Bulletin of the Geological Society of Malaysia 57 (2011) 39 – 46

Upper Tertiary chronosequence stratigraphy of offshore Sabah and Sarawak, NW Borneo, Malaysia: A unified scheme based on graphic correlation

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Abstract: Graphic correlation analysis of biostratigraphic data from wells drilled in Sabah and Sarawak reveals that their Upper Tertiary sections consist of numerous chronosequences that are separated by hiatuses (unconformities or condensed sections). These hiatuses converge and diverge and are highly variable in duration, but their timing and maximum durations are similar, although not identical, between Sabah and Sarawak. This similarity forms the basis for a single, unified stratigraphic framework for Sabah and Sarawak. Major tectonic, and possibly eustatic, events had a widespread effect on sedimentation in both regions.

Keywords: graphic correlation, biostratigraphy, Sabah, Sarawak

INTRODUCTION

In the oil and gas industry, seismic data are commonly used to interpret the subsurface structure and stratigraphy of sedimentary basins. The technique of identifying and mapping seismic "sequences," characterized by similar seismic attributes and bounded by unconformities, is called seismic stratigraphy (Emery & Myers, 1996). It is particularly useful in poorly explored basins with good quality seismic data. As with all methods in earth science, however, seismic stratigraphy has its pitfalls. For example, although unconformities are often easily recognized with seismic data, they may be confused and miscorrelated, particularly in such structurally complex basins as offshore Sabah and Sarawak. In these basins, unconformities may merge, diverge, or disappear between folds and faults and from shelf to basin, producing very complex stratigraphies that are difficult to interpret. When unconformities are miscorrelated, the stratigraphic framework and all modeling (depositional, geochemical, structural, etc.) within that framework are flawed. To avoid such errors, other datasets must be brought to bear.

In a similar fashion, wire line logs from wells are frequently used to correlate and establish a framework for sequence stratigraphy (Emery & Myers, 1996). Key events such as unconformities and condensed sections are recognized using logs (particularly the gamma ray log), and the rock units or sequences between these surfaces are placed within the context of systems tracts. Although very useful, reliance only upon them also has its hazards. As with seismic data, wire logs do not produce unique, non-repetitive responses to unconformities and condensed sections, and as such, they may be confused and miscorrelated. Such mistakes are less likely to occur within small areas such as oil fields, but the use of wire line logs for distant correlations within structurally complex basins is dangerous.

Much less used within the industry for stratigraphic analysis is biostratigraphic data from wells. In basins with marine sediments and abundant microfossils (foraminifera and calcareous nannofossils), such as offshore Sabah and Sarawak, biostratigraphic data are particularly useful in identifying and correlating unconformities and condensed sections. Unlike seismic and geologic datasets, biostratigraphic data consists of unique events (inceptions and extinctions) within the stratigraphic record which have been calibrated to absolute geologic time. Unconformities and condensed sections can be identified, distinguished, and correctly correlated and calibrated to geologic time. The technique of using biostratigrahic data, calibrated to absolute geologic time, to identify hiatuses, measure their duration and the geologic time in the rock sequences between them, is herein termed "chronosequence stratigraphy."

PREVIOUS WORK

Numerous stratigraphic frameworks for offshore Sabah and Sarawak have been devised from geological and geophysical data over the last 30 years (see Malek *et al*., 2007). Ho (1978), using gamma ray/spontaneous potential logs and biostratigraphic data, divided the Upper Eocene-Quaternary sedimentary fill of offshore Sarawak into eight "cycles", each bounded by regional transgressions. He conceded, however, that cycles must be identified by their micropaleontological content: "Although cycles are recognised on the basis of depositional environments, it is necessary that they be dated and correlated by biostratigraphic methods for consistent identification." His stratigraphic nomenclature is still widely used in offshore

Sarawak, but the use of biostratigraphic data to corroborate correlations is much less common.

Two years later, Bol & van Hoorn (1980), using seismic data, divided the Cenozoic rocks of the Sabah shelf into four "stages." Stages I and II consisted of Upper Cretaceous-Oligocene rocks, and Stage III comprised Lower and Middle Miocene rock. Stage IV (Middle Miocene-Quaternary) was divided into seven sub-stages, A to G, regionally mappable seismic sequences. All stages were separated by an unconformity, of which there were nine. Although these seismic stages were calibrated to geologic time, biostratigraphic data was not referenced by the authors, and they warned, "Even with dense grids of modern seismic data it is a difficult task to find correlations over relatively short distances. Well correlations are hard to make not only due to the numerous faults but also to the presence of discontinuous sand bodies." Levell (1987) named the regional seismic unconformities in the Middle Miocene-Pliocene section (Deep Regional Unconformity, Lower and Intermediate Unconformity, Shallow Regional Unconformity, Horizon II, and Horizon I) and provided biostratigraphic evidence for their ages. He related each unconformity to the tectonic evolution of Sabah and traced their geographic extent in the subsurface, noting that each unconformity passed into an onlap surface further offshore.

Morrison & Lee (2003), seeking a stratigraphic framework for all northwest Borneo, advocated using the eustatic TB sequences of Haq *et al*. (1988). This approach, they wrote, requires the use of "high resolution" biostratigraphy to correlate well and seismic data to the TB sequences. Morrison & Lee (2003) acknowledged that the application of a eustatic model developed from distant passive margins to a highly active tectonic margin was open to question, but, they argued, in many cases eustatic falls in sea level coincide with uplift, thus enhancing the resultant unconformity. When major uplifts do not correspond with global sea level falls, then intermediate TB zones are required (e.g., TB 2.6.2 sb). They also acknowledged that rapid tectonic subsidence may mask the effects of eustasy (van Vliet & Schwander, 1987), but insisted that channeling, onlap geometries, etc. combined with high resolution biostratigraphy allow for the recognition of TB sequence boundaries. This approach, however, has proven extremely difficult to use in offshore Sabah and Sarawak and has led to frequent misinterpretations (F.L Kessler, pers. com.).

In addition to the stratigraphic nomenclature developed by Shell personnel, other companies have developed their own internal schemes. Murphy, for example, has named seismic horizons and sequences off the Sabah shelf for the Middle Miocene-Lower Pliocene section, and these horizons have been calibrated to geologic time by biostratigraphic data (Malek *et al.,* 2007), and Shell has recently developed a nomenclature for deepwater Middle and Upper Miocene fans in offshore Sabah (Malek *et al.,* 2007).

In summary, Sabah and Sarawak have different stratigraphic frameworks for the Upper Tertiary, and different nomenclatures exist for the shelf and deepwater of Sabah. Furthermore, different schemes exist between companies (e.g., Shell and Murphy), and the relationship of all these models to each other is open to debate (see Figure 1). The

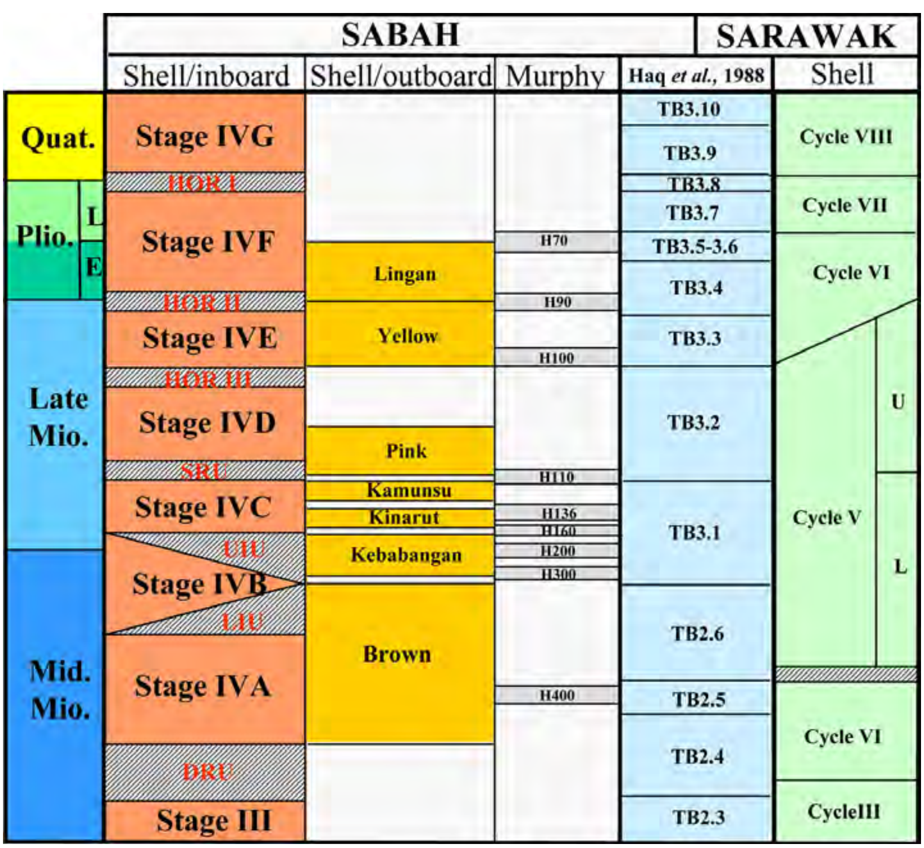

Figure 1: Current stratigraphic schemes for Sabah and Sarawak. The eustatic TB sequences have been applied in both states. The relationship of these schemes to each other is controversial.

global TB sequences of Haq *et al*. (1988) have been applied across northwest Borneo, but this model is not based on data from Borneo and assumes that eustasy was the dominant control of sedimentation on this highly active tectonic margin. The purpose of this paper is to present a single, unified stratigraphic framework derived from northwest Borneo (Sabah and Sarawak) that is free of assumptions or pre-conceived ideas.

METHODOLOGY

Unconformities and condensed sections are boundary events in sequence stratigraphy that represent discontinuities in deposition (Emery & Myers, 1996). Unconformities represent periods of geologic time not preserved in the rock record – a hiatus. Condensed sections are thin rock intervals which comprise so much geologic time that they resemble hiatuses. Biostratigraphic data can be used to detect these hiatuses and their origins — erosion (unconformity) or slow deposition (condensed section). "Chronosequences" are the rock intervals between hiatuses (unconformities or condensed sections) that have been detected by biostratigraphy, and are the fundamental unit of "chronosequence stratigraphy".

Graphic correlation of biostratigraphic well data is a practical method of identifying hiatuses and chronosequences in the subsurface (Carney and Pierce, 1995). A graphic correlation plot relates rock thickness to geologic time: vertical thickness vs. horizontal geologic time (Figure 2). The line of correlation (LOC), drawn through microfossil datums, depicts geologic time in a rock section. Flat line segments, or terraces, signify periods of geologic time not preserved or highly condensed in sedimentary rock (hiatuses). Oblique line segments between terraces constitute chronosequences. Assuming true vertical thickness, accumulation rates are directly proportional to the slope of line segments

In graphic correlation, biostratigraphic datums, the tops and bases of microfossil species in well or outcrop sections are calibrated to absolute geologic time and a cross-plot is made of their stratigraphic occurrences in sections (vertical axis) against their ranges in geologic time (horizontal axis) (Figure 2). All points are scrutinized with regard to reworking and caving, and a line of correlation, consisting of line segments, is drawn through reliable datums. The LOC represents the relationship between geologic time and a rock section. The LOC usually consists of oblique

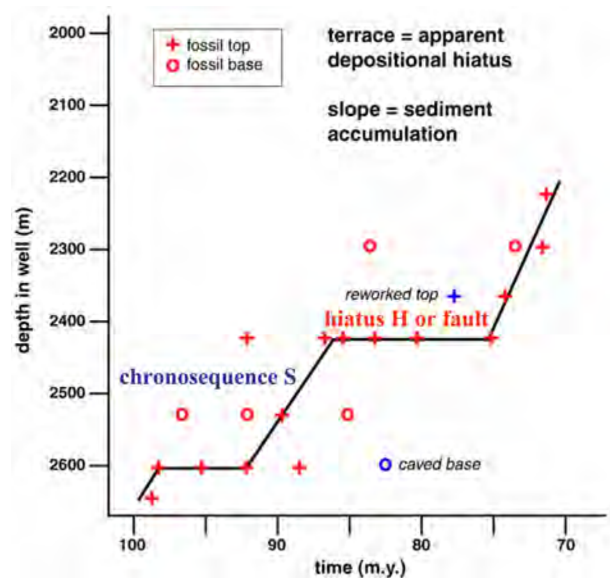

Figure 2: Graphic correlation plot of a well section. The flat line segments (terraces) represent hiatuses (unconformities or condensed sections) or faults. The oblique line segments are "chronosequences." In vertical rock sections, the steepness of the line segments is proportional to sedimentation rate. Graphic correlation of biostratigraphic data facilitates the recognition of hiatuses and chronosequences, the foundation of chronosequence stratigraphy.

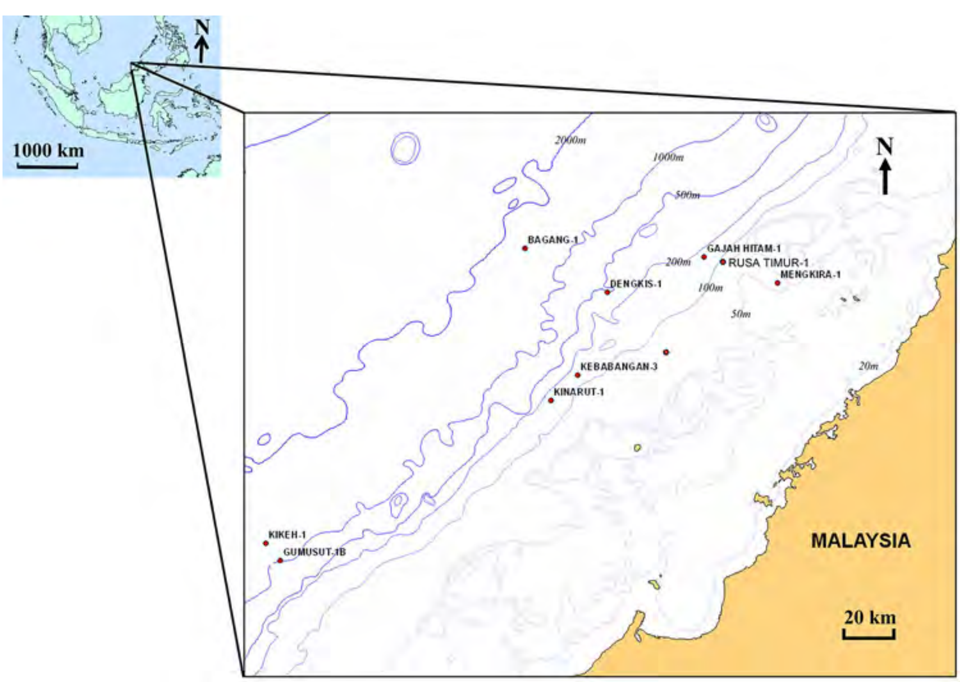

Figure 3: Location of 9 type wells in offshore Sabah, Malaysia.

line segments that are bounded by horizontal segments or terraces. The oblique segments represent rock sequences, or chronosequences, that are defined by geologic time and bounded by graphic terraces or hiatuses (time not represented in the rock record). Hiatuses, if not fault related, may represent unconformities, condensed sections, bypass surfaces, or a combination of these features. Because of sampling intervals, however, condensed sections often appear as terraces on graphic correlation plots. The method of graphic correlation thus divides well (or outcrop) sections into natural low-order sequences that are bounded by hiatuses. The results are useful for correlating well sections, understanding sequence stratigraphy, calibrating seismic data to geologic time, and establishing the chronostratigraphy of a basin.

RESULTS

Sabah

Although more than 60 wells in offshore Sabah were successfully analyzed using graphic correlation, only nine wells have been chosen as "type" wells in this study (Figure 3). Among those wells are Kikeh-1 (Figure 4) and Gumusut-1B (Figure 5). In both wells, the line of correlation was controlled by the occurrences of key species of calcareous nannofossils and planktonic foraminifera. The section in Kikeh-1 spans the Middle Miocene to lowest Pliocene and is punctuated by six hiatuses. The chronosequences between the hiatuses appear to have accumulated rather rapidly based on the steep slope of their line segments. The section in the nearby Gumusut-1B well ranges in age from early late Miocene to late Pliocene, has hiatuses similar to those in Kikeh-1, and also accumulated very rapidly. Figure 5 is a nomogram having the LOC's for the Kikeh-1 and Gumusut-1B as well as the seven other wells. In total, the rocks span the Upper Lower Miocene to Quaternary and are punctuated with at least 15 hiatuses (H05-H120) that divide the section into 16 chronosequences (S05-S130). Each chronosequence bears the same number as the hiatus beneath it. Figure 7 depicts all the key microfossils associated with each hiatus and chronosequence. All other wells in offshore Sabah posses some of these hiatuses or a combination of them. In any case, the well depth of each hiatus and its approximate duration (Ma) were recorded for all analyzed wells.

Figure 9 illustrates the chronosequence stratigraphy resulting from the graphic correlation analysis of all wells in offshore Sabah and its relationship to the Shell stages (Bol & van Hoorn, 1980; Levell, 1987). The hiatuses H05-H120 are depicted as horizontal triangles on the left margin, and the chronosequences S05-S130 occupy the spaces between the triangles. The base of the triangle represents the maximum known duration of the hiatus based upon graphic correlation results, and when the bases of triangles merge, the chronosequence between them disappears. In other words, when hiatuses coalesce, the rock between them does not exist. The size of the triangle is proportional to the maximum duration of the hiatus. Conversely, as the triangle tapers towards its apex, the duration of the hiatus lessens and more geologic time is comprised in the chronosequence. Beyond the triangle's apex where the hiatus no longer exists, chronosequences merge.

The middle of Figure 9 depicts the relationship of this stratigraphic framework to the Shell stages for offshore Sabah. This comparison was made possible by Shell (Peter Osterloff, per. com.) which kindly provided horizon picks in Sabah wells that had been analyzed by graphic correlation. Note that their seismic horizons correspond to biostratigraphic hiatuses, but that the latter are more numerous than the former. These additional hiatuses revealed by graphic correlation may prove useful in correlating within seismic sequences and verifying their identities.

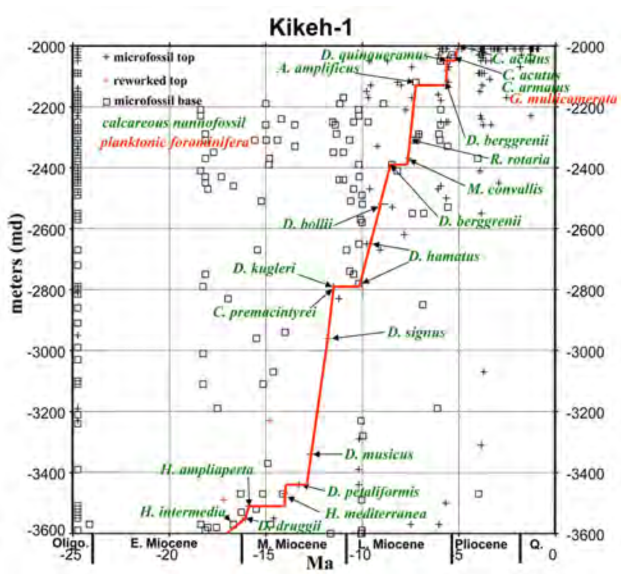

Figure 4: The graphic correlation plot of Kikeh-1, offshore Malaysia. Note the terraces (hiatuses) that divide the section into chronosequences.

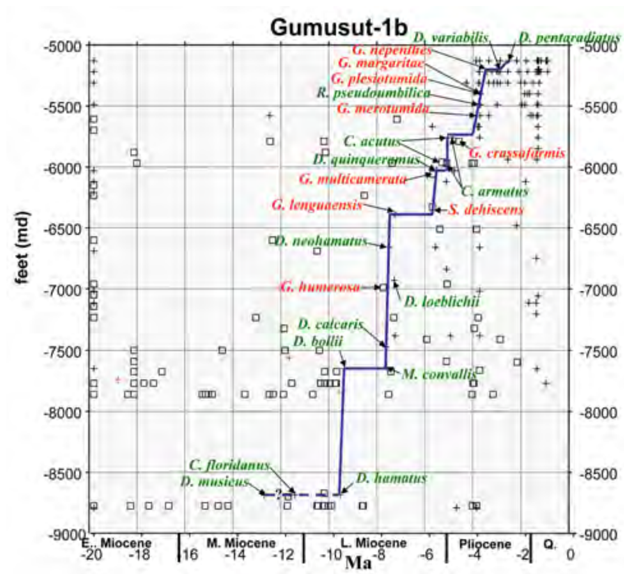

Figure 5: The graphic correlation plot of Gumusut-1B. Note that the chronosequences accumulated rapidly and that more geologic time is comprised in hiatuses than is represented in the rock record.

Sarawak

In offshore Sarawak, nearly 70 wells have been analyzed by graphic correlation, of which 16 have been selected as type wells (Figure 9). These wells range from proximal (Acis wells) to distal (Mulu-1, Bako-1) locations. Figure 10 is a nomogram of the results from these key wells. It reveals that the age of rock penetrated in offshore Sarawak ranges from Oligocene to Quaternary and that this section is divided into at least 20 chronosequences (S05-S170) by 20 hiatuses (H05-H170?). Figure 11 depicts these hiatuses and chronosequences with their key microfossil datums, and Figure 12 displays their relationship to the Shell Sarawak cycles (Ho, 1978). This integration was made possible by comparing the cycle boundaries to graphic correlation

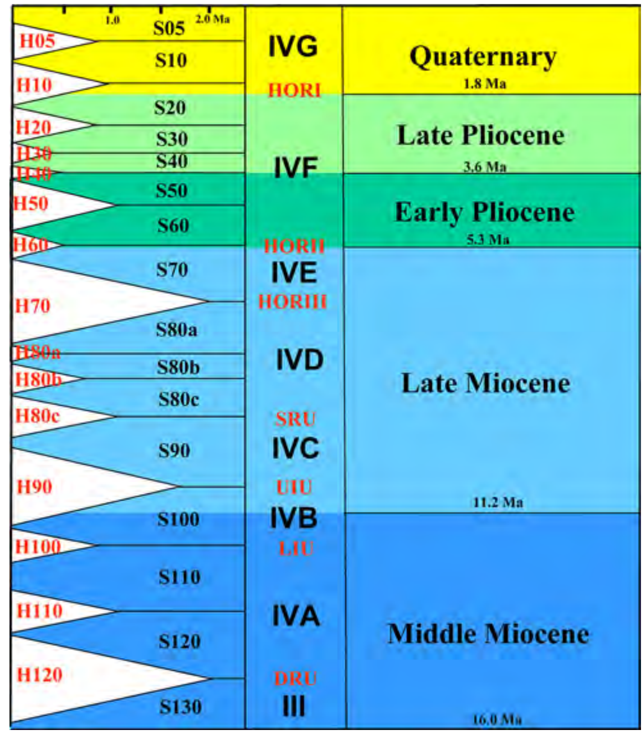

Figure 8: Upper Tertiary Sabah chronosequence stratigraphy. The base of the triangles represents each hiatus at its maximum duration as well as its height (see scale). Chronosequences are between hiatuses and disappear when hiatuses merge (triangle bases touch). Chronosequences merge beyond the apex of each triangle because there is no hiatus. Note the relationship of this model to the Shell Sabah stages (Bol & van Hoorn, 1980; Levell, 1987).

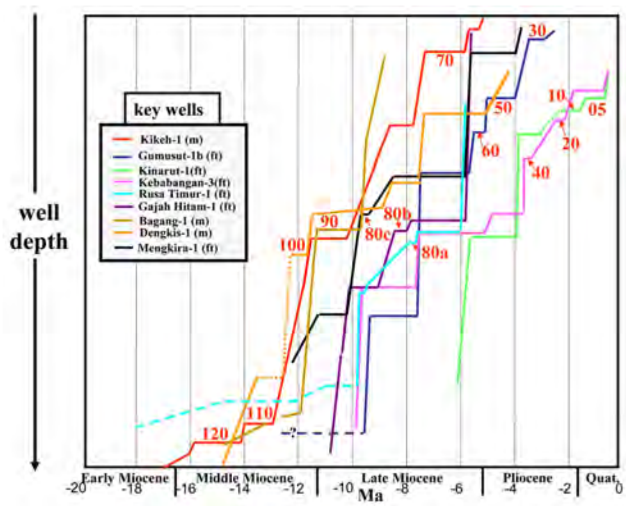

Figure 6: Nomogram displaying the line of correlation for all nine type wells in Sabah. The section spans the Middle Miocene-Quaternary and is divided into 16 chronosequences by 15 hiatuses.

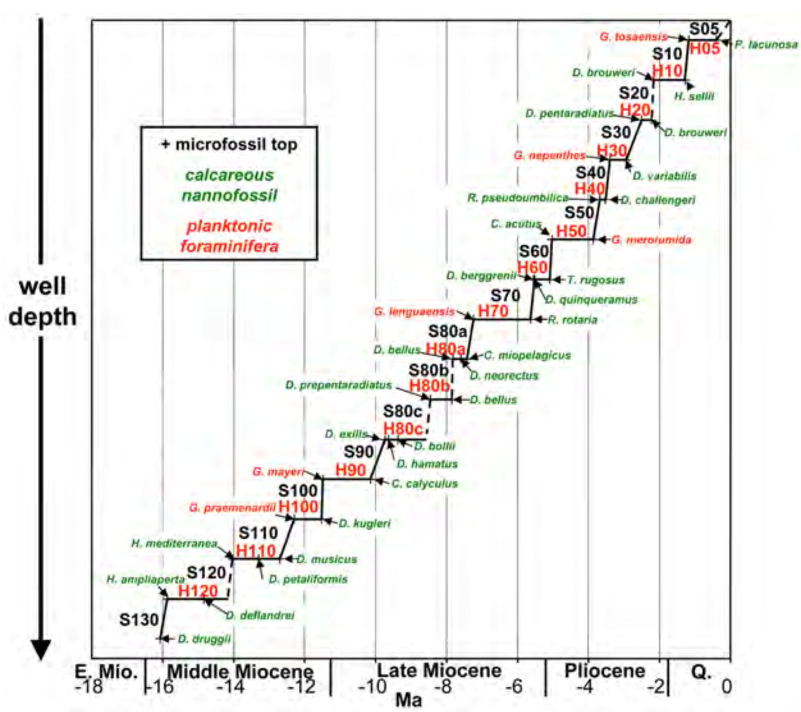

Figure 7: Idealized line of correlation for offshore Sabah displaying al hiatuses (H05-H120) at their maximum duration and all chronosequences (S05-S130) with associated key biostratigraphic markers (calcareous nannofossils and planktonic foraminifera).

results in several key wells. As in offshore Sabah, hiatuses in offshore Sarawak are variable in their duration and commonly merge and diverge.

Although an older section was penetrated in Sarawak than in Sabah, the Middle Miocene-Quaternary sections can be compared. Figure 13 depicts the hiatuses and chronosequences for Sabah and Sarawak as idealized LOC's. Although not identical, the similarities are striking; the hiatuses and chronosequences in both regions are closely correlative. This indicates that key tectonic and possibly eustatic events in northwest Borneo during the late Tertiary had a widespread effect on sedimentation in both Sabah and Sarawak, and that this commonality of response forms the basis for a single chronosequence stratigraphy for the region. These results, depicted in Figure 14, highlight the similarities between Sabah and Sarawak and facilitate the integration of the Shell Sabah stages with the Shell Sarawak cycles. The origins of these widespread hiatuses and their associated chronosequences require their integration with seismic and geologic data.

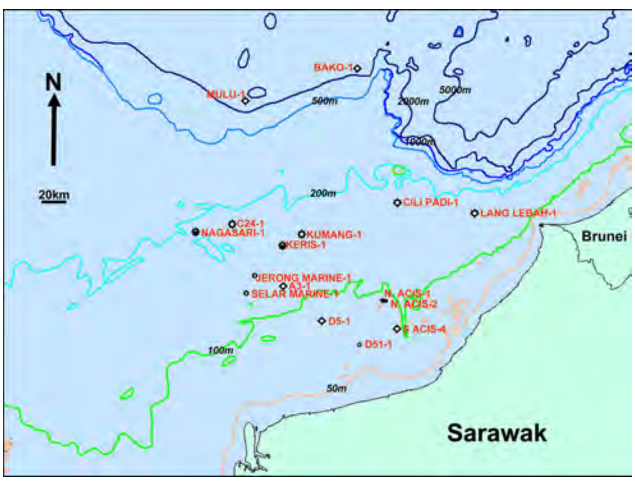

Figure 9: Location map of 16 types wells in offshore Sarawak, Malaysia.

CONCLUSIONS

- The Upper Tertiary of offshore northwest Borneo consists of numerous chronosequences that are separated by hiatuses.
- All hiatuses and chronosequences have key microfossil datums.
- Hiatuses converge and diverge and are highly variable in duration.
- The timing and *maximum* duration of hiatuses are similar, but not identical, between Sabah and Sarawak.
- Major tectonic/eustatic events had a widespread effect on sedimentation in Sabah and Sarawak.
- Chronosequences and the hiatuses that bound them are the foundation for a single, unified stratigraphic framework for Sabah and Sarawak.

ACKNOWLEDGMENTS

The author would like to thank Rashidah bt Karim for her encouragement and support during this project work and my colleagues Thomas Stump, Barry Boyce, and Arthur van Vliet for helpful discussions and suggestions. This paper benefitted from the helpful critiques of Drs. Mazlan Madon and Frank L. Kessler. I am grateful to Petronas Carigali Sdn. Bhd. for permission to publish these results.

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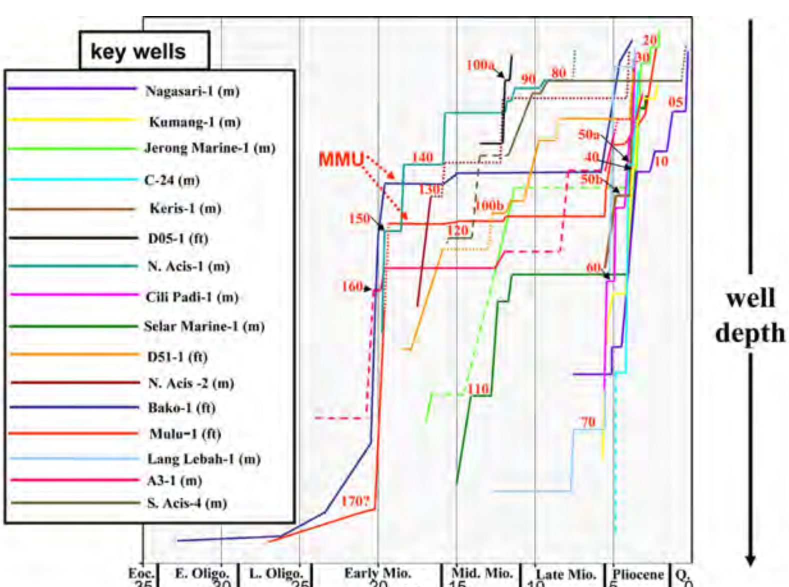

Figure 10: Nomogram displaying the lines of correlation of all 16 types wells in Sarawak. The section spans the Oligocene-Quaternary and is divided into 20 chronosequences by 20 hiatuses.

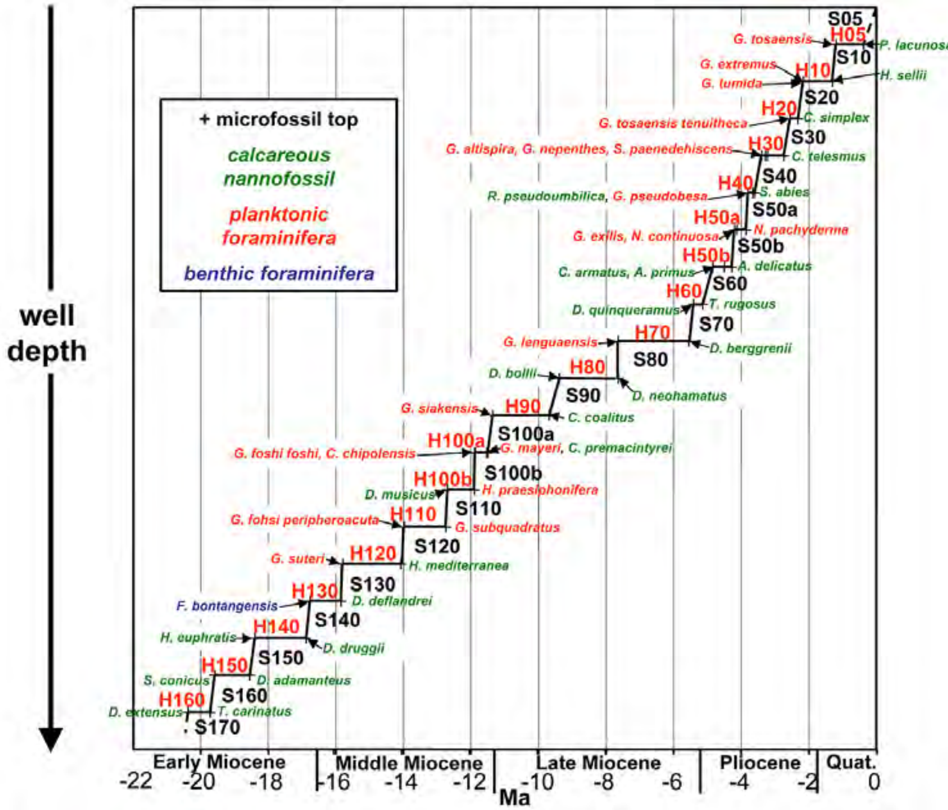

Figure 11: Idealized line of correlation for offshore Sarawak displaying all hiatuses (S05-S170?) at their maximum duration and all chronosequences (S05-S170) with associated key biostratigraphic markers (calcareous nannofossils and planktonic foraminifera).

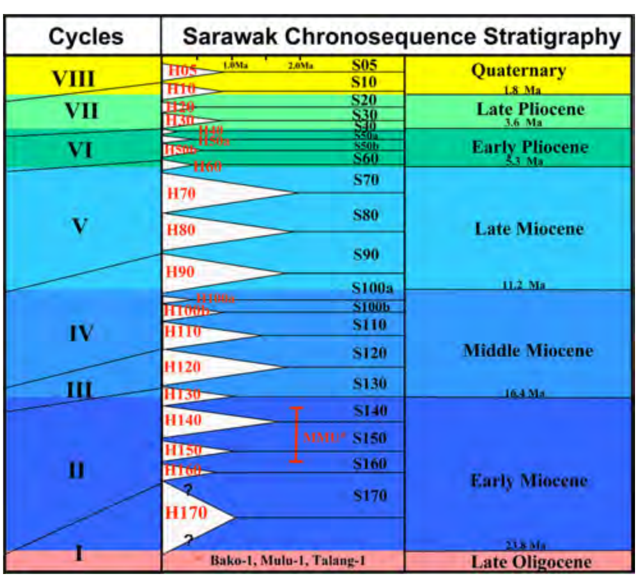

Figure 12: Tertiary Sarawak chronosequence stratigraphy. See Figure 8 caption for explanation. Note the relationship of these results with the Shell Sarawak cycles of Ho (1978).

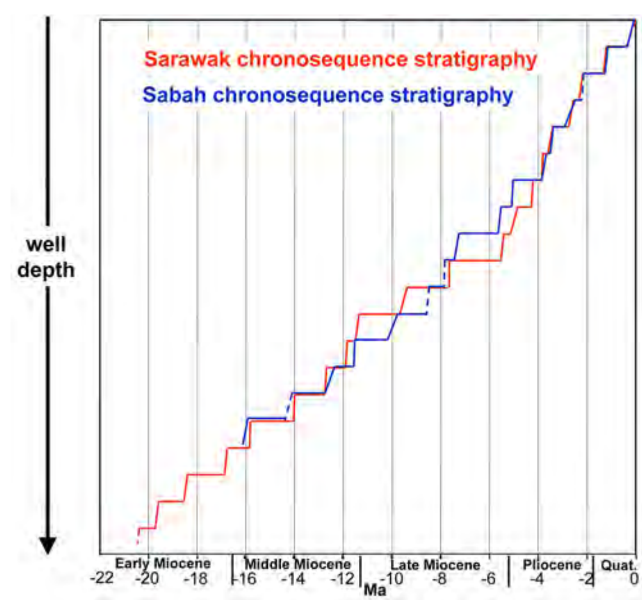

Figure 13: Comparison of the idealized lines of correlation of Sabah and Sarawak. Note the coincidence of many hiatuses indicating the similar stratigraphies.

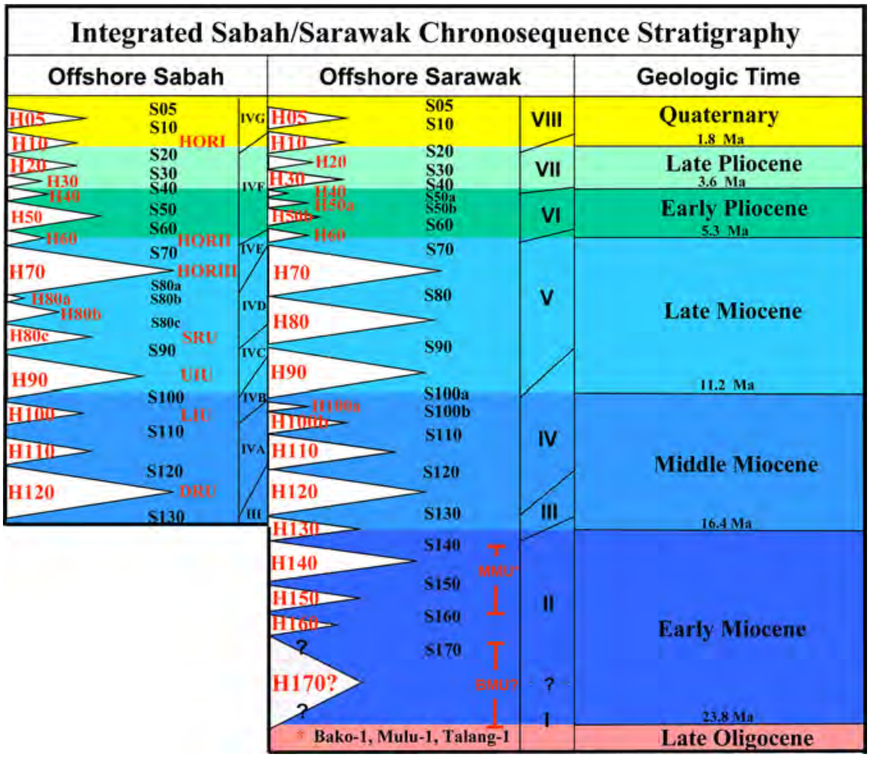

Figure 14: Integrated Sabah/Sarawak chronosequence stratigraphy. Nearly identical hiatuses occur in both states and can be used to correlate along the margin of northwest Borneo. They facilitate the integration of the Shell Sabah stages with the Shell Sarawak cycles.

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Manuscript received 27 October 2011