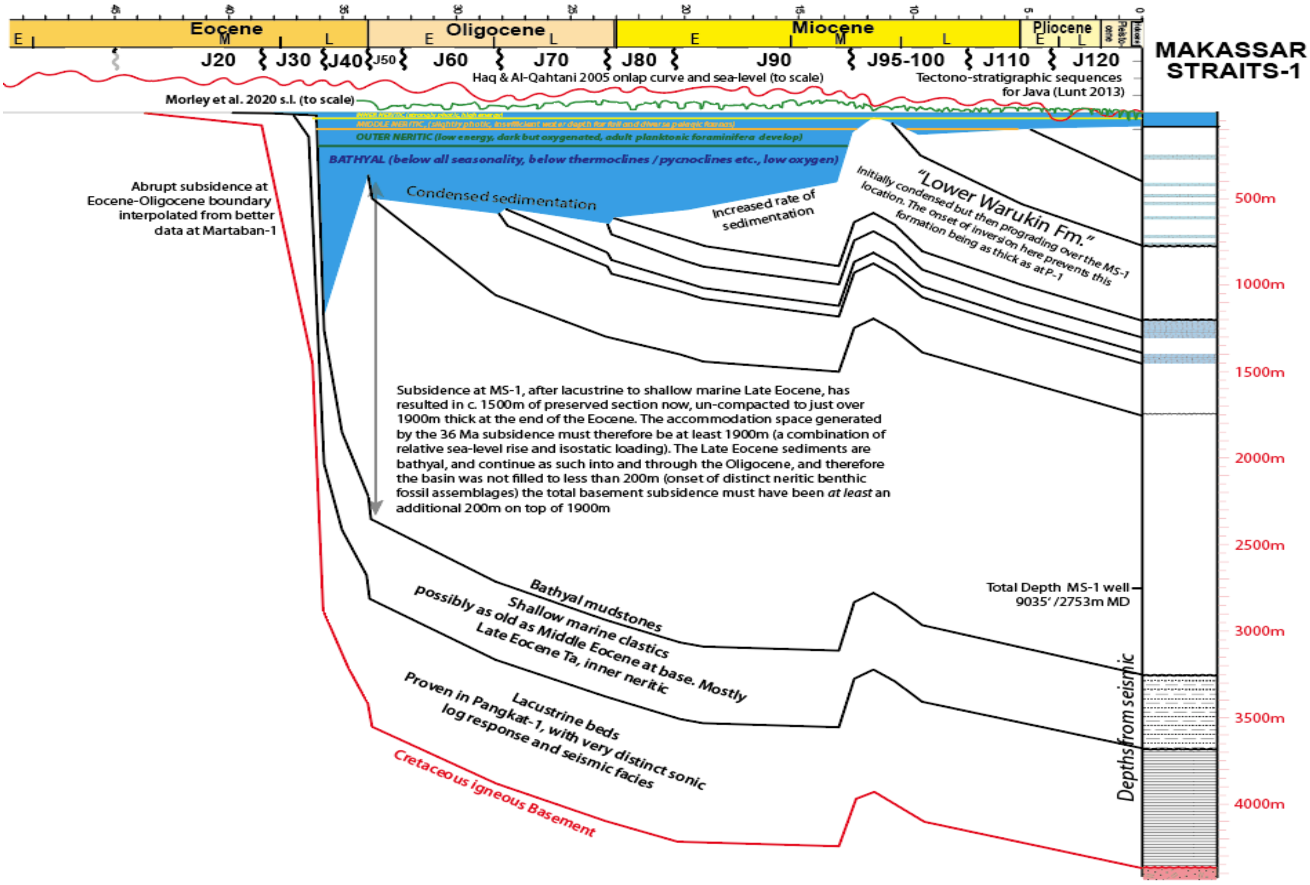


Figure 9: *Makassar Straits-1 geohistory modified from Lunt and van Gorsel (2013) and the new data from Martaban-1 (Figure 10)*

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

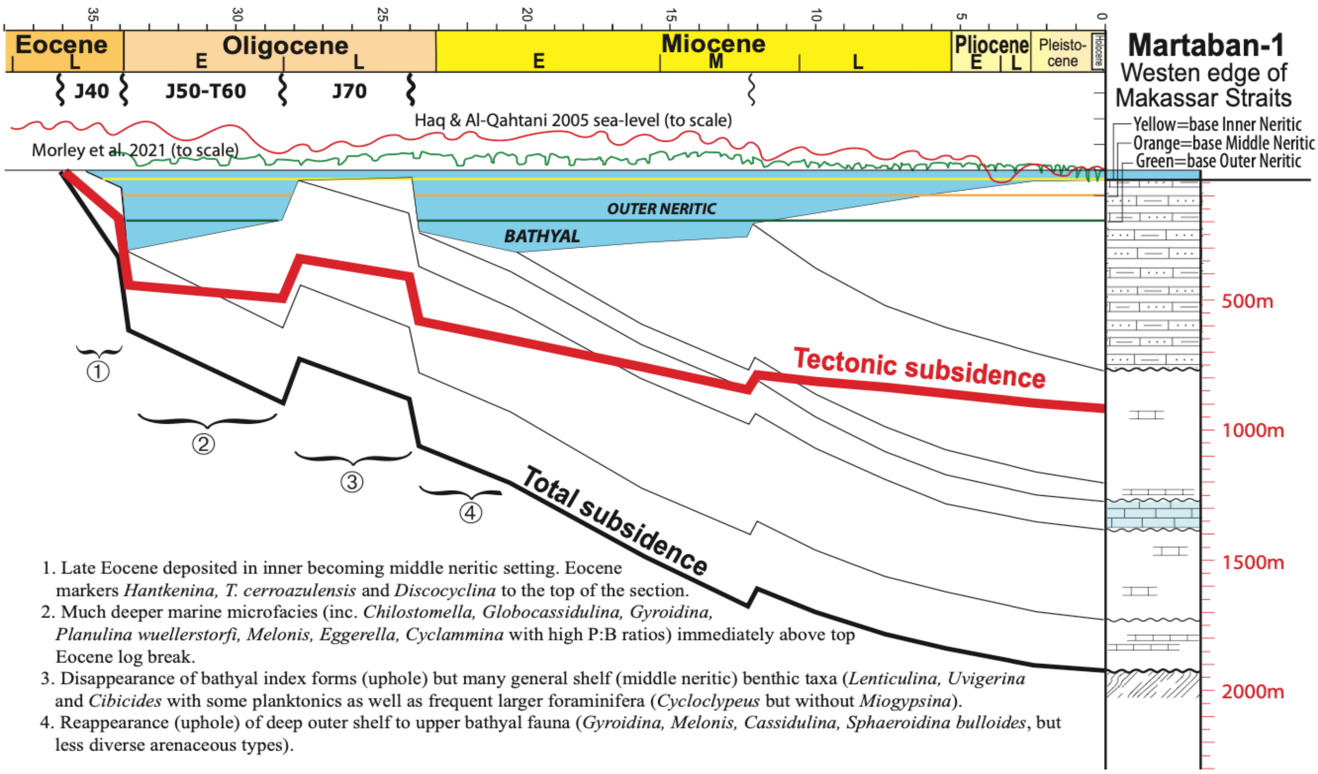


Figure 10: *Martaban-1 geohistory scheme.*

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

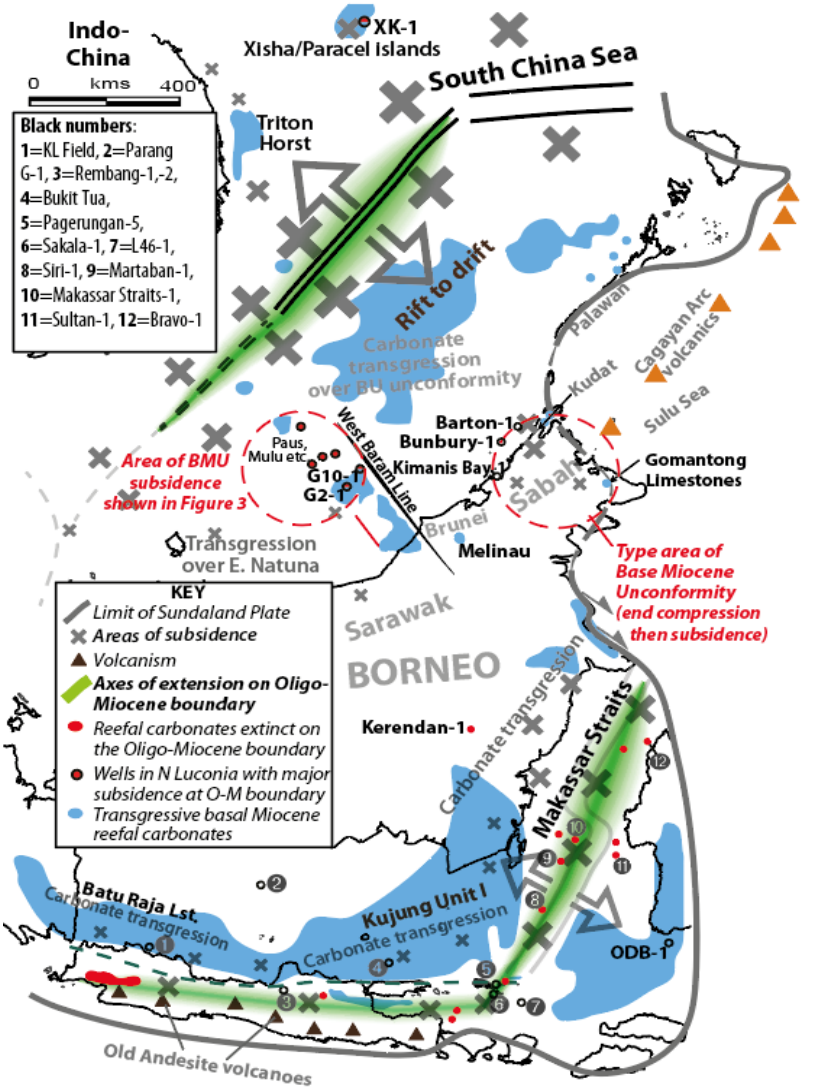


Figure 11: *Tectono-stratigraphic summary map of Sundaland at the Base Miocene Unconformity (BMU; modified from Luan and Lunt 2022, their Figure 20). The larger the grey cross, the larger the estimated subsidence. This was the time of plate spreading "ridge-jump" into the central South China Sea (green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

Lithofacies interpretation and depositional model of Talangakar Lacustrine Deposits: A Study in the Ardjuna Field, Eastern Sunda Basin

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Abstract

The Ardjuna Field in the Northwest Corner (NWC) block is located on the eastern side of Sunda Basin and is adjacent to the Seribu Fault. Producing reservoirs in the Ardjuna Field are mainly of the Talangakar (TAF) fluvio-deltaic sandstones, however all wells within the four production platforms of the field had been shut in November 2006. Hence it is necessary to re-evaluate remaining potential and to seek new reservoirs within the field in order to reactivate oil and gas production from the structure.

The main focus of our study is to evaluate the remaining potential of TAF fluvio-deltaic producing zones and identify new potential in the TAF lacustrine deposits. We used a total of 8 exploration wells, 17 development wells, and a 3D seismic dataset during our evaluation. Out of the 25 wells, only two wells have penetrated the lacustrine deposits interval, i.e. W-1 and S-5 wells. The S-5 well proved flowing HC of up to 1,043 MMCFGPD and 332 BOPD from DST.

The lower TAF lacustrine deposit is characterized by the occurrence of typical freshwater pollens, displaying a serrated and coarsening upward log pattern, thin succession, and absence of sediment structures. Seismic interpretation and Acoustic Impedance (AI) analysis indicate that low AI value (< 7200 gr/cc*ft/s) correlate with high porosity, interpreted as sandstone. The AI-guided seismic attribute reveals a relatively regular lobate shape resembling a fan measuring 1.7 km by 2.5 km. Furthermore, low AI values are more prevalent and widely distributed, particularly on top of the closure.

Keywords: *Talangakar Formation, lacustrine, synrift fan, Ardjuna Field, Sunda Basin*

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INTRODUCTION

The Ardjuna structure is located in the Sunda Basin, adjacent to the Seribu Fault. This structure is currently producing oil fields within the Northwest Corner (NWC) Block (Figure 1). The first exploration well in the Ardjuna structure was S-1 well, which was drilled in 1982 and produced 6,500 BOPD with 0% water cut during DST. Previous volumetric calculation indicates that the Ardjuna structure contains approx. 43.7 BSCF and 49.9 MMBO of hydrocarbons in place. The field produced oil from the Talangakar fluvio-deltaic reservoirs through two platforms, namely Ardjuna-A and Ardjuna-C. The Ardjuna-A platform has 13 development wells, with peak production reaching a rate of 9,056 BOPD and 16.7 MMCFD in 1986. The Ardjuna-C platform has 8 development wells, with the peak production rate of 2,856 BOPD and 5.4 MMCFD. When HC production was shut down in November 2006, a total of 30.1 BSCF of gas and 7.9 MMBO of oil were produced cumulatively. Therefore, the recovery factor (RF) for gas and oil were 68.9 % and 15.9%, respectively.

This study was conducted to summarize the remaining potential from existing production zones, and to evaluate the upside potential of the Talangakar lacustrine deposit. Further studies on the economic and development strategies are necessary to determine the appropriate approach for redeveloping a mature structure with significant upside potential.

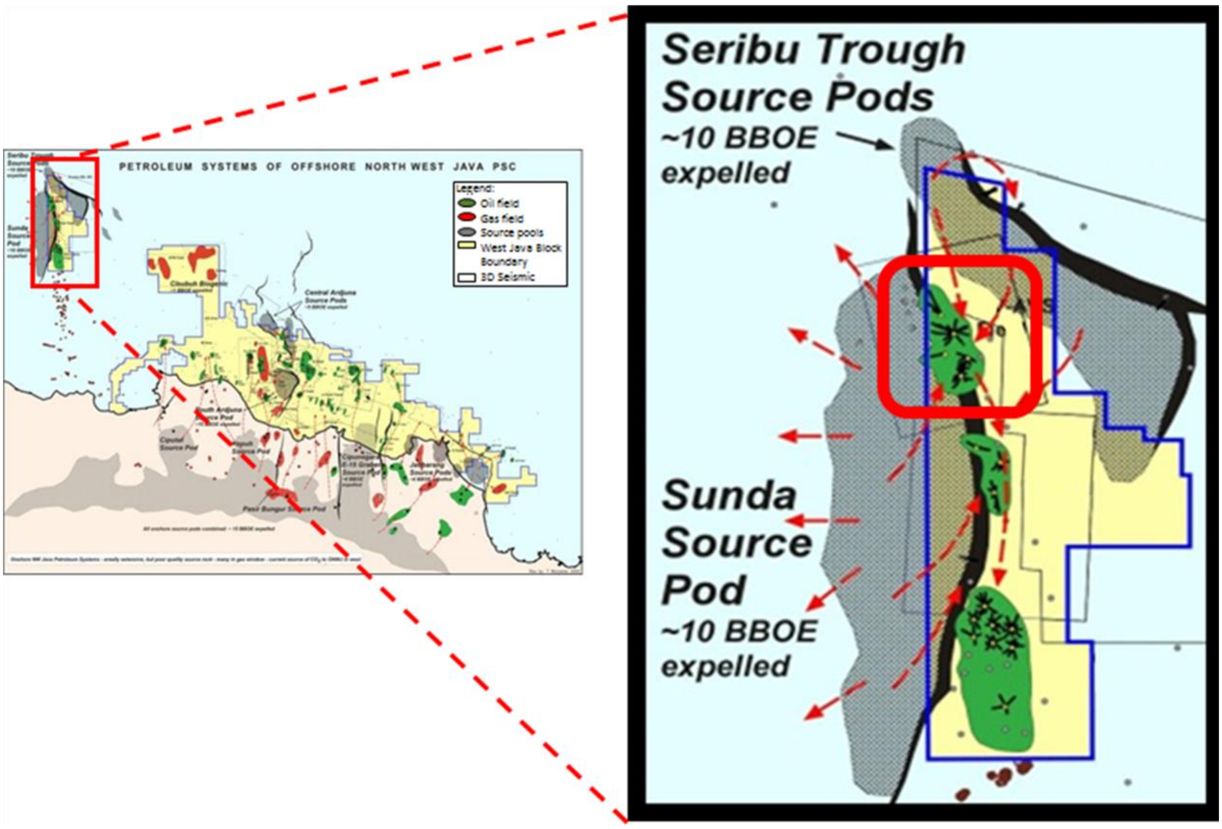

Figure 1: Location of Ardjuna structure within the Northwest Corner Block, eastern Sunda. Basin

DATA AND METHODOLOGY

In total, 8 exploration wells, 17 development wells and 3D seismic data were utilized in this study. However, only 2 wells were utilized to evaluate lacustrine potential since these were the only wells that penetrated the lacustrine interval.

This study was conducted to re-evaluate the presence and distribution of hydrocarbon in the Talangakar lacustrine interval by integrating biostratigraphy, core sedimentology, mudlogging & wireline log data, 3D seismic data and DST result. Seismic attribute was analyzed to understand facies boundary trend and porosity distribution i.e., acoustic impedance. Afterward, 3D static model was built to acquire more robust volumetric calculation with uncertainty analysis.

GEOLOGICAL SETTING

Tectonic and Basin Evolution

The Northwest Corner (NWC) block is located in the Offshore Northwest Java Basin (ONWJ) working area, specifically within the Sunda Basin, adjacent to the Seribu fault. The Sunda Basins reservoirs are mainly from the syn-rift deposits which are currently positioned in a back arc setting, but the rift system did not form as a back-arc basin (Ralanarko, 2020). The history of the Asri and Sunda Basin (as a part of Sundaland) can be subdivided into the several stages of tectonic megasequences as described below (Longley, 1997):

- Stage I (50 – 43.5 Ma) – Corresponds to a period of early continental collision which led to the formation of many of the older synrift grabens. The India – Eurasia collision caused a slow-down in the oceanic spreading rates in the Indian Ocean reducing the convergence velocity along the Sunda Arc subduction system and resulting in a phase of extension in the adjacent fore-arc and back-arc areas. Daly et al. (1987) pointed out that the velocity decrease would cause the subduction slab to sink, with consequent decoupling of the slab and creation of an extensional environment in the arc region.

- Stage II (43.5 – 32 Ma) – Major plate reorganizations took place, resulted in the formation and active subsidence of the younger rifts. This extension resulted in the opening up of numerous half-grabens whose geometry and orientation were influenced by basement heterogeneity. Hall (1995) mentioned that South Sumatra has been rotated by approximately 15 degrees clockwise since the Miocene resulting in a present-day graben orientation.

- Stage III (32 – 21 Ma) – Contemporaneous with sea floor spreading of the South China Sea, was a period during which rift ceased, local inversion took place, and a major marine transgression marked the beginning of postrift development.

- Stage IV (21 – 0 Ma) – Characterized by a maximum transgression followed by several collision phases that led to inversions, uplift and the development of regressive deltaic sequences. This is equivalent to the early and late postrift stages.

Stratigraphy

The stratigraphy of Sunda Basin (Figure 2) can be subdivided into several formations from younger to older as described below (Eksindo Pratama, 1996):

- Cisubuh Formation

  Cisubuh Formation is dated as Early Pliocene to Late Miocene age. The presence of a diverse palynoflora consisting of marine, mangrove, and peatswamp suggest deposition in an outer littoral to inner sublittoral environment, close to mangrove vegetation and near to fluvial sediment provenance.

- Parigi Formation

  Parigi Formation is dated as Early Pliocene to Late Miocene. The benthonic fauna consist mainly of shallow water similar to Cisubuh formation.

- Main-Massive Formation

  The Main-Massive sequence is dated as Early to Middle Miocene in age and consist of outer neritic, locally bathyal mudstone with sand overlain by complex of sandstone and mudstone deposited in neritic environment. The upper part of Main-Massive sequence is mostly dated as Early Miocene in age and relatively deposited in middle neritic as calcareous mudstone.

- Baturaja Formation

  The Baturaja (BRF) limestone is dated as Early Miocene in age and deposited in open marine neritic origin, with a distinct relatively deepwater (middle to outer neritic) facies in upper part.

- Talangakar Formation

  Talangakar Formation (TAF) was deposited during Early Miocene to Late Oligocene and it can be subdivided into 3 sequences as below (Figure 2):

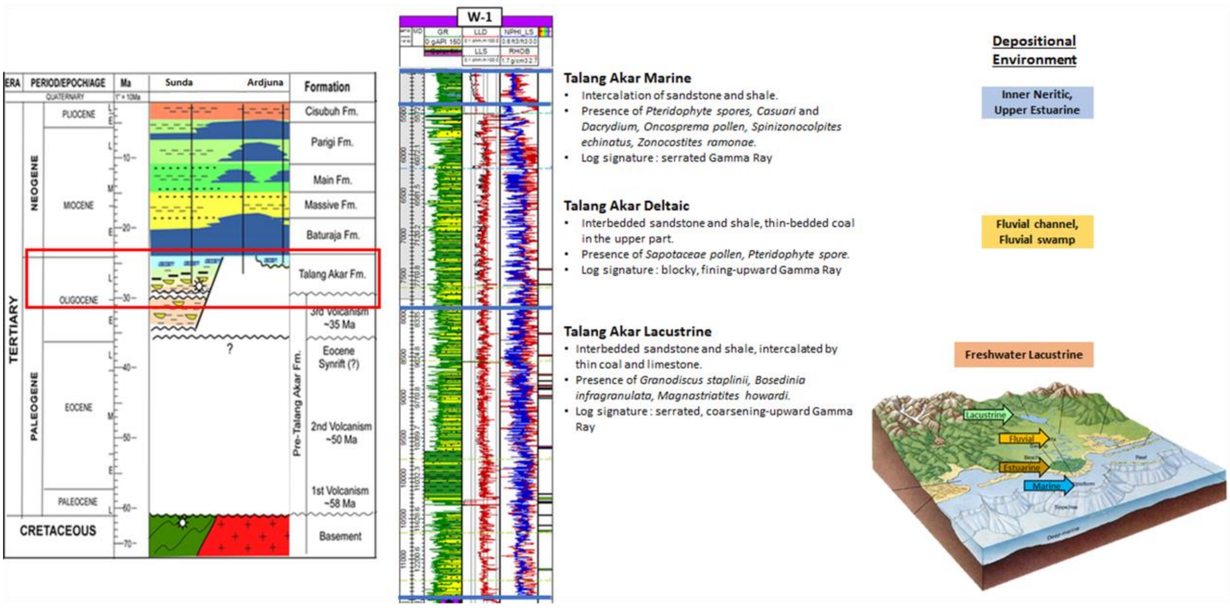

Figure 2: *Stratigraphic column of the Sunda Basin (modified after Aveliansyah et al., 2016)*

1. Talangakar marine consists of calcareous shale intercalation with limestone streak and locally carbonaceous shale or coal. This interval is the transition between fluvio-deltaic sediment to marine. Unfortunately, lack of sand deposits and no hydrocarbon was detected in this interval.

2. Talangakar fluvio-deltaic to estuarine is characterized by interbedded of sandstone and shale with coal deposit that were deposited in fluvio-deltaic to upper estuarine. This interval is the main production layer.

3. Talangakar lacustrine consists of interbedded sandstone and shale, predominantly shale with intercalation of coal and limestone. This interval is the focus interval in this study.

RESULT AND DISCUSSION

<u>**Talangakar Lacustrine in the Ardjuna structure**</u>

The lacustrine section of TAF was identified from biostratigraphy, log characteristics, core interpretation and seismic attribute analysis. The following section describes the characteristic of Talangakar lacustrine interval within the Ardjuna structure:

- *Biostratigraphy Approach*

Detailed biostratigraphic analyses such as micropaleontology, nannofossils, and palynology were performed from cutting samples of the W-1 and S-5 wells to determine the age and depositional environment (Eksindo Pratama, 1996). *Bosedinia infragranulata* type 'C' is abundant in the interval of 8850' – 10710' and this is a similar event as seen in the West Natuna Sea, within the basal part of Barat Formation (Eksindo Pratama, 1996). This event is dated by graphic correlation at about 24.5 Ma which equivalent to Early Miocene. *Granodiscus staplinii* and *Bosedinia laevigita* are observed at 10740' to 12812', which is usually found within and below Keras Formation in the West Natuna Sea (Eksindo Pratama, 1996). This datum is dated by graphic correlation at about 27 Ma which is equivalent to Late Oligocene. The presence of *Bosedinia* spp., *Magnastriatites howardi*, *Pediastrum* spp., *Granodiscus staplinii,* and *Bosedinia infragranulata* at interval 7860' – 12812' suggests this interval was deposited in lacustrine with fluvial swamp influence. Meanwhile, fluvio-deltaic deposition of the upper Talangakar is characterized by the occurrences of *Sapotaceae* pollen, *Pteridophytes* spores, *Zonocostites ramonae, Spinizonocolpites enchinatus*, and *Florschuetzia* spp.

- *Core Interpretation*

The full 28-foot conventional core from the lacustrine section of TAF, retrieved at the W-1 well includes various lithofacies such as shale, sandstone, and coal (Figure 3). The sandstone lithofacies is light grey, well-sorted, very fine-grained with ripples indicating syn-sedimentary deformation. This is followed by lacustrine shale lithofacies, characterized by dark greenish, grey mudstone with minor silty lamination sand lenses occurring in several places.

- *Wireline Log Characteristics*

In the 8150' – 12745' interval in W-1 well and 8200' – 9767' interval in S-5 well, a pattern of serrated, coarsening upward

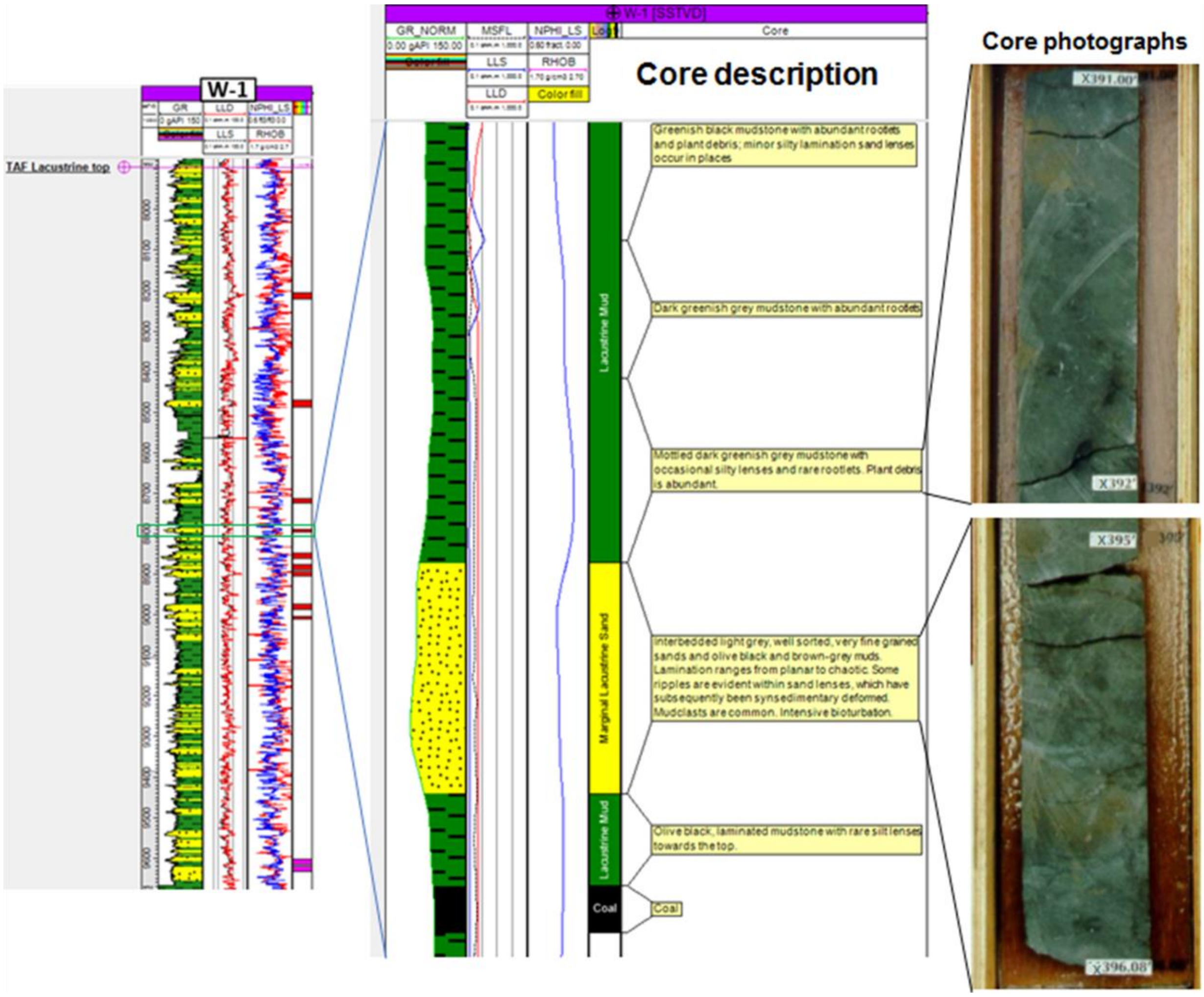

Figure 3: *Core description on lacustrine sandstones and shales at W-1 well.*

and frequent thin sands (3 – 20 ft) suggested lacustrine deposits. The serrated log pattern, indicative of laminated muds and thin, very fine-grained sandstones implies a deposition in a low-energy system. In contrast, the fluvio-deltaic interval shows a blocky to fining upward log signature with relatively thick (5 – 40 ft) of coarser sand bedding (Figure 4), indicating relatively higher energy of deposition. Comparatively, the TAF lacustrine section, with up to 863 ft of total thickness and 24% sand to gross ratio, predominantly contains more shales than the TAF fluvio-deltaic section that has 30% sand to gross ratio despite its total thickness of 755 ft. This smaller sand to gross ratio within the lacustrine section is as expected because in general there is less sand in a deep lake compared to it is in the fluvio-deltaic setting.

- *Seismic Attribute Analysis*

The 3D seismic data revealed a three-way dip fault structural trap resembling a fan bounded by a major N-S trending fault (Figure 5A). Prior to delineating the lateral distribution of sand bodies, a crossplot of p-impedance versus porosity in W-1 well indicated a noticeable separation between sand and shale lithologies ($R^2 > 0.7$ and

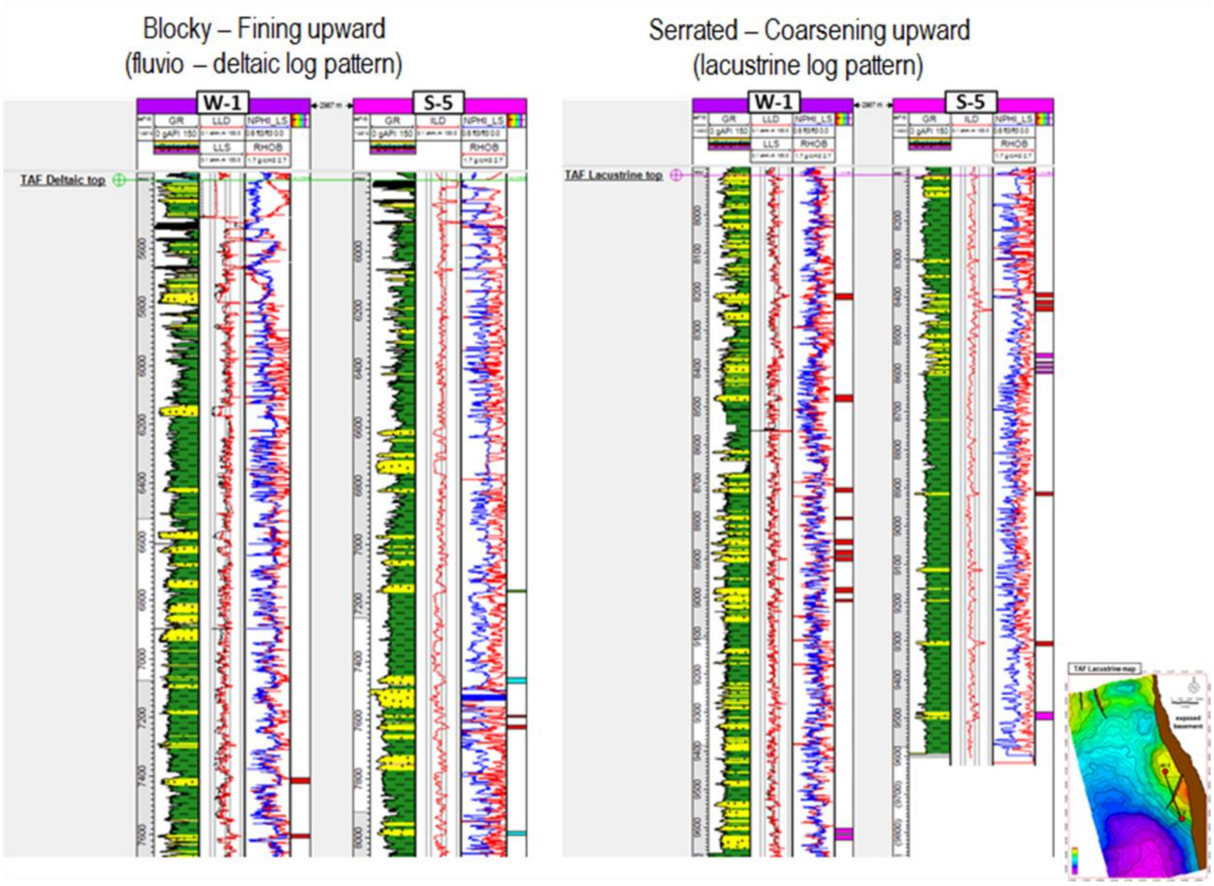

Figure 4: *Well correlation of W-1 and S-5 wells comparing the deltaic and lacustrine sections of the TAF.*

sand value < 7200 gr/cc*ft/s). Consequently, acoustic impedance (AI) inversion displayed the lateral distribution of sand and porosity. Slicing the AI volume unveiled sand (yellow to bright red colors) and shale (dark blue to black colors) distribution emphasizing the fan-like geometry in close proximity to the major fault (Figure 5B).

Depositional Model

Through various approaches, it is demonstrated that the lithology of the targeted interval in the W-1 and S-5 wells is predominantly mudstone with intercalations of siltstone and fine sandstone. The occurrence of bio-event (*Magnastriatites howardi, Pediastrum* spp., *Granodiscus staplinii*, and *Bosedinia infragranulata),* a serrated log signature with relatively thin sand, and a fan geometry revealed by seismic interpretation and AI inversion indicate that the deposits are of shallow subaqueous fan of lacustrine system (Figure 6). The final product, incorporating the depositional model cartoon and the AI-guided seismic attribute of sandstone, is then modeled in the 3-dimentional facies model to facilitate volumetric calculations.

A modern-day analog for the lacustrine section of TAF in the Ardjuna Field probably exists in Lake Singkarak, West Sumatra. At the lake, the Malalo alluvial fan delta exhibits an irregular, lobate shape with dimensions of 2.1 km by 2.3 km (Figure 7).

Likewise, the lacustrine section of TAF in the Sunda Basin is approximately 2.5 km wide and 1.7 km long displaying a relatively regular lobate shape. According to Sihombing et al. (2016), the Malalo alluvial fan delta comprises five distinct facies associations: upper, middle, lower, subaqueous fans and lacustrine shale. This study suggests that the lower and subaqueous fans are favorable reservoir locations characterized predominately by medium to coarse-grained sandstone with moderate to well-sorted fabric, indicating good porosity and permeability. However, TAF lacustrine in the study area, characterized by olive-black, well-sorted, very fine-grained sandstone may also be deposited in subaqueous locations showing similarities to the sandstone interval of Malalo Fan in Lake Singkarak.

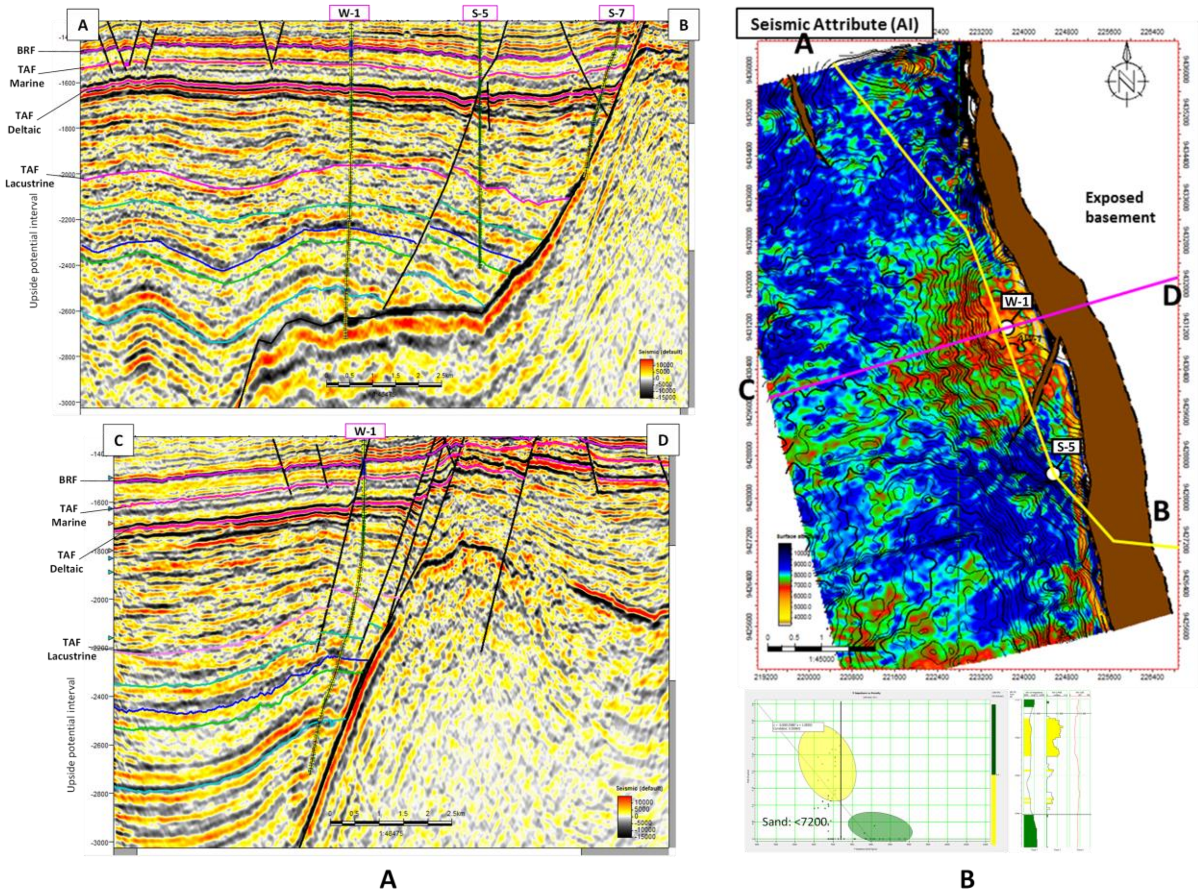

Figure 5: *(A) Seismic section of Lacustrine Deposits. (B) The fan-like geometry of slicing AI.*

DST tests further confirm the potential of the lacustrine petroleum system. Tight, thin sand packages serve as reservoirs, while shale/mudstone facies act as both source rock and seal rock. Hydrocarbon, predominantly oil, are present in almost all sand-packages penetrated by W-1 and S-5 wells in the lacustrine interval.

CONCLUSIONS

The Talangakar Formation (TAF) exhibits three distinct depositional environments, from older to younger: TAF Lacustrine, TAF Fluvio-Deltaic, and TAF Marine. The TAF Lacustrine section in the study area was

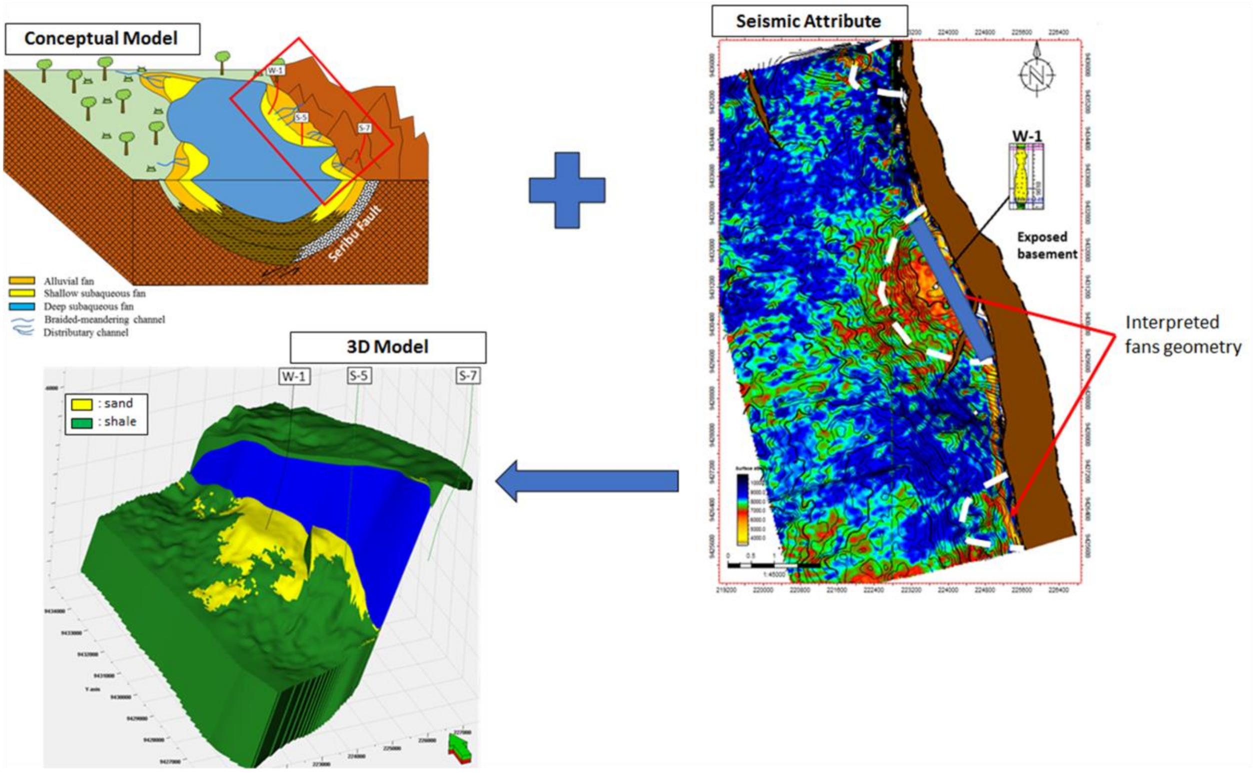

Figure 6: *3D facies model based on conceptual geological model and seismic attribute.*

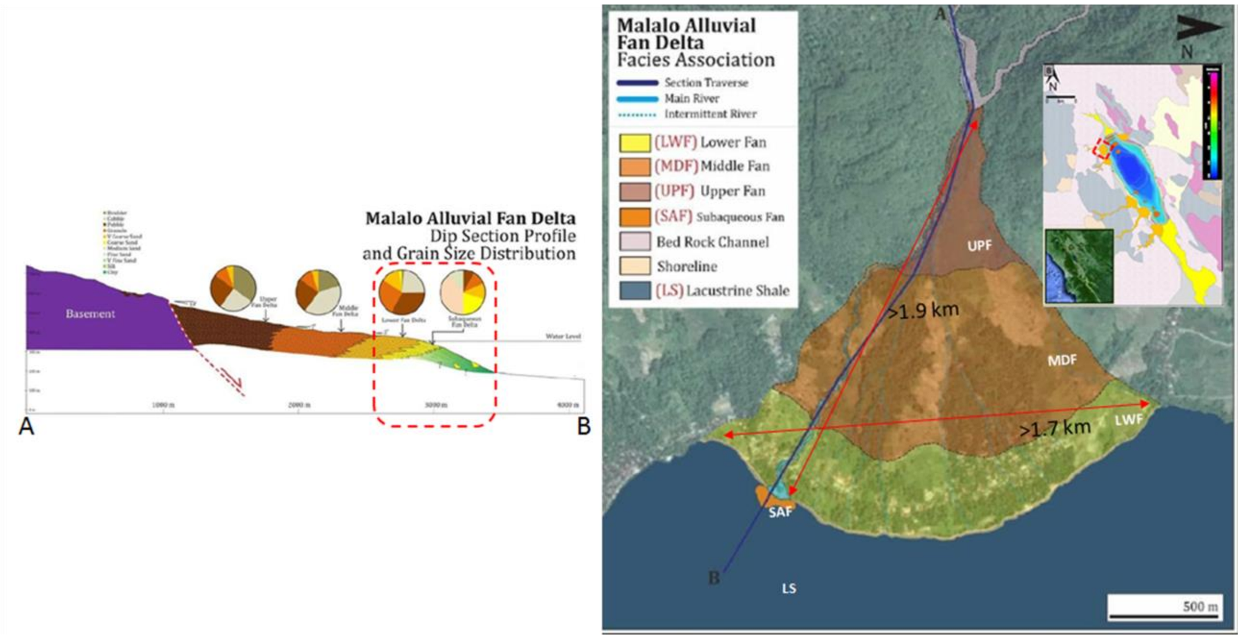

Figure 7: *Modern-day lacustrine deposits in Malalo Alluvial Fan Delta, Lake Singkarak (Sihombing et al., 2016).*

deposited in a freshwater lake with several alluvial fans along a major N-S trending fault. Analyzed data indicate that lacustrine sandstone tends to be thin and composed predominantly of shale facies compared to its fluvio-deltaic sandstone counterparts. Despite this, the thinly bedded sandstones of the lacustrine section are favorable for hydrocarbon accumulation, as evidenced by Drill Stem Test (DST) results in this interval. Seismic interpretation reveals that the study area resembles a relatively regular lobate shape of a fan delta with dimensions of 1.7 km by 2.5 km, similar to the modern analogue in Lake Singkarak. Additionally, low Acoustic Impedance (AI) values, indicative of sandstone, are more frequently and widely distributed, primarily occurring on top of the closure.

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REFERENCES

Aveliansyah, P. P., Triono, W., and Saefullah, U. A., 2016. Pre-Talang Akar Formation: New Hopes for Hydrocarbon Exploration in the Offshore North West Java Basin. Proceedings, Indonesia Petroleum Association, 40th Annual Convention & Exhibition, IPA16-146-G, xxp.

Eksindo Pratama, 1996. Biostratigraphy of the Interval 2010' – 12812 of the AW-1 Well, drilled in the Arjuna Basin by Atlantic Richfield Indonesia Inc. Internal Report by PT Eksindo Pratama, 50p. (unpublished)

Longley, I.M, 1997. The tectonostratigraphic evolution of SE Asia. *In*: A.J. Fraser, S.J. Matthews and R.W. Murphy (Eds.), Petroleum Geology of SE Asia, Geological Society of London, Special Publications, 126, 311-339.

Primadani, G.S., Watkinson, I.M., Gunawan, H., and Ralanarko, D., 2018. Tectonostratigraphy of the Asri Basin, SE Sumatera, Indonesia: Unlocking the hidden potential of Oligo-Miocene reservoirs and implication for hydrocarbon prospectivity. Proceedings, Indonesia Petroleum Association, 42nd Annual Convention & Exhibition, IPA18-19-G, 14p.

Ralanarko, D., Wahyuadi, D., Nugroho, P., Rulandoko, W., Syafri, I., Almabrury, A., and Nur, A.A., 2020. Seismic expression of Paleogene Talangakar Formation – Asri and Sunda Basins, Java Sea, Indonesia. Berita Sedimentologi, 46 (1), 21 – 43.

Sihombing, E. H., Oetary, N., Fardiansyah, I., Waren, R., Finaldhi, E., Fitris, F., Semimbar, H., Graha, S., Talib, A.F., and Paksi, W. R., 2016. Modern Fluvio-Lacustrine System of Lake Singkarak, West Sumatra and Its Application as an Analogue for Upper Red Bed Fm. in the Central Sumatra Basin. Berita Sedimentologi, 36(1), 9 – 34.

Indonesian Stratigraphic Lexicon: past, present, and future

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ABSTRACT

The Stratigraphic Lexicon is an important source of regional geological information. Due to the development of the science and the geological understanding, the lexicon needs to be updated. Following the first Indonesian Stratigraphic Lexicon by Marks (1957), Harahap et al. (2003) made an update to the lexicon. The latter version was later published online as a website. A GIS format of the lexicon will soon be available for geoscientists to use. This paper also provides suggestions for improving the lexicon, which includes the preparation of logs type for each section. A systematic approach to periodically ever greening the lexicon is necessary. The Geological Survey of Indonesia and the Indonesian Association of Geologists should be involved in the future improvement of the lexicon.

Keywords: *stratigraphic lexicon, Indonesian stratigraphy*

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INTRODUCTION

The stratigraphic lexicon is an important document to geoscientists since it has become a preliminary guidebook to understand the geology of a certain area. The lexicon is helpful in showing all the existing lithostratigraphic terminologies of a respective area. The lexicon contains the name of the formations, the type localities, a brief description of the lithology, age of the formation including the index fossils and references.

In Indonesia, the stratigraphic lexicon was initially published by Marks (1957) and was updated by Harahap et al. (2003). The Indonesian Stratigraphic Lexicon contains information on the lithostratigraphic units, either formal or informal, in the following aspects: names, age, nomenclature, type locality, description, fossil content, thickness, distribution, depositional environment, tectonic setting, economic aspect, remark, boundaries with the underlying and overlying Formations, and related references. In some cases, the lexicon also describes the lateral relationship with the other Formations. Therefore, it is important to update the stratigraphic lexicon.

PAST

The first Stratigraphic Lexicon was compiled by Marks (1957) with 146 type locations. This publication described the lithological composition of the Formations, including the identified fossils. It includes the references, type locality, and geographical distribution. The ages were stated for most of the Formations. Some Formations had more description than others. An atlas of the lexicon was published in 1961. It consists of 116 geological maps indicating the locations of various rock units that is subdivided into Groups, Formations, Members, Beds, and Layers, as detailed in P. Marks (1957). It also includes almost all regions in Indonesia with age range from Carboniferous (Paleozoic) found in Sumatra to the youngest Pleistocene in Java. These publications are available as paper copies with hard covers (Figure 1).

Since the outset of the PELITA 1 (the first Five-Year Development Program) in 1969, various geological research activities were carried out by governmental institutions (either with or without the support of foreign institutions), mining companies, petroleum companies, academicians, and individual earth scientists. This has brought a fast-growing accumulation of new geological information in Indonesia, including stratigraphic nomenclatures and concepts. Therefore, with these developments, the lexicon of Marks (1957) has been left far behind and an update was made.

The Center for Geological Survey, Indonesian Geological Agency updated the lexicon in 2003 (Harahap et al., 2003) and reported 1,856 lithostratigraphic units. This number was more than 10 times larger than the publication of Marks (1957). Compared to the first publication, Harahap et al. (2003) covered wider study areas, as the access to the interior had improved significantly. This great number of lithostratigraphic units might be caused by the complexity of the geology of the region. It might also be explained by the occurrences of synonymy of the same

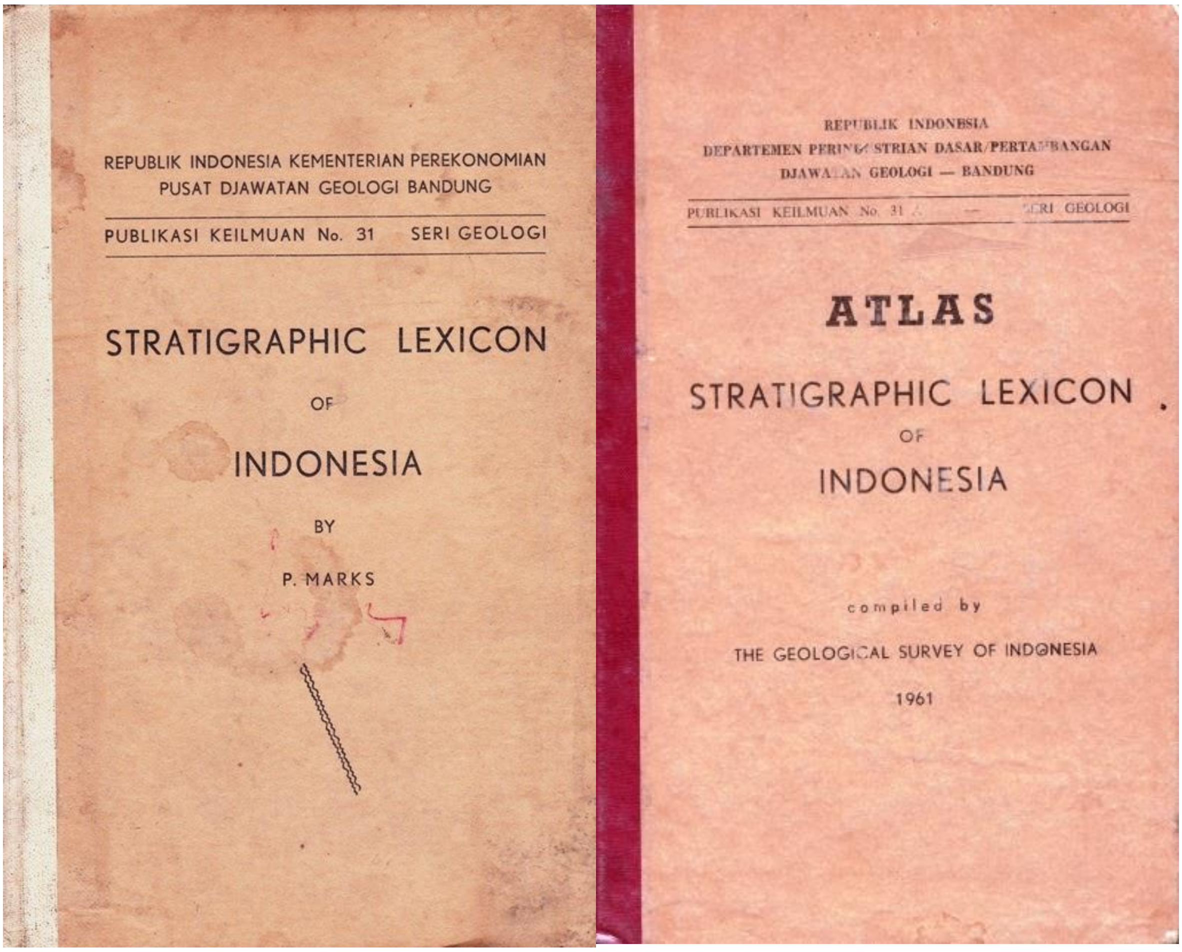

Figure 1: *The cover of the first stratigraphic lexicon, published by P. Marks in 1957 (left) and the atlas (right), published in 1961.*

lithostratigraphic units, given rise by different concepts among workers or simply due to their ignorance.

By November 2001, a bound draft of the stratigraphic lexicon of the Eastern of Indonesia entitled "Nomenclature Compilation of the Stratigraphy of the Eastern Indonesian Region" was completed, followed by that of the Western part entitled the "Nomenclature Compilation of the Stratigraphy of the Western Indonesian Region". The drafts have been exposed for discussions in some meetings, which were held by universities, the Indonesian Association of Geologists (IAGI), and the Center for Geological Survey. During such meetings, invaluable comments, suggestions, and criticisms were obtained. In 2003, Harahap et al. (2003) completed the second stratigraphic lexicon. The main source of this lexicon was the 239 systematic geological maps produced by the Center for Geological Survey (formerly Geological Research and Development Center/GRDC), covering Jawa and Madura Islands at a scale of 1:100.000 and other regions at a scale of 1:250.000.

PRESENT

The Indonesian Stratigraphic Lexicon is now available on the website

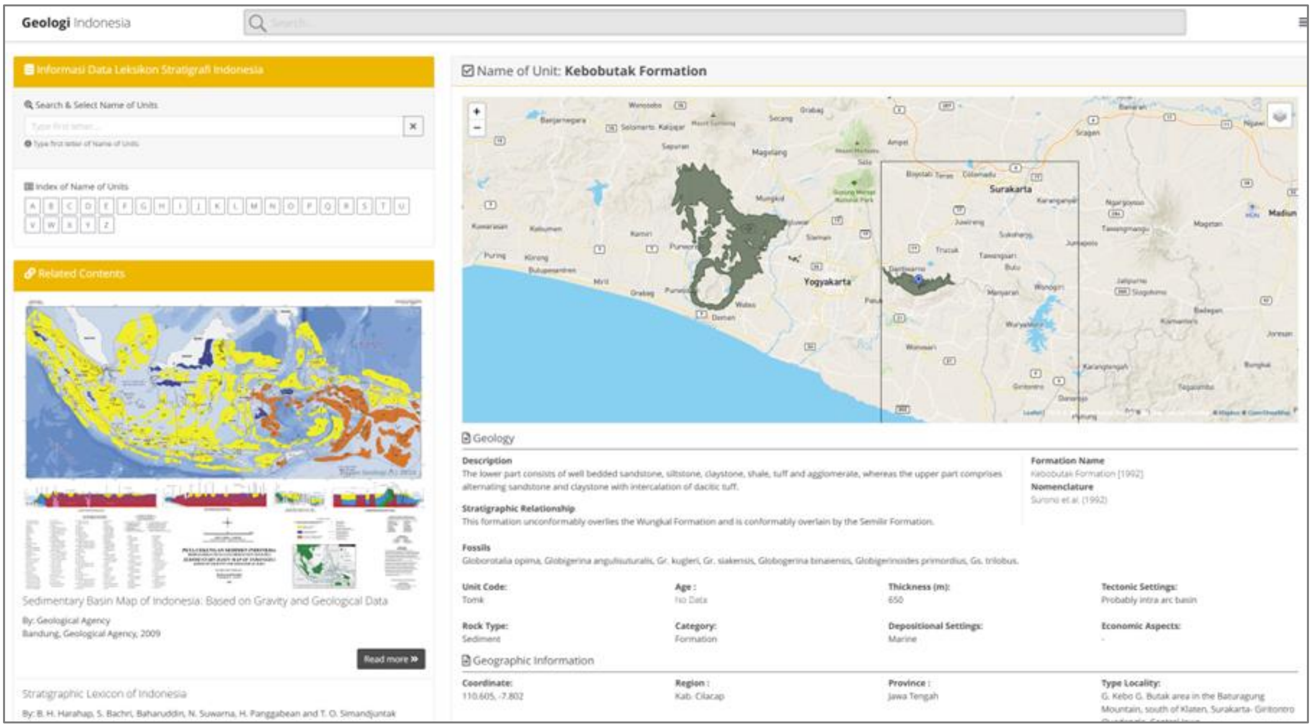

Figure 2: *A display of the web-based stratigraphic lexicon of Indonesia, published by the Geological Survey of Indonesia*

(https://geologi.esdm.go.id/geolindo/lexicon/index). Users can simply type the name of the formation and the distribution map, age, thickness, rock type, depositional and tectonic setting, economic aspects, and the index fossil will appear. The map on the website is interactive, as the user can retrieve the source of the formation information (Figure 2).

INDOGEO Social Enterprise has recently completed a GIS (Geographic Information System) layer of stratigraphic location types, which is downloadable from their website (www.indogeo.org) in the first quarter of 2024. Figure 3 shows a comparison of digitised type locations in Marks (1957) and Harahap et al. (2003). The shape file provided will also have a hyperlink to connect to the web-based lexicon mentioned in the previous paragraph. During the shapefile/GIS layer preparation, some problems were exposed, and they were documented in the attribute of the GIS shape file.

With GIS, users can overlay the stratigraphic location types with geological maps, topographic maps, satellite images, etc. This will be very useful for detailed geological studies. Figure 4 shows an example of how the type locations are overlaid on top of the geological map and depicts the attribute of the GIS layer. If there is a problem, such as a website broken link or error, or typo error in the lexicon, a note will be provided in the remark's column.

FUTURE

Each formation is described well in the lexicon with some information on the type location (Marks, 1957; Harahap et al., 2003). This study proposes that the development of a web-based lexicon and

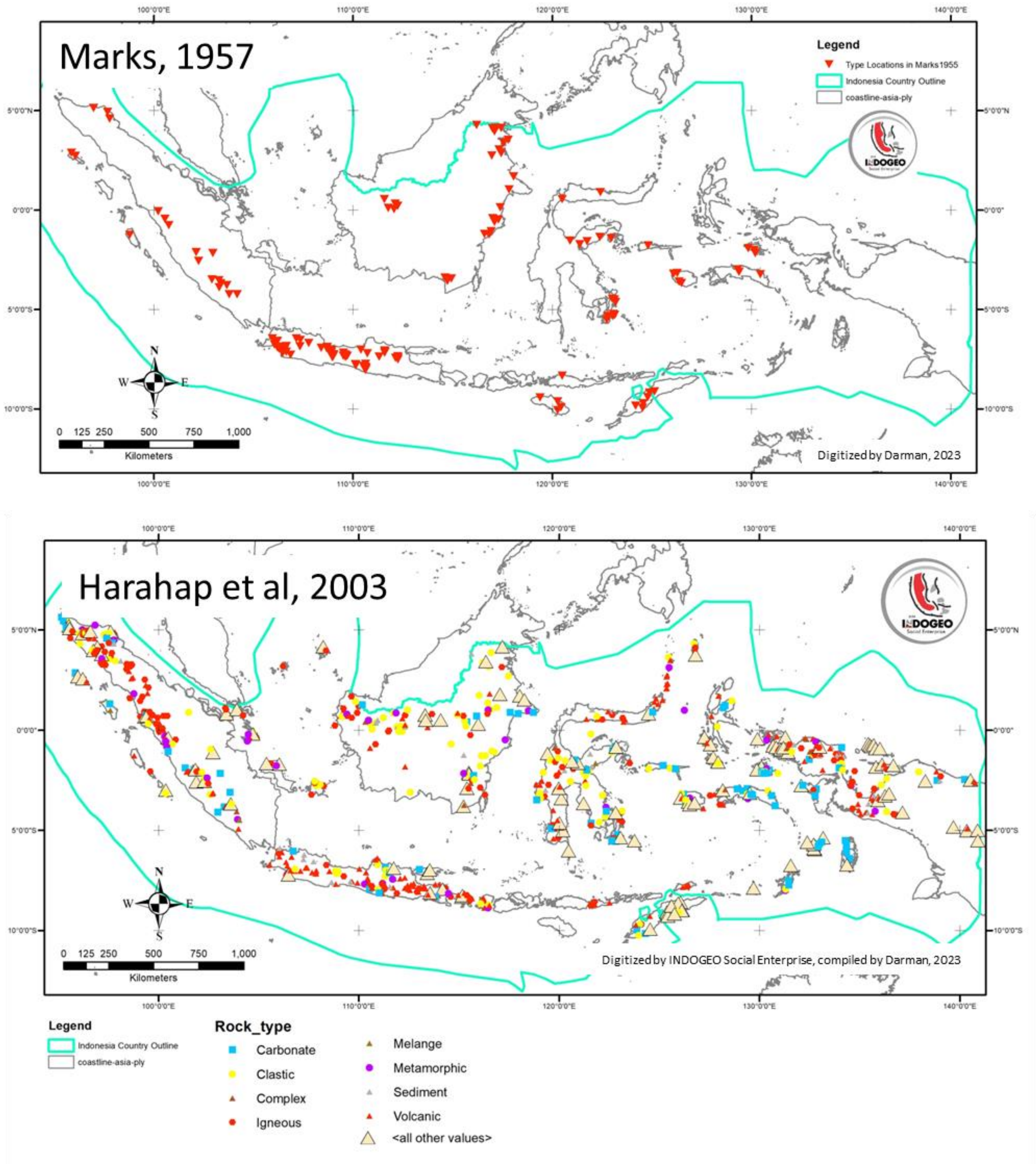

Figure 3: *Distribution map of type locations documented in Marks, 1957 (146 locations, above) and in Harahap et al. (2003) [1856 units, 829 locations]. Both are digitised by INDOGEO Social Enterprise.*

GIS-based digitation of type locations should be followed by the documentation of stratigraphic sections of the type locations, or stratotypes. The stratotypes may originate from outcrop and subsurface studies.

As an example, in 1988, IUGS-UNESCO published Triassic outcrop sections in the

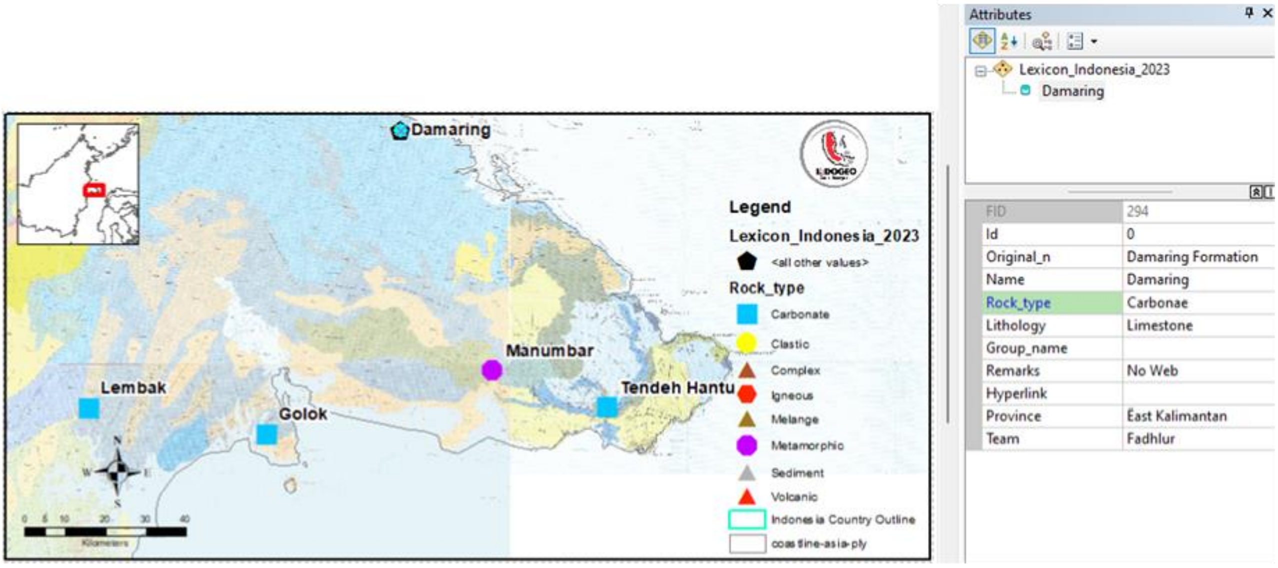

Figure 4: *An example of the GIS display of the location type data in Mangkalihat Peninsula, East Kalimantan. A 1:250,000 scale geological map is displayed as a backdrop of the type of location map (left) and the attribute table of each location (right). Note that Damaring Formation in the north of the map only occur in Lexicon Map of Harahap et al. (2003), but no description in the text.*

Asia Pacific region. The report included 5 stratotypes published from Timor Leste, which was part of Indonesia at that time. These sections were drawn using a standard legend (Figure 5). The legend will help in maintaining the consistency of different researchers or geoscientists who are reporting the stratotype. Additional outcrop pictures will make it better.

Collaboration between IAGI and the universities, as well as the research institutes and agencies, should be able to provide consistent stratotypes across Indonesia. These stratotypes are important to be documented because they do not last forever, as rapid development in Indonesia may destroy the original stratotypes.

Maintenance of the web-based lexicon is important to be conducted in the future. As mentioned earlier, the web-based lexicon contained errors, which were noted in the GIS layer. The web-based lexicon needs to have a contact person since it is important to collect feedback from users for improving the website.

The type locations should be available to the geoscientists who work in the field. With the geographic information, the type locations could be displayed in hand-held instruments (e.g. Through Gear-ID, https://gearid-geo.com/).

CONCLUSION

As a matter of course, the present edition of the lexicon is beyond perfection and, therefore, one may find it unsatisfactory to their need. Issues on the lexicon that need improvements include inconsistencies, synonymies, lack of proper information, and unavoidable mistakes. They should be dealt with in the future edition. For this, further suggestions, criticisms, and contributions from those who are involved in the stratigraphy of Indonesia are required.

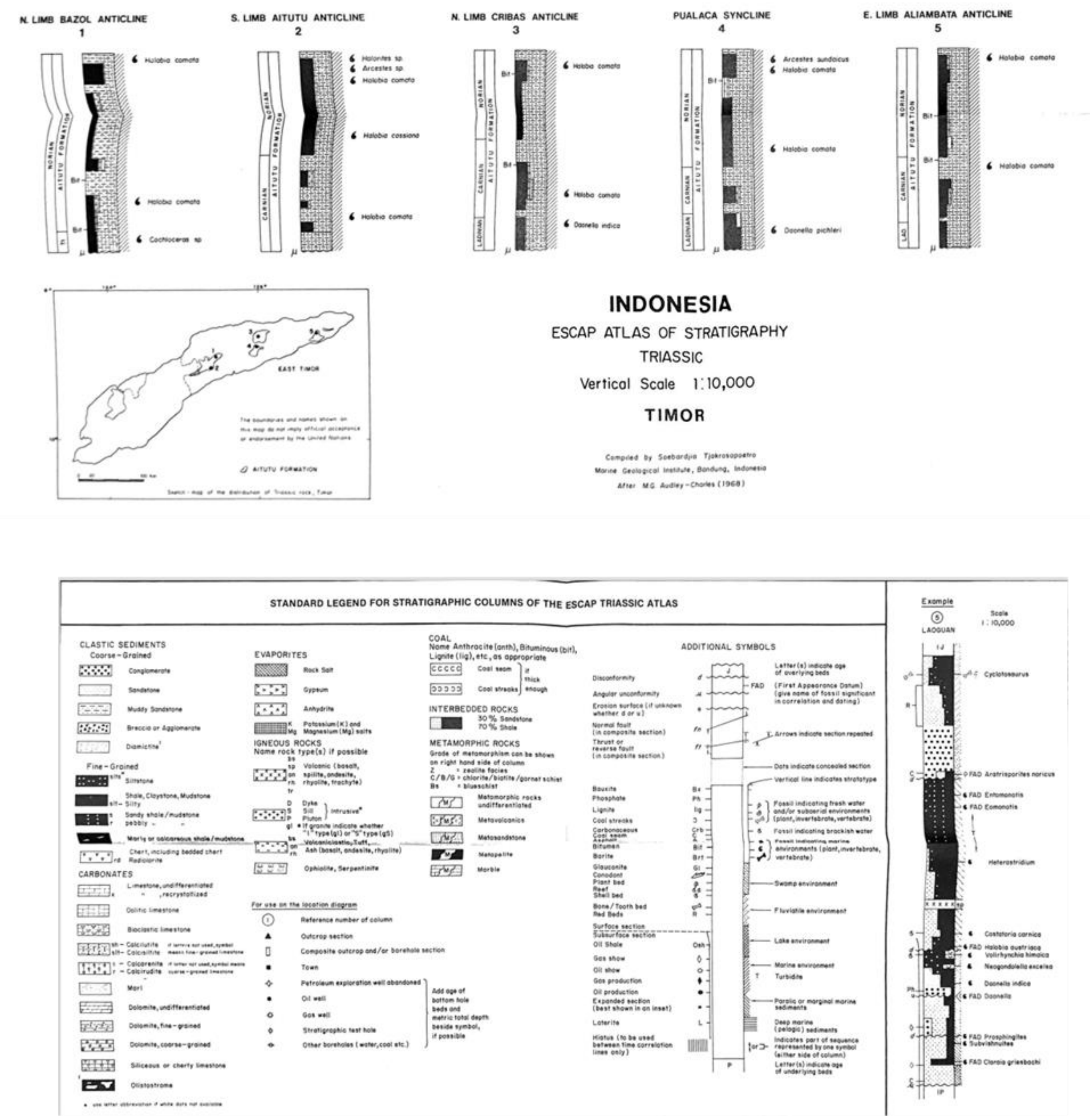

Figure 5: *Type logs or stratotypes of several Triassic type locations in Timor Leste (was registered as Indonesia, in 1988 IUGS-UNESCO report, above). The logs in the report used a standard legend (below) to maintain the consistency of all sections in the report.*

The lexicon needs systematic updates and improvement. Currently, it is handled by the Geological Survey of Indonesia which is limited in terms of budget and resources. The Indonesian Association of Geologists (IAGI) could organize some support by organizing scientific discussions during their annual meeting or other special events and facilitating discussions among their members. Regular meetings, such as sessions in PIT-IAGI (Pertemuan Ilmiah Tahunan or Annual Scientific Meeting of IAGI) are probably a good forum to discuss the stratigraphy of Indonesia.

The universities in Indonesia could contribute by providing type logs from their studied area. They were supposed to publish type logs of their research areas using a common type log template and published them.

ACKNOWLEDGEMENT

The map digitation was completed in November 2023 by the INDOGEO Social Enterprise team which consisted of Indonesian fresh graduates in geoscience. The authors would like to acknowledge these strongly motivated and talented young geoscientists. Those who involved and supported the project, in alphabetic order, were Afriliani M. Handini, Brimas Aptanindia Pangestu, Cintia Amalia Syaadah, Elsandra Pinky Sasmita, Fadhlur Rahman, Hafid Rizki Nur Rohman, Imtiyaz Atsarina, Krishna Agra Pranatikta, Rani Izdihar, Rena Nur Fauziah, Ririn Setyowati, Shafa Samratul Fuadah, Siti Salsabila Akrima, Sonia Fauziah, Sri Wahyuni, and Tedy Wiku Setiaji.

REFERENCES

Geological Survey of Indonesia, 1961. Publikasi Keilmuan No. 31A, Seri Geologi, Republik Indonesia Kementerian Perekonomian, Pusat Djawatan Geologi, Bandung.

Harahap, B. H., Bachri, S., Baharuddin, Suwarna, N., Panggabean, H., and Simandjuntak, T. O., 2003. Stratigraphic Lexicon of Indonesia, Bandung, Geological Research & Development Centre.

IUGS-UNESCO, 1988. ESCAP Atlas of Stratigraphy VII, Triassic of Asia, Australia and the Pacific, Stratigraphic Correlation Between Sedimentary Basins of the ESCAP Region, Mineral Resouces Development Series No. 56, United Nations.

Marks, P., 1957. Stratigraphic Lexicon of Indonesia, Publikasi Keilmuan No. 31, Seri Geologi, Republik Indonesia Kementerian Perekonomian, Pusat Djawatan Geologi, Bandung.

A proposed model of Width-Thickness Ratio for tidal shelf sand ridge reservoirs within Upper Cibulakan Fm. in the Ajata Field, Offshore Northwest Java Basin

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ABSTRACT

The Upper Cibulakan reservoir of the Ajata Field in the Northwest Java Basin represents tidal shelf sand ridges deposited in an open-mouthed shallow marine environment. One hundred fifty-three wells have been drilled to develop this reservoir since 1970. The average density of wells in the Ajata Field is 400-500 m, making it an ideal case for reconstructing tidal shelf sand ridges reservoir model. This study aims to determine tidal shelf sand ridges heterogeneity and geometry, especially through width-thickness ratio, in the Ajata Field and to identify similar reservoirs in other fields or basins. The data used in this study are 900 ft conventional core data, 74 Routine Core Analysis (RCA) data, 152 well logs, and 3D seismic data.

Tidal shelf sand ridges conventional cores analysis shows six lithofacies in the Upper Cibulakan Formation, namely: claystone-siltstone, lenticular siltstone, flaser sandstones, cross-bedded sandstones, non-calcareous massive sandstones, and calcareous sandstones. These six lithofacies are grouped into four facies associations and they reflect the tidal shelf ridge development stages: embryonic, immature accretion, mature accretion, and abandonment. These facies associations create a cyclicity pattern bounded by chronostratigraphic markers of marine flooding surfaces. Well-to-well correlation and seismic interpretation results show several trends and geometry of the tidal shelf sand ridges. Three zones of width thickness ratio (W-T) analysis in every parasequence are concluded in this study: Zone I (width: maximum 800 m; thickness: less than 25 ft), Zone II (width: 700 – 1300 m; thickness: 25 – 45 ft), and Zone III (width: 1000 – 1900 m; thickness: thicker than 45 ft).

Keywords: *Tidal shelf sand ridges, Upper Cibulakan, Northwest Java Basin*

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INTRODUCTION

Sandstone reservoirs from the Upper Cibulakan Formation are the largest oil producer in the Northwest Java Basin. More than 80% of the hydrocarbon production in the Offshore Northwest Java fields come from these reservoirs. Most sandstone reservoirs from the Upper Cibulakan Formation represent tidal shelf sand ridge deposits. The reservoirs were deposited in an open-mouthed shallow marine embayment with high control of tide current during deposition (Figure 1).

Lack of information about the basic concept of shelf ridges geometry becomes a significant problem in interpreting tidal shelf sand ridges reservoirs. The only published example of tidal shelf sand ridges deposits that formed in an open-mouthed, shallow marine embayment is from the Quaternary deposits in the Yellow Sea, China (Xu et al., 2017). Due to this condition, the Upper Cibulakan Formation in the Northwest Java Basin can be another example to develop tidal shelf sand ridges deposit geological models.

The Ajata Field is one of the most significant oil fields in the Northwest Java Basin, with most of oil production derived from the Upper Cibulakan Formation's reservoirs. In this field, one hundred fifty-three wells have been drilled to develop this reservoir since 1970. The average wells density in the Ajata Field is 400-500 meters. As a giant oil field in the Northwest Java Basin, the Ajata Field has a complete subsurface database and high well data density. This condition allows the Ajata Field to be a suitable location for constructing a model on the tidal shelf sand ridges deposit (Figure 2).

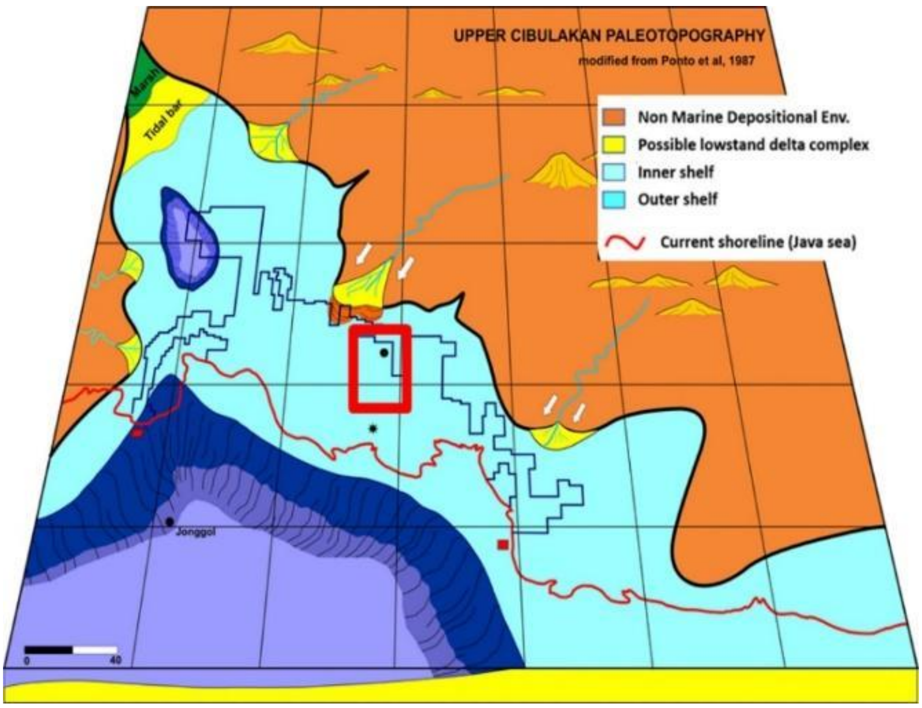

Figure 1: *Upper Cibulakan paleo-topography reconstruction (modified after Ponto et al., 1987).*

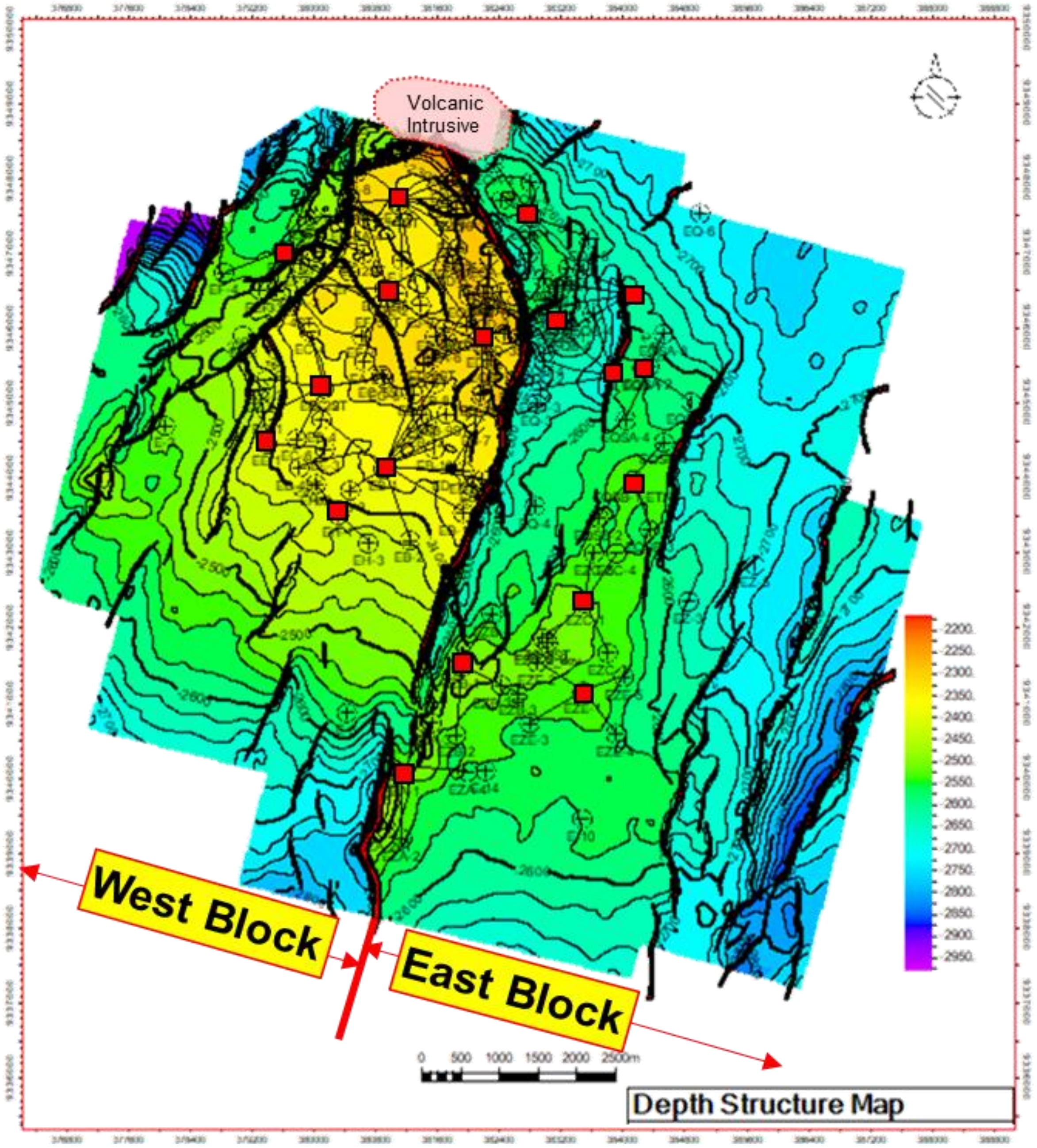

Figure 2: *Ajata Field Depth Structure Map.*

DATA AND METHODOLOGY

The study aims to determine tidal shelf sand ridges heterogeneity and geometry, especially through width-thickness ratio, so that it can become analogue for other fields or basins having similar reservoir type. The data utilised in this study are 900 ft conventional core data, 74 RCA data, 152 well logs, and 3D seismic data.

The research methodology used in this study involves sequence stratigraphy approach, which consists of dividing rock relationships within the geological time framework and identifying genetically related facies units. The objective of this concept is to identify geometry of strata

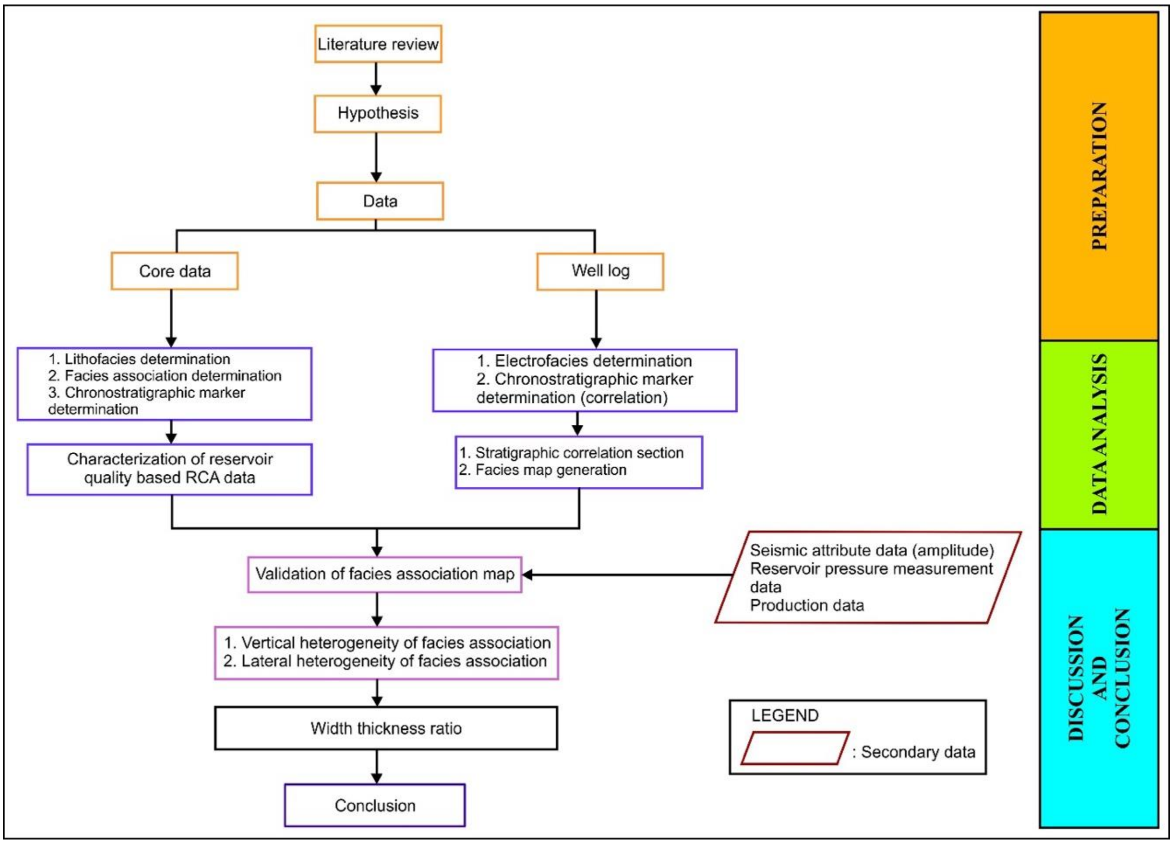

Figure 3: *Study Workflow.*

and facies patterns within sedimentary basins and to analyse the distribution of hydrocarbon accumulation areas. The high-resolution sequence stratigraphy approach in this research helps in analysing sedimentary units at a parasequence scale, allowing to determine the geometry, distribution, and characteristics of reservoir facies (Figure 3).

In this study, facies association of tidal shelf sand ridges is analyzed using pie chart method. A depositional parasequence cycle of tidal shelf sand ridges begins with the presence of the Transgressive Surface (TS) marker and ends with the flooding surface. In some conditions, the presence of the TS marker is challenging to be identified, as the marker is overlapped with the flooding surface. In the pie chart method, the thickness of the parasequence is reflected as the circle's diameter, while the percentage within the pie chart represents thickness ratio of each facies association to the measured total thickness. Afterward, the integration of pie chart method and qualitative seismic interpretation is conducted to define the trends of each tidal shelf sand ridge. The distribution of each facies association will be controlled by the trends of each ridge, especially for facies with good reservoir quality (Figure 4).

Posamentier (2002) interprets the deposition of the Upper Cibulakan Formation sandstone as tidal shelf ridge morphology, which is a product of tidal solid influences. As a background, Lopez et al. (2016) subdivides the depositional sequence for tidal shelf ridge deposits into three (3) main stages: embryonic,

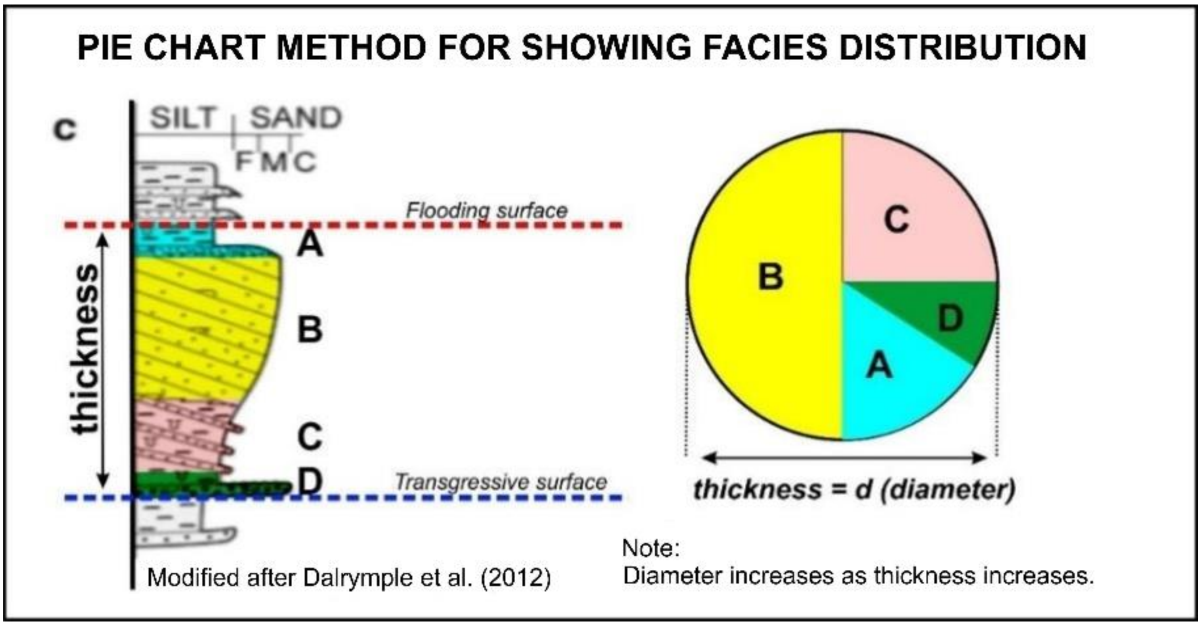

Figure 4: *Pie chart methodology applied used in this study.*

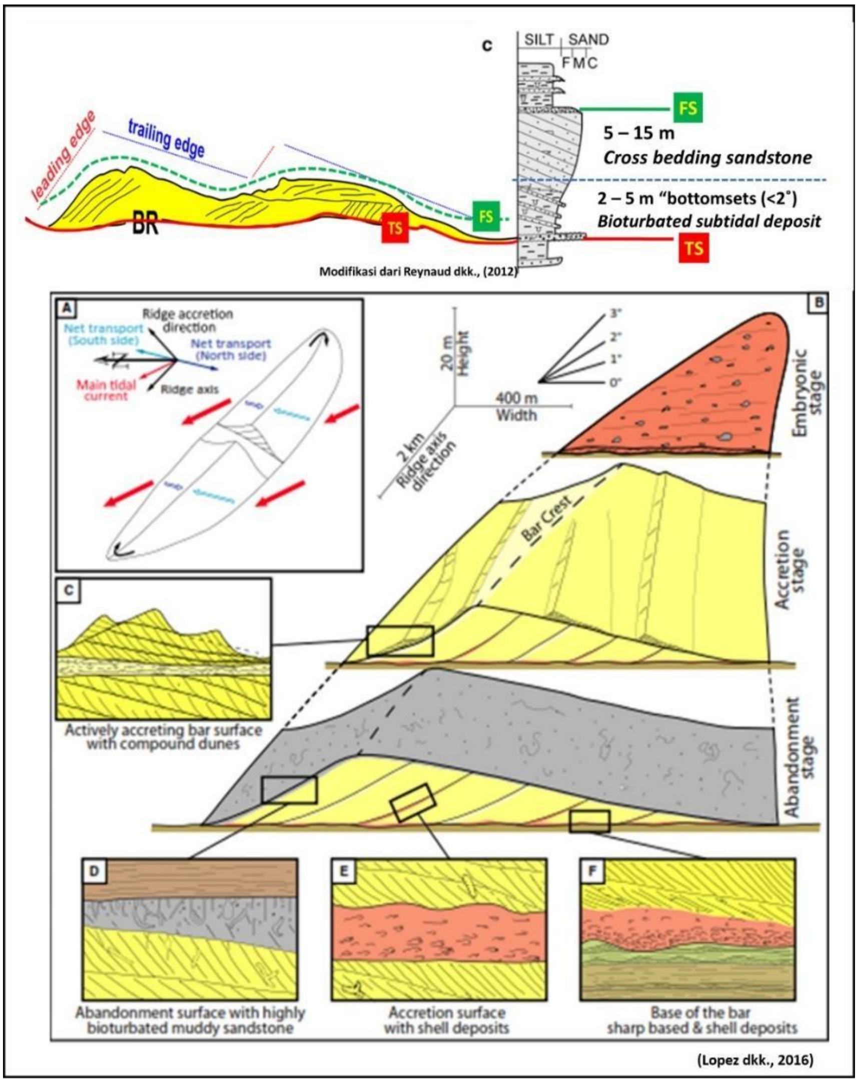

Figure 5: *Tidal Shelf Ridges Morphology and Development Stages (modified after Dalrymple et al., 2012 and Lopez et al., 2016).*

accretion, and abandonment (Figure 5). These three stages are represented by facies associations reflecting two fundamental aspects: reservoir quality and geometry of the facies associations.

RESULT AND DISCUSSION

Tidal Shelf Sand Ridges Lithofacies Interpretation

The description of the core data in the Upper Cibulakan Formation results in six lithofacies (Table 1): claystone-siltstone, calcareous sandstone, lenticular siltstone, flaser sandstone, non-calcareous “massive sandstone”, and cross-bedded sandstone.

Table 1. *Lithofacies “analysis result based on core data in Ajata Field*

No	Lithofacies	Characteristics	Remarks (ft MD)
1	Calcareous sandstone	Calcareous shell fragments; Siltstone-sandstone clastics	▪ LC-2: 2516’-2517’, 3304’-3305’, 3368’-3371’ ▪ LJ-1: 2437’-2438’, 2452’-2453’, 3328’-3330’ ▪ LQB-2: 4871’-4873’ ▪ LZC-2: 3319’-3201’
2	Claystone-siltstone	Massive; Bioturbation	▪ LC-2: 2513’-2515’, 3287’-3295’ ▪ LJ-1: 2446’-2451’, 2606’-2615’, 2570’-2575’, 2558’-2564’
3	Lenticular siltstone	Lenticular sedimentary structure; Bioturbation	▪ LC-2: 2448’-2452’, 2508’-2514’, 2683’-2685’, 3409’-3415’ ▪ LJ-1: 2444’-2446’, 2602’-2606’ ▪ L-3: 2421’-2423’, 2433’-2442’ ▪ L-2: 2260’-2262’ ▪ LQB-2: 4861’-4864’ ▪ LZC-2: 3452’-3455’
4	Flaser sandstone	Flaser sedimentary structure	▪ LC-2: 2446’-2448’, 2506’-2508’, 3281’-3287’, 3307’-3319’, 3381’-3385’, 3393’-3398’ ▪ LJ-1: 2443’-2444’, 2567’-2569’, 3293’-3295’, 3318’-3321’ ▪ L-3: 2420’-2422’ ▪ L-2: 2661’-2663’ LQB-2: 4879’-4886’, 4892’-4900’, 4857’-4861’ ▪ LZC-2: 3209’-3215’
5	Non-calcareous “massive sandstone”	Massive (>1 m); Structureless	▪ LC-2: 2434'-2446', 2466'-2492', 2498'-2506', 3230'-3279 ▪ LJ-1: 2438'-2443', 2453'-2466', 2547'-2555', 2578'-2585', 3279'-3292' ▪ L-2: 2255'-2260' ▪ LQB-2: 3320'-3326', 3388'-3400', 4278'-4303', 4847'-4853' ▪ LZC-2: 3202'-3209'
6	Cross-bedded sandstone	Cross-bed sedimentary structure	▪ LQB-2: 4238'-4245', 4252'-4265'

Tidal Shelf Sand Ridges Facies Association

The lithofacies analysis based on the core data from the Ajata Field mainly shows a facies association deposited in the shallow marine environments (from foreshore to offshore area). The determination of the facies association from the analysis in lithofacies obtained from the Ajata Field refers to the facies association subdivision based on Lopez et al. (2016), subdividing the tidal shelf ridge deposits in the shoreface-offshore environment into three stages of formation: embryonic, accretion, and abandonment (Table 2). The stages represent facies associations of their constituent lithofacies.

Table 2. *Relationship between lithofacies, facies association, and reservoir character.*

Lithofacies	Facies association (Lopez et al., 2016)	Remark
Calcareous sandstone	Embryonic Abandonment	Non-reservoir
Claystone-siltstone	Embryonic Abandonment	Non-reservoir
Lenticular siltstone	Accretion	Reservoir (poor quality)
Flaser sandstone	Accretion	Reservoir (poor quality)
Non-calcareous “massive sandstone”	Accretion	Reservoir (good quality)
Cross-bedded sandstone	Accretion	Reservoir (good quality)

In the Ajata Field, the embryonic stage's facies association consists of calcareous sandstone and claystone-siltstone lithofacies. The embryonic facies association represents the initial stage of the formation of tidal shelf ridges, starting with the deposition of transgressive lag deposits followed by the deposition of claystone-siltstone lithofacies. The accretion facies association is the main stage of the growth of tidal shelf ridge morphology, characterized by an increasing rate of sediment supply, resulting in the formation of lens-shaped claystone-siltstone lithofacies, flaser sandstone, non-calcareous massive sandstone, and cross-bedded laminated sandstone. The abandonment facies association marks the cessation of deposition of tidal shelf ridge due to a decrease in sediment supply rate, characterized by calcareous sandstone resulting from calcareous cementation at the top of the shelf ridge and claystone-siltstone lithofacies (Figure 6).

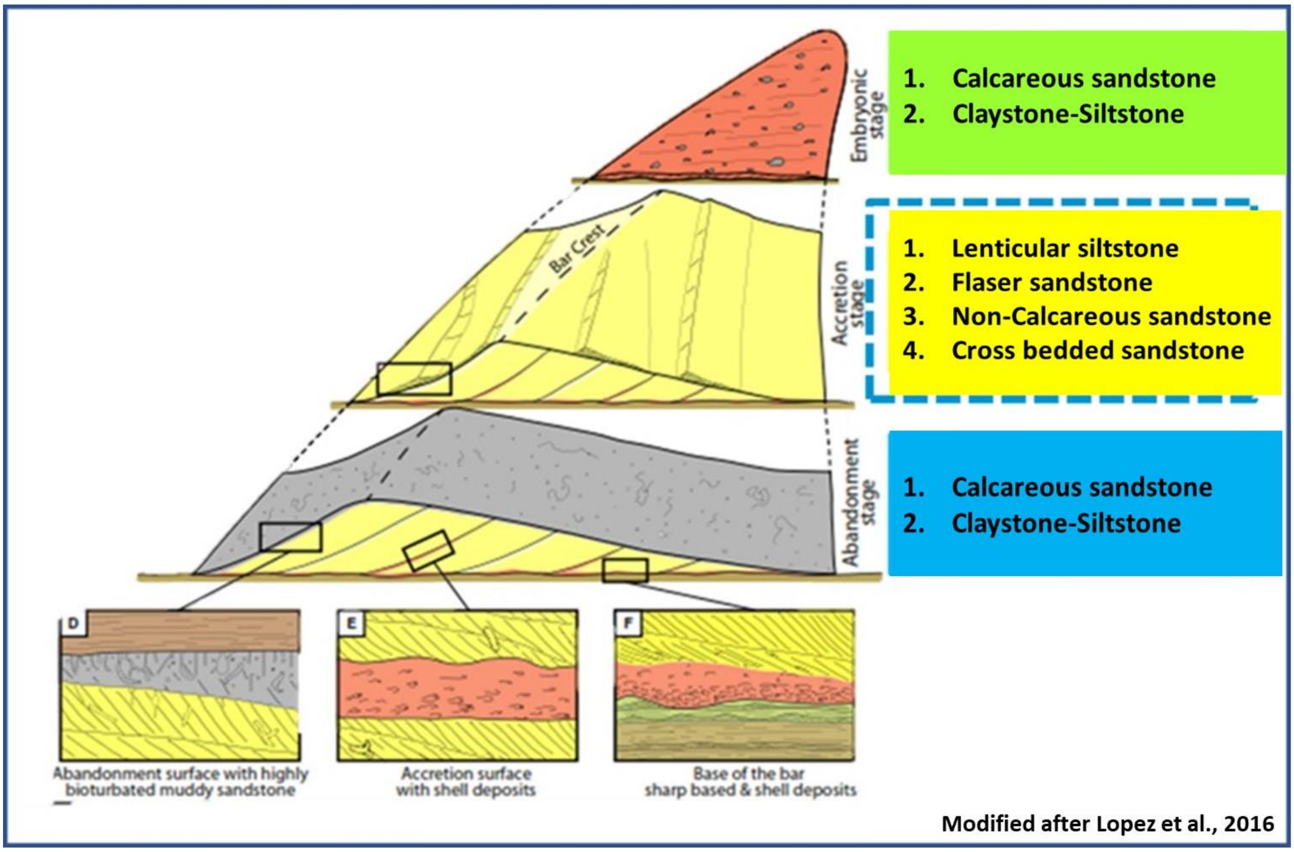

Figure 6: *Facies association determination and relationship (modified after Lopez et al. [2016])*

The flooding surface is the chronostratigraphic marker at the top of the abandonment facies association.

Depositional environment of the Northwest Java Basin during the deposition of the Upper Cibulakan Formation has a range of tidal currents with a macro to mega tidal type. It is reflected by the four lithofacies in this study area which comprise reservoirs: lenticular siltstone, flaser sandstone, non-calcareous massive sandstone, and cross-bedded sandstone. Lenticular siltstone and flaser sandstone indicate deposition dominated by tidal currents or tides. On the other hand, non-calcareous massive and cross-bedded sandstone are formed in a depositional environment with robust current systems due to wave action. These two depositional currents forming the Upper Cibulakan Formation indicate tidally modulated shore face (TMS) (Figure 7).

This study subdivides the accretion facies association of Lopez et al. (2016) into two categories: immature and mature accretions. Based on core data analysis, the deposition of the former facies' association is followed by the latter. Lithofacies constituting immature accretion facies association are lenticular siltstone and flaser sandstone, which are strongly influenced by tidal currents. This facies association is formed after the deposition of embryonic facies association and indicates an increase in sediment supply. Moreover, mature accretion facies association is deposited during intensifying fair-weather wave, and it is characterised by non-calcareous massive

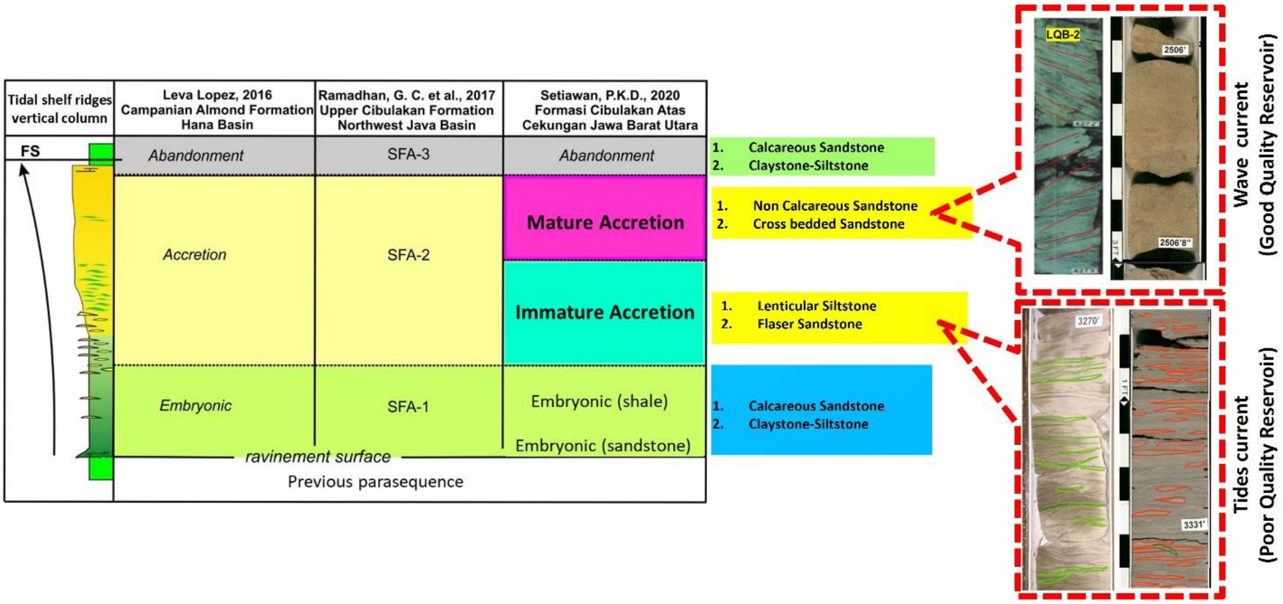

Figure 7: *Tidal shelf sand ridges facies association model compared with previous model.*

sandstone and cross-bedded sandstone lithofacies.

The immature and mature accretion facies associations show different reservoir characteristics. Immature accretion facies association displays high percentage of shale, resulting in poor quality reservoirs. Mature accretion facies association has good sorting and low mud content due to increased sediment washing, leading to good reservoir quality (Figure 7). Such sediment washing results from the combination of fair-weather waves, increased sediment supply, and macro to mega tides.

Tidal Shelf Sand Ridges Depositional Environment.

The depositional environment in the coastal area consists of several depositional environments controlled by the presence of wave and tidal currents. Dashtgard et al. (2012) subdivides the coastal environment into several zones: backshore, foreshore, upper shoreface, middle shoreface, lower shoreface, and offshore. Generally, the depositional environment developed during the deposition of the Upper Cibulakan Formation in the Ajata Field is the shoreface and depositional environments towards the land such as foreshore and backshore (Figure 8).

The embryonic facies association represents the initial deposition of tidal shelf ridges in the lower shoreface-offshore environment. The deposit of this facies association begins with subaqueous erosion during sea level rise in the lower shoreface area. The sediment supply rate during the deposition of the embryonic facies association is low, forming the domination of lithofacies with fine grain sizes, such as silty mudstone. The increased sediment supply rate and control from the tidal range lead to the deposition of the immature accretion facies in the middle shore face-lower shore face environment. The tidal process strongly influences from the lower to middle shoreface environment. The condition results in the formation of lithofacies with sedimentary structures characterized by tidal processes such as lenticular and flaser bedding. The continuous increase in sediment supply rate leads to the shallowing of the seabed. This situation leads to wave activity forming the mature accretion facies association. During the deposition of this facies association, the shoreface environment is mostly located in the upper shoreface-middle shoreface area (Figure 8).

Tidal Shelf Sand Ridges Total Porosity-Permeability Relationship.

There is a linear relationship between facies association, total porosity, and permeability as shown in the cross-plot in Figure 9. The mature accretion facies association has the best total porosity and permeability quality, followed by the immature accretion facies association. The immature and mature accretion facies associations are the main reservoir types in the Upper Cibulakan Formation. The embryonic and abandonment facies associations are categorized as non-reservoir facies associations.

The total porosity values in this study area range from below 15% to 38%, while the permeability is from 0.01 mD to 2000 mD (Figure 9). The mature accretion facies association has good reservoir quality with a range of total porosity from 21% to 38% and is dominated by a total porosity range from 31% to 35%. The permeability values based on RCA data in this facies association range from 100 mD to 2000 mD (Figure 9). The immature accretion total porosity range based on RCA data is 11% - 25%, with the most significant data dominance from 16% to 20%. The immature accretion facies association has permeability values below 100 mD (3 mD - 100 mD). The embryonic and abandonment facies associations are categorized as non-reservoir facies. These facies have the worst properties compared to the reservoir facies associations. The total porosity of the embryonic and abandonment facies associations is below

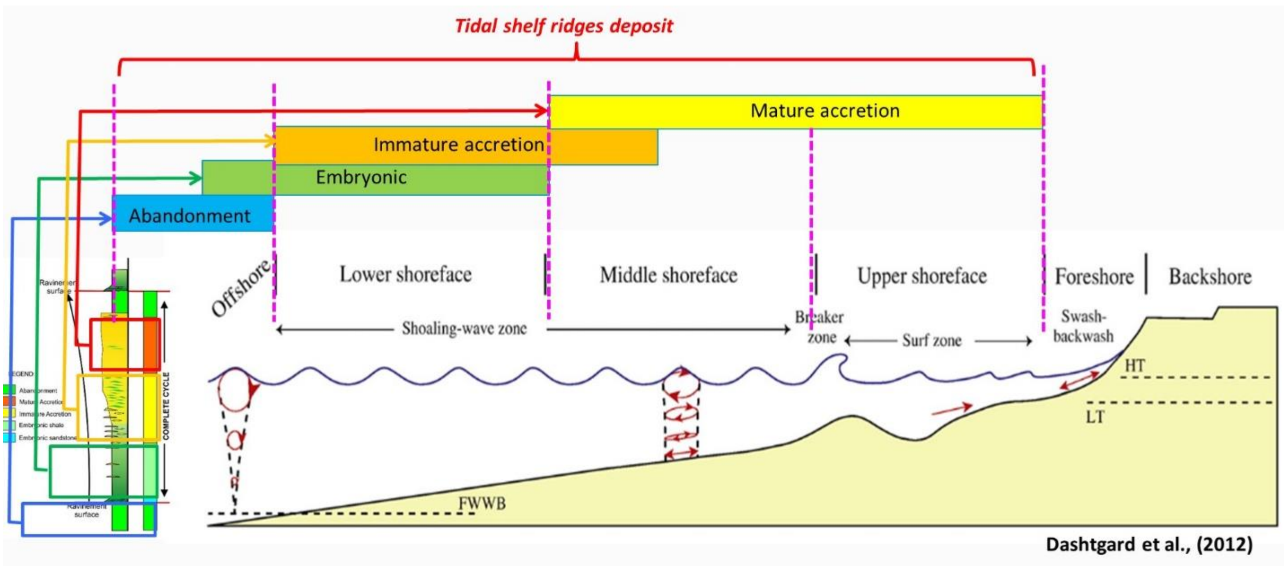

Figure 8: *Tidal shelf sand ridges depositional model (modified after Dashtgard et al. 2012).*

15% with permeability values of 0.01 mD - 5 mD (Figure 9).

Tidal Shelf Sand Ridges Vertical and Lateral Reconstruction.

The west-east stratigraphic section shows the morphology of tidal shelf ridge deposits, and it is perpendicular to the direction of sediment supply (Figure 10). The reconstruction of ridge morphology is conducted by flattening the chronostratigraphic markers below the reservoir interval, including transgressive and flooding surfaces.

The stratigraphic section of the tidal shelf ridges reservoir interval in the Ajata Field shows the configuration of several ridges. There are five to six ridges formed in each reservoir interval. The shelf ridges have widths ranging from 800 meters to 1,600 meters. The thickest part (leading edge) of each ridge has the potential presence of the mature accretion facies association, as found in the well sections LC-1, LC-2, LC-3, LB-1, LZ-3, and LZC-5. The thinnest area~~s~~ (trailing edge) between the ridges of the tidal shelf ridge deposits ~~are~~ dominated by the immature accretion facies association, as observed in well L-1, interval reservoir LRS-22A (Figure 10).

The reconstruction analysis in the LRS-22B interval shows the presence of five ridges constituting the LRS-22B reservoir. The mature accretion facies association appears at the uppermost part of the ridge. Mature accretion facies association of the tidal shelf ridge deposits indicates more intensive wave action during deposition. On the other hand, the immature accretion facies association mainly occurs in the thinnest part of the tidal shelf ridge deposits. This thinnest area represents the deepest area during deposition coeval with less wave influence

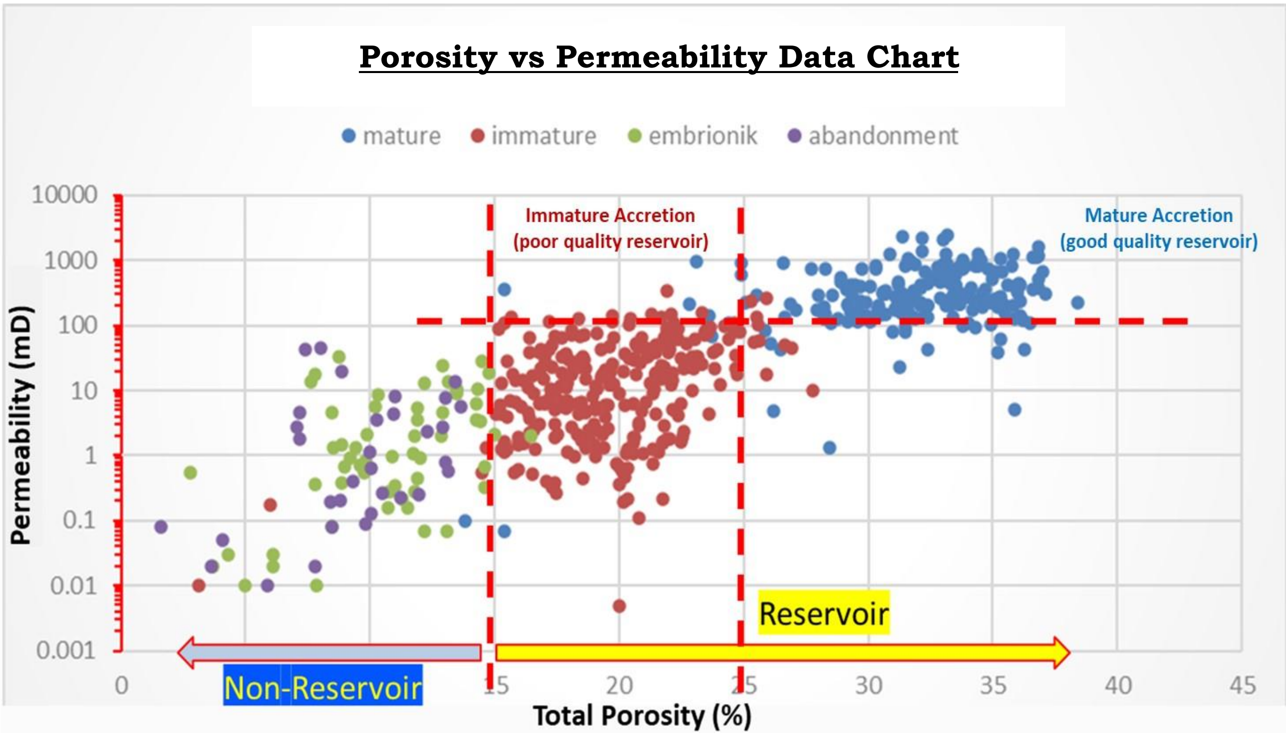

Figure 9: *Facies association, total porosity and permeability relationship based on RCA data in the Ajata Field.*

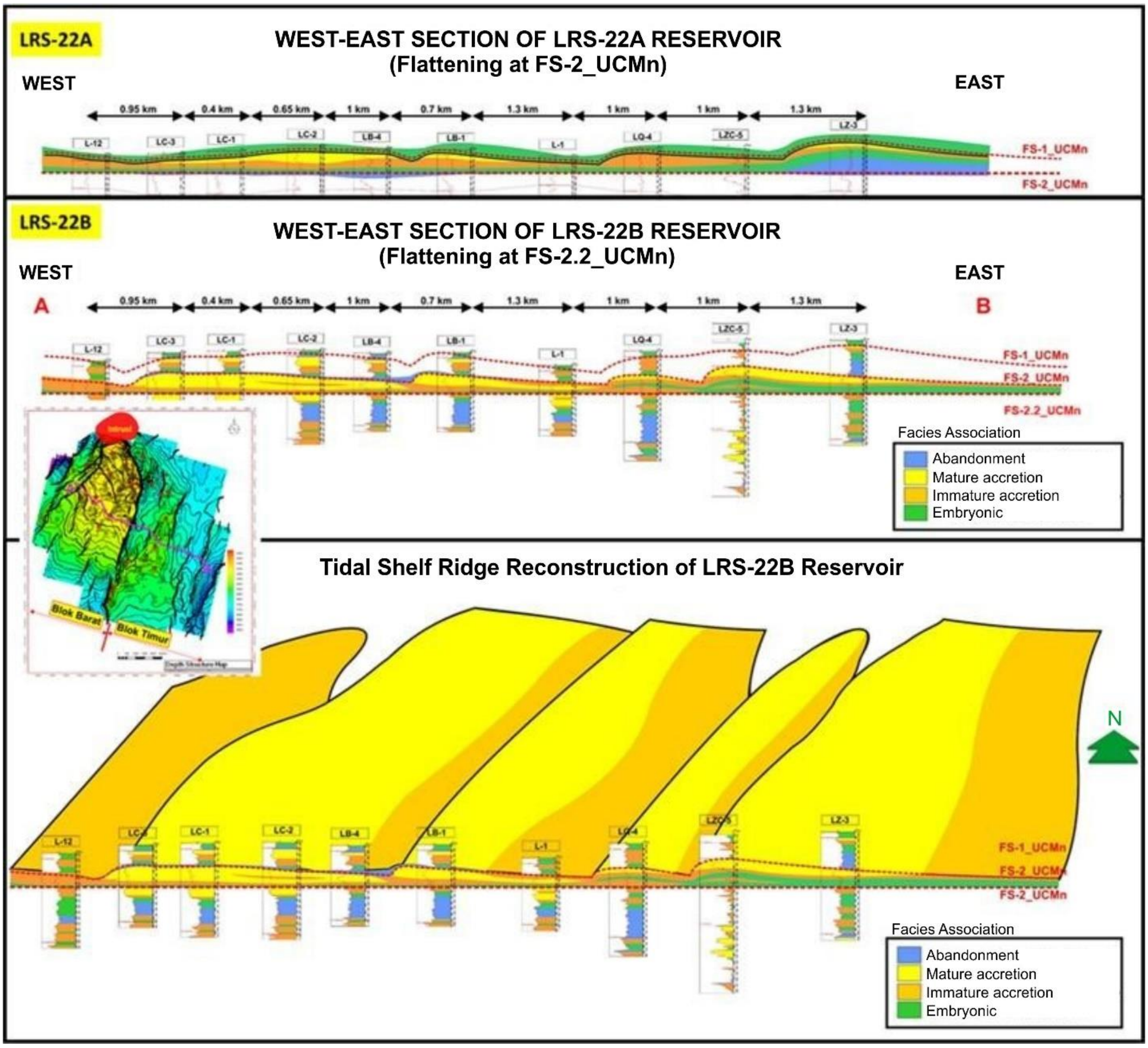

Figure 10: *Stratigraphic cross-section and tidal shelf sand ridges reconstruction in Ajata Field*

and more dominance of tidal currents. (Figure 10).

The reconstruction of the LRS-22A tidal shelf ridge sequence (Figure 11) is constrained by the chronostratigraphic markers at the bottom and top, which coincide with the top of the sandstone reservoir. The correlation results from these markers are presented as pie charts in each well penetrating the reservoir interval. The diameter of the pie chart reflects the vertical thickness or true vertical thickness (TVT) between the two markers that bound the reservoir interval. The filled color segments inside the pie chart represents the thickness ratio of each facies association of the parasequence. The tidal shelf ridge deposits are characterized by large-diameter pie charts at the crest of the ridges and small-diameter pie charts in the inter-ridge valleys.

The distribution map of the facies association pie charts (Figure 11) shows five prominent ridges that form the LRS-22A reservoir deposit. The dashed blue lines in the image represent the straight lines of the valleys that form the boundaries between the two ridges. The trend of the ridges is northeast-southwest with a slope angle of about N12°E. The width of each ridge ranges from 800 m to 1,500 m. The direction derived from the pie chart map is used to create the parasequence isopach map. The thickness of the parasequence ranges from 5 ft to 40 ft. The inter-ridge valley areas have thickness range from 5 ft to 15 ft, while the ridge crest has thickness from 30 ft to 42 ft (Figure 11).

The facies association ratios displayed by the color segments in the facies association pie charts are used to control the distribution of the LRS-22A tidal shelf ridge facies associations. In the Ajata

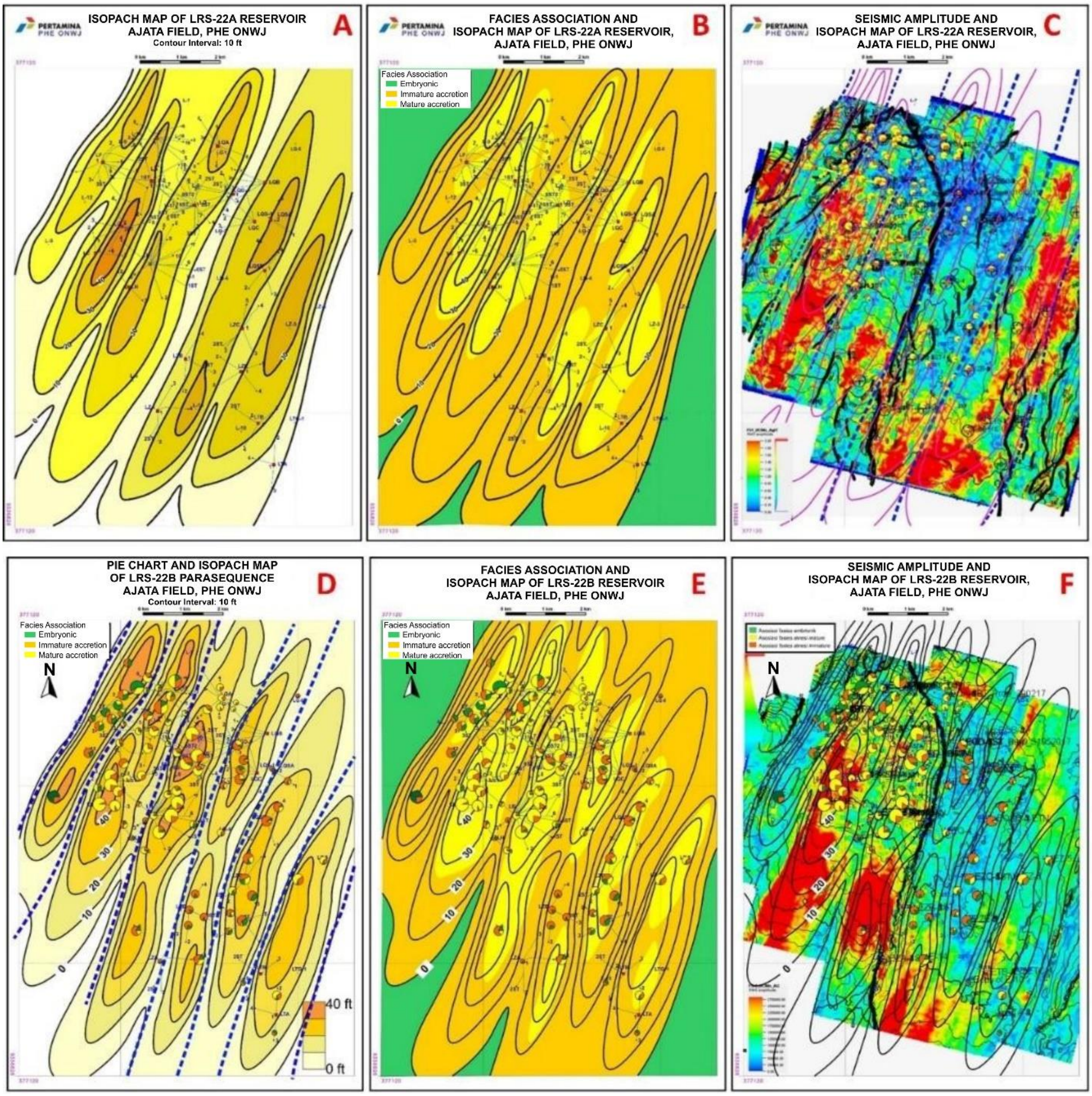

Figure 11: *Isopach and facies association reconstruction of tidal shelf sand ridges deposit in Ajata Field*

Field, the immature accretion facies association in the LRS-22A zone is widely distributed. The mature accretion facies association is mainly located at the crest of the ridges and does not extend into the inter-ridge areas. The distribution of the embryonic or non-reservoir facies association is interpreted to be located south of the study area or basinward. The distribution of the embryonic facies association in the western and eastern parts of the study area is interpretive due to the wells data absence in those areas (Figure 11).

Seismic amplitude attribute data from the LRS-22A sequence is overlain by the tidal shelf ridges thickness map to determine the qualitative relationship between the thickness (isopach) map and the seismic attribute data (Figure 11). Figure 11 shows that several ridge trends, such as in the western and eastern parts of the study area, coincide with seismic amplitude data. The overlay result shows several ridge trends of the LRS-22A tidal shelf ridges visible in the seismic amplitude data, such as in the western and eastern parts of the study area. The seismic attribute quality is good in the western-southwestern and eastern parts of the study area. Conversely, seismic data with poorer quality is observed in the central and northern parts of the study area due to the presence of closely spaced production platforms, which affected the seismic acquisition process conducted in 1996. Generally, the LRS-22A tidal shelf ridge distribution trend is towards NNE-SSW (north-northeast to south-southwest) with a trend angle of 12° relative to the north direction (Figure 11).

Tidal Shelf Sand Ridges Vertical Heterogeneity and Facies Association Cyclicity

The analysis of core data, RCA data, and well log data in the Upper Cibulakan Formation interval in the Ajata Field, Northwest Java Basin, shows the vertical variation of facies associations that make

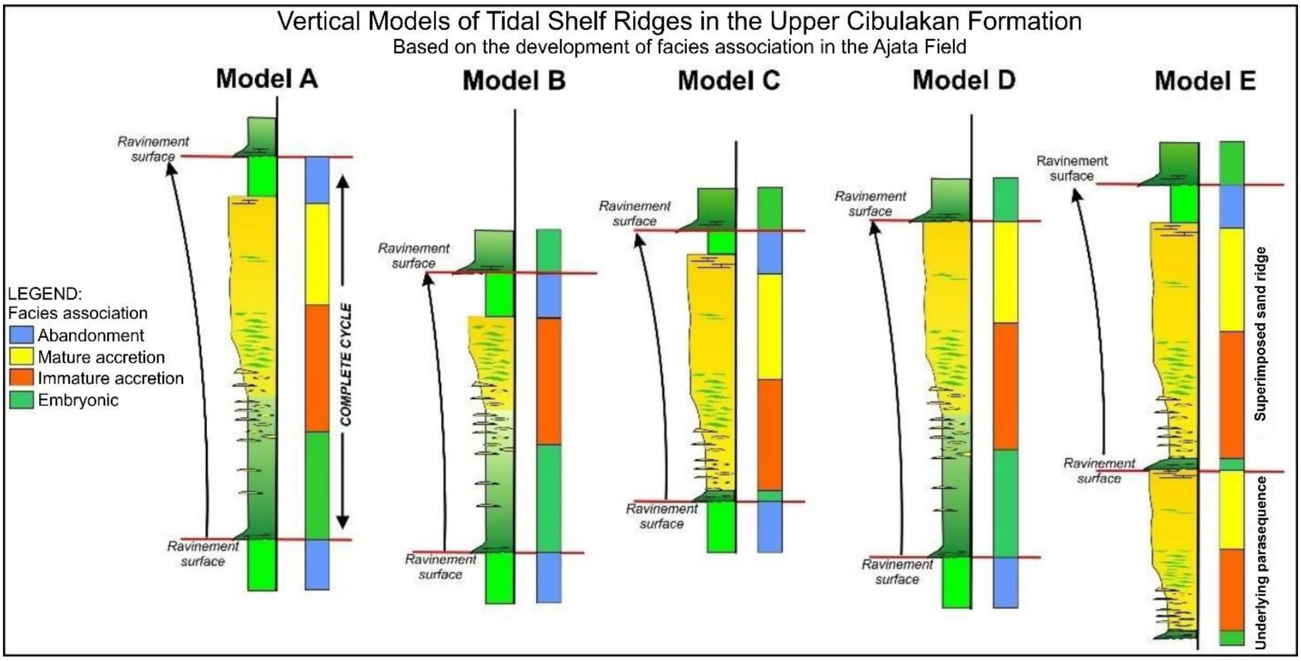

Figure 12: *The Upper Cibulakan Fm. tidal shelf sand ridges vertical cyclicity model in Ajata Field.*

up the tidal shelf ridges sedimentary parasequence. The four facies associations are embryonic facies, immature accretion facies, mature accretion facies, and abandonment facies associations. These four facies associations form cycles or sequences within the tidal shelf ridge sediment, starting with the presence of the transgressive surface (TS) and ending with the flooding surface (FS) chronostratigraphic markers. The vertical heterogeneity of the tidal shelf ridge deposits is reflected by these facies associations within each parasequence. The cyclicity of the facies associations in the tidal shelf ridge deposits reflects changes of currents during deposition, starting with tidal currents and ending with wave control at the crest of the ridges, while tidal currents occur in the inter-ridge valleys.

The results of facies association propagation based on un-cored wells in the Ajata Field (Figure 12) reveal five main models of vertical succession within each cyclicity of the tidal shelf ridge sedimentary sequence. Model "A" depicts a cyclicity with the accumulation of intact facies associations, starting with the presence of the embryonic facies association, followed by the immature accretion facies association, the mature accretion facies association, and the abandonment facies association as the top layer in each cycle. The "A" model parasequence occurs at the top or thickest part of each ridge because this area is more likely to be influenced by wave currents during deposition.

Model "B" shows incomplete accumulation within a tidal shelf ridge parasequence. The mature accretion facies association is missing in the parasequence body. Model "B" parasequence (Figure 12) reflects the absence of wave influence during deposition. The model possibly formed in several conditions, such as during relatively small sediment supply rate, deposition in basin-ward position, and deposition in the inter-ridge valley. Dashtgard et al. (2012) states that the absence of wave influence during tidal shelf ridge deposition reflects a tidally influenced shore face environment. Parasequence of model "B" forms reservoirs with poor quality.

Model "C" (Figure 12) represents the absence of the embryonic facies' association within the arrangement of tidal shelf ridge parasequence. This condition occurs when there is a significant sediment supply rate immediately after the formation of transgressive surface, resulting in the absence of fine-grained sediments. The possible location for this arrangement is the area close to the sediment supply (landward).

Model "D" (Figure 12) is characterised by the absence of the abandonment facies association as the top layer of the cyclic tidal shelf ridge parasequence. This model occurs when the deposition of the tidal shelf ridge parasequence ceases relatively quickly and is immediately overlaid by a new parasequence. The location that allows the formation of this model is in the high ridge area close to the sediment supply for the subsequent tidal shelf ridge parasequence or relatively landward.

Model "E" (Figure 12) is a combination of the "D" and "C" models, forming a vertical succession without the presence of the embryonic facies association as a separator between the parasequence. The

"C" parasequence will directly overlie the "D" parasequence. Posamentier (2002) describes this stacking model as a superimposed shelf sand ridge, and these two parasequences will form a single reservoir because they have vertical connectivity.

Tidal Shelf Sand Ridges Deposit Width-Thickness Ratio

The geometry of valleys and ridges firmly controls the lateral distribution patterns of tidal shelf ridges facies associations. The width of each ridge is determined by several factors, such as the rate of sediment supply, paleomorphology, and the depth of the fair-weather wave base (FWWB) during deposition. Embryonic facies associations form in a wide area. The immature accretion facies associations have a relatively extensive spread, forming ridges perpendicular to the shoreline. The geometry of mature accretion facies associations generally forms in the peak areas of the ridges. Abandonment facies associations are widely distributed and relatively thin out landwards.

The cross-plot analysis of the parasequence thickness data with the width of tidal shelf ridges in the Ajata Field can be seen in Figure 13. The cross-plot analysis shows a nearly linear relationship between the parasequence thickness data and the width of the tidal shelf ridges, with a correlation coefficient of 0.55. Based on the cross-plot, the equation for determining the width of the parasequence tidal shelf ridges in the Upper Cibulakan Formation is as follows:

$$Y = 17{,}482\ (X) + 385.2$$

Y represents the width of the ridges in meters.

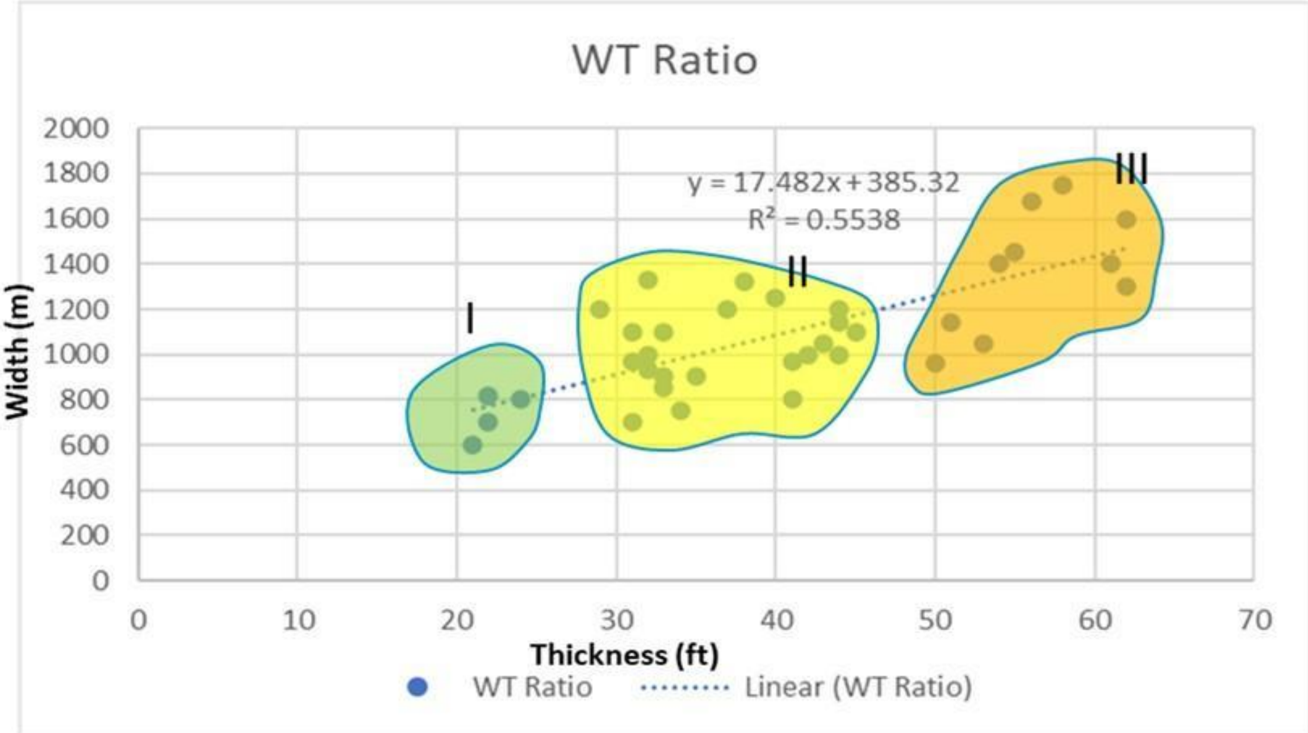

Figure 13: *Tidal shelf sand ridges width-thickness ratio in Ajata Field.*

X represents the thickness of the parasequence in feet (ft).

The equation can assist in analysing the tidal shelf ridges parasequence deposit in the Upper Cibulakan Formation that have limited well data or low-quality seismic attribute data. Based on the graph above, three main zones indicate the relationship between ridge width and parasequence thickness. Zone "I" is characterized by areas with parasequence thickness < 25 ft and ridge widths ranging from 600 m to 800 m. Zone "II" has parasequence thickness between 28 ft and 45 ft, with potential ridge widths ranging from 700 m to 1300 m. Zone "III" is the zone with parasequence thickness > 50 ft, and in this zone, the range of tidal shelf ridges width is from 1000 m to 1900 m. As the thickness of the tidal shelf ridge increases, the width of the ridges also rises (Figure 13).

The mature accretion facies association exhibits a distinct pattern, mainly found at the peaks of the ridges. The relationship between the thickness and width of the mature accretion facies association in the Ajata Field shows three trends (Figure 14): P90 (low case), P50 (best case), and P10 (high case). The correlation coefficients between mature accretion thickness and facies width have ranged from 0.81 to 0.90. These conditions indicate a strong relationship between thickness and width for each P90, P50, and P10 trend. The trends (P90, P50, and P10) can be used to determine the dimensions of the mature accretion facies associations in other fields with similar depositional settings. These formulas can also be applied to construct static uncertainty models for

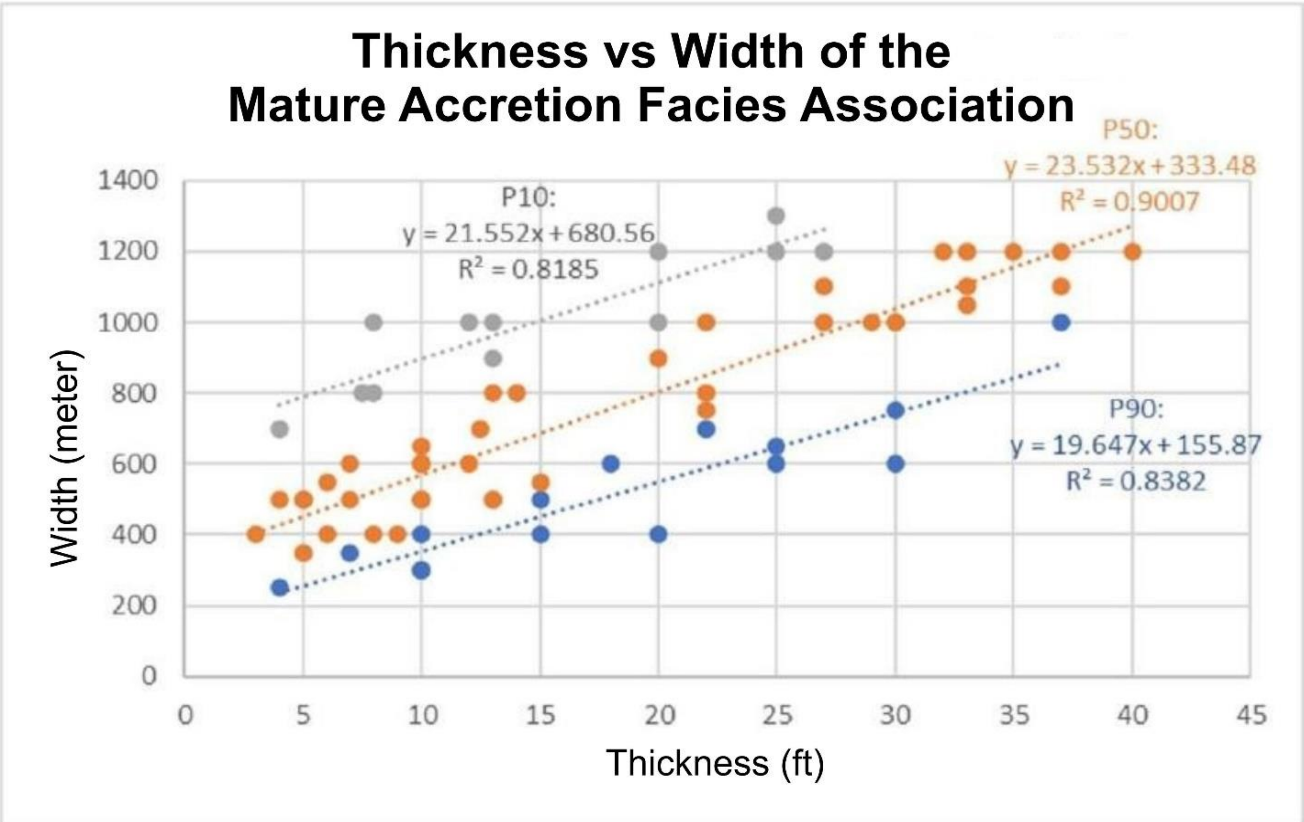

Figure 14: *Mature accretion facies association width-thickness relationship (x axes is thickness in ft, y axes is width in m)*

the same reservoir type in different areas (Figure 14).

CONCLUSIONS

Conventional core data of the tidal shelf sand ridges within the Upper Cibulakan Formation shows six lithofacies forming four facies associations.

The facies associations generating the deposits of parasequence tidal shelf sand ridges are embryonic, immature accretion, mature accretion, and abandonment facies association.

These four facies associations form tidal shelf sand ridge deposits and exhibit cyclic variations within each ridge.

The associations between immature and mature accretion facies form reservoir rock sequences in the Upper Cibulakan Formation. The immature accretion facies association creates low-quality reservoirs, while the mature accretion facies association constructs a good-quality reservoir.

There are three zones of width thickness ratio for the parasequence tidal shelf sand ridges, namely Zone I, II, and III. Cross-plot of the thickness and ridge width shows a relatively linear relationship.

Cross-plot between thickness and reservoir width of the mature accretion facies association reveals P90, P50, and P10 trends.

The zonation of width thickness ratio for the tidal shelf sand ridges parasequence and the thickness-width relationship trend of the mature facies association can be applied to predict sand distribution of similar deposits of tidal shelf sand ridges in the other fields or basins.

REFERENCES

Dashtgard, S.E., MacEachern, J.A., Frey, S.E., and Gingras, M.K., 2012. Tidal effects on the shoreface: Toward a conceptual framework. *Sedimentary Geology*, 279, 42-61.

Davis Jr., R.A. and Dalrymple, R.W., 2012. Principle of tidal sedimentology, Springer Dordrecht, New York, USA, 621 pp.

Lopez, J.L., Rossi, V.M., Olariu, C., and Steel, R.J., 2016. Architecture and recognition criteria of ancient shelf ridges; an example from Campanian Almond Formation in Hanna Basin, USA. *Sedimentology*, 63(6), 1651 – 1676.

Ponto, C.V., Pranoto, A., Wu, C.H., and Stinson, W.H., 1987. Control of hydrocarbon accumulation in the Main and Massive sandstone of the Upper Cibulakan Formation, Offshore North West Java Basin. 6th Regional Congress on Geology, Mineral and Hydrocarbon Resources of Southeast Asia (GEOSEA VI), Jakarta.

Posamentier, H.W., 2002. Ancient shelf ridges-A potentially significant component of the transgressive systems tract: Case study from Offshore Northwest Jawa. *AAPG Bulletin*, 86, 75–106.

Reynaud, J-Y. and Dalrymple, R.W., 2012. Shallow marine tidal deposit. *In*: R.A. Davis Jr. and R.W. Dalrymple (Eds.), *Principle of Tidal Sedimentology*, Springer Dordrecht, New York, USA, p. 335–369.

Setiawan, P.K.D., 2021. The Upper Cibulakan Sandstone Reservoir Facies Analysis and Characterization, Ajata Field, Northwest Java Basin. Master Thesis, Institute of Technology Bandung (ITB), Bandung.

Setiawan, P.K.D., Amrizal, Syuhada, P., and Noeradi, D., 2019. Depositional Stages of Tidal Shelf Sand Ridges Deposit and Its Implication for Upper Cibulakan Sandstone Reservoir Geometry and Characteristic at Echo Field, Northwest Java Basin, JCY IAGI-IATMI-HAGI, Yogyakarta.

Setiawati, Y.D., Ramadhan, G.C., Setiawan, P.K.D., Ginanjar, A., and Syuhada, P.I., 2017. Sand ridge facies architecture of the transgressive shelf system using sand width and thickness ratios: A study case of the Main & Massive Interval of Uniform Field, North West Java Basin, *Proceedings, Indonesian Petroleum Association,* 41st Annual Convention & Exhibition, IPA17-139-G.

Xu, F., Tao, J., Zhou, Z., Coco, G., and Zhang, C., 2017. Mechanism underlying the regional morphological differences between the northern dan southern radial sand ridges along the Jiasu Coast, China, *Marine Geology*, 371, 1–17.

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