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Sequence stratigraphic framework of Northwest Borneo

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Abstract: The character of the Cenozoic sedimentary sequence of NW Borneo exhibits the interplay of eustatic sea level change and the commonly dramatic effects of tectonic events. In this paper, we show how the adoption of a unified stratigraphic nomenclature, tied to the Global Sequences of Haq *et al.* (1988), can help unravel the superimposition of eustatic and tectonic processes. We also assess the importance of these processes in terms of the genesis, character and the distribution of the basin fills. The results give us a greater understanding of the key exploration plays in the region and a framework to link the play elements.

INTRODUCTION

The Cenozoic sedimentary basins of the NW Borneo margin covers an area of over 260,000 km^2 encompassing both on- and off-shore Sarawak, Brunei and Sabah. Oil prospecting started onshore in the late 1800's with the first discovery (the Miri Field) being made in 1910. Subsequent discoveries were later made in both on- and offshore basins, transforming the margin into a prolific hydrocarbon region with the most significant provinces being the Central Luconia area and the Baram Delta (Fig. 1). Combined discovered reserves for the margin now exceed 20 billion boe (Sandal, 1996; PETRONAS, 1999).

The economic importance of the NW margin of Borneo, combined with academic interest in the complex geology, has resulted in a considerable body of research on the region, much of which is excellently summarized by PETRONAS, 1999. However, as a result of tectonic complexity and also political boundaries, research has commonly been fragmented and hampered by the lack of a consistent stratigraphic nomenclature.

Early in the exploration of the region, workers recognized the cyclical depositional character of the prospective Miocene-Quaternary sedimentary packages in the onshore and offshore basins of Sarawak, Sabah and Brunei. The depositional "Cycles" (in Sarawak) or "Stages" (in Sabah) were recognized at basin scale, used for intra-basin correlations and applied at a much smaller scale to well-to-well correlations of single sedimentary packages (reservoirs/seals). However, the recognition of the local "Stages" and "Cycles" across basinal boundaries was believed to be difficult or impractical and the division of offshore NW Borneo into Malaysian and Bruneian sectors has compounded the difficulties of a consistent NW Borneo correlation.

With the introduction of sequence stratigraphic techniques in the late 1980's, the "Cycle" and "Stage" boundaries have been shown to often coincide with "classical" sequence components. It is now possible to base a regional correlation on the assignation of the earlier "cycles" to the TB sequences (3^{rd} order sequences) of Haq *et al.* (1988). The regional correlation of these TB sequences is based on the iterative integration of detailed biostratigraphy from well sections with seismic data. The recognition of these main sequences is important because it allows the reconstruction of the sedimentary history at basin scale and forms the basis for correlation across basin and political boundaries. With this framework in place, interpretations on the effect and relationship of the main tectonic and eustatic events can be made. Further, the framework significantly enhances the ability to predict lithological development and the delineation of prospective exploration fairways.

LIMITATIONS OF EXISTING STRATIGRAPHIC SCHEMES

Existing NW Borneo stratigraphic schemes are summarized in Figure 2 and include:

1. Lithostratigrahic schemes, developed largely from the study of onshore geology. Although generally widely recognised, such schemes suffer from a number of limitations. Formations are commonly time transgressive and this presents problems in widespread basin analysis, while the broadly similar stratigraphy over a long period of geological time makes the differentiation of one formation from the other difficult.

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2. Sarawak and Brunian sedimentary "Cycles", based on regressive packages in the Baram Delta Province (Ho, 1978; van Borren *et al.*, 1996). An ideal cycle is defined as an overall regressive succession starting with a transgressive surface. The assignment of a cycle boundary becomes somewhat arbitrary in areas where this is limited vertical change in depositional environments e.g., the Late Oligocene coastal plain section in the Balingian Province and the Middle Miocene carbonate section in Luconia Province. An additional complication is the inconsistent cycle nomenclature used in Sarawak and Brunei that causes significant confusion and complicates geological correlations.
3. Sabah "Stages", based on unconformity-bounded sections. This was developed in the 1970's (Bol and van Hoorn, 1980) and is a reflection of the generally greater tectonic overprint in Sabah compared to Sarawak and Brunei. However, within these Stage boundaries we do have regressive cycles typical of deltaic sequences. An example of this is the extension of the East Baram Delta from Brunei (Cycle nomenclature) into Sabah (Stage nomenclature) resulting in multiple terminologies within a geologically continuous province.

These locally applicable stratigraphic frameworks have proven themselves as robust and have formed the basis for many decades of successful hydrocarbon exploration. However, without a consistent nomenclature it becomes difficult to take our knowledge the additional step to create a unified understanding of the entire NW Borneo margin.

TB SEQUENCE FRAMEWORK

Over the last few years, Shell Malaysia has been developing a consistent sequence stratigraphic framework for NW Borneo based on the Global Tertiary TA/TB Sequences of Haq *et al.* (1988). (Note: TA prefix is for Paleocene to Late Oligocene (29.3 Ma), TB prefix used for sequences from Late Oligocene to Present). The key sequences for hydrocarbon exploration in NW Borneo are Late Oligocene age or younger and we only refer to the TB sequences for the remainder of this paper. The advantages of moving to the TB Sequence framework are:

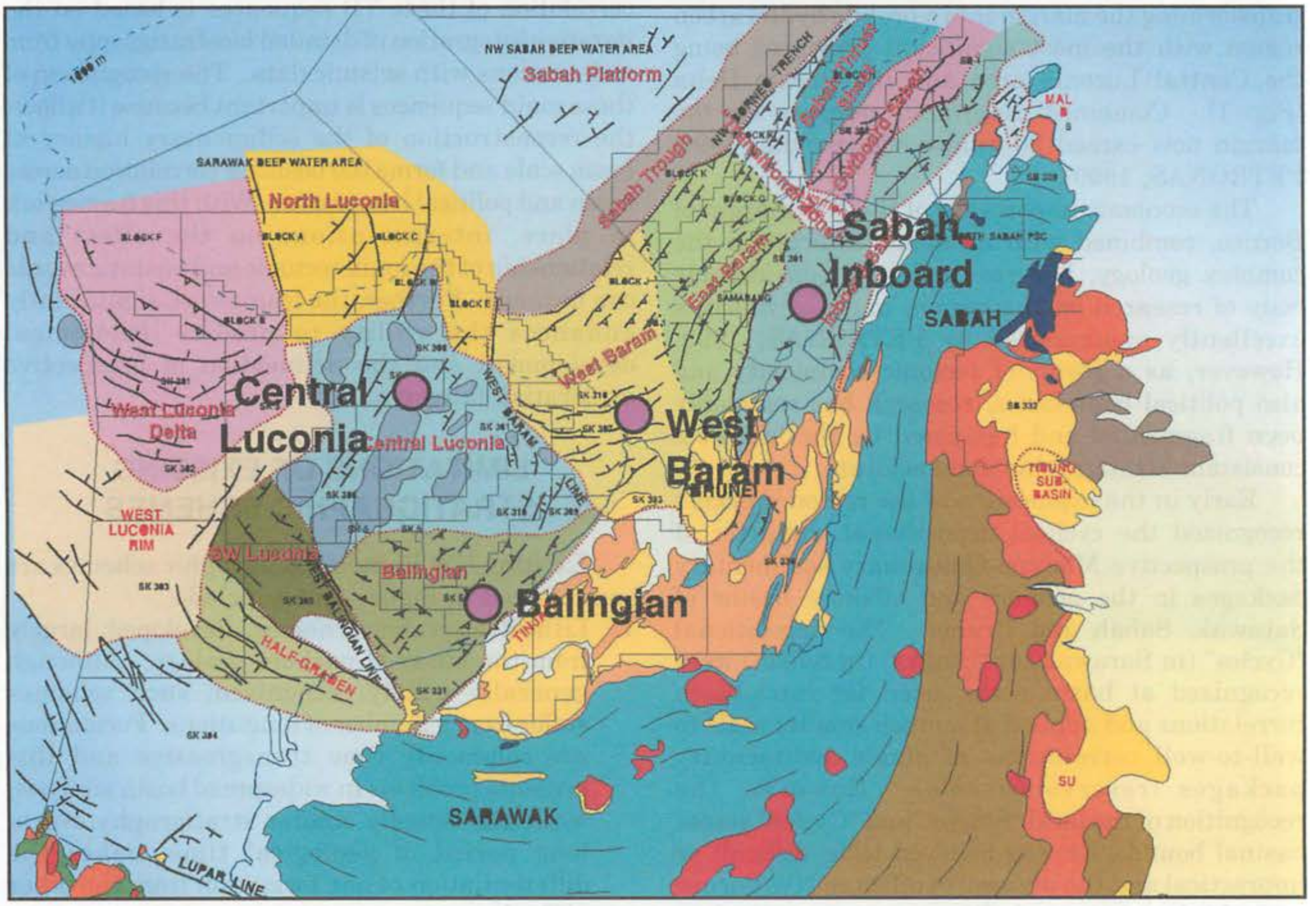

Figure 1. NW Borneo geologic provinces.

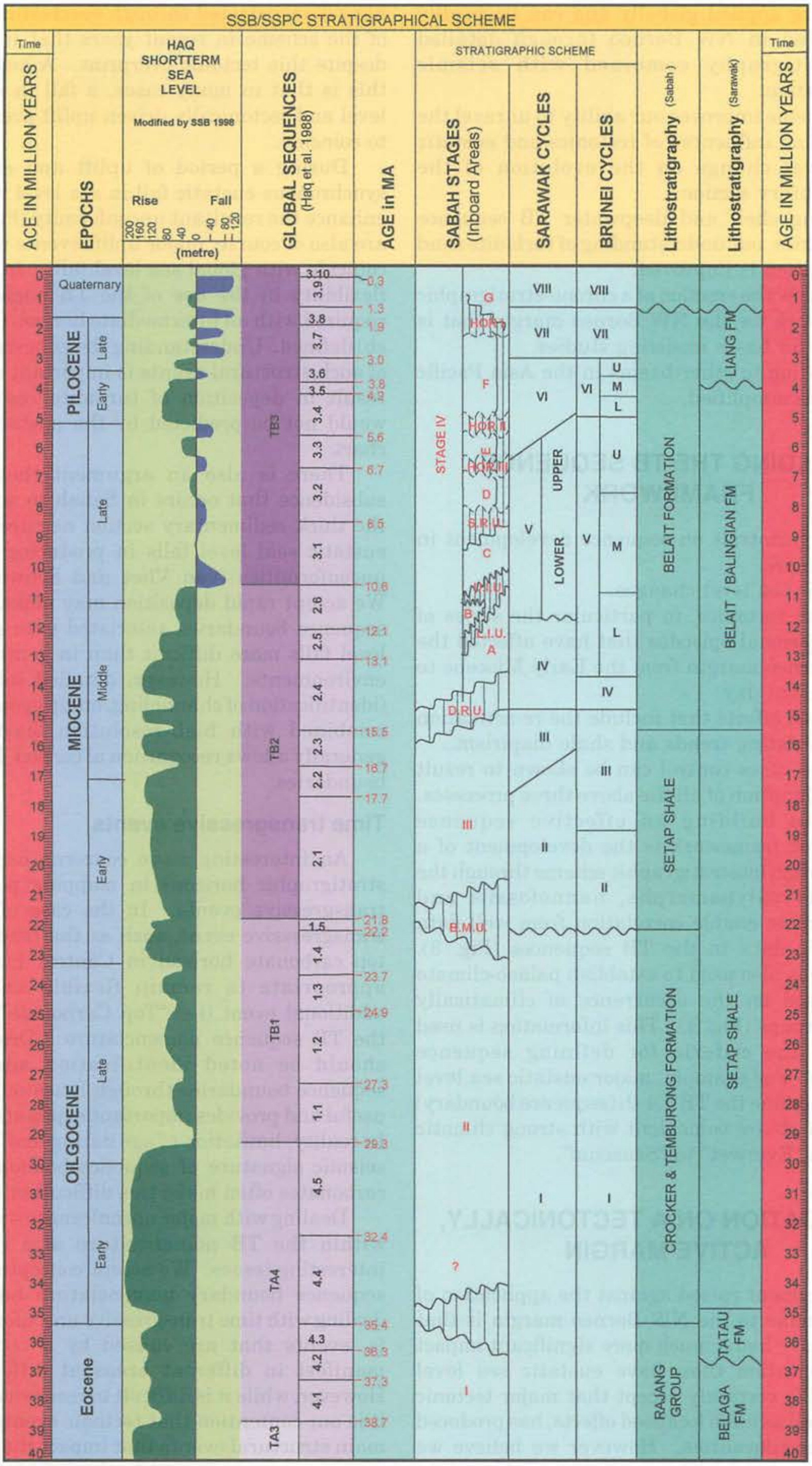

Figure 2. Existing NW Borneo stratigraphic schemes.

1. They are applied globally and can be readily identified in NW Borneo through detailed biostratigraphy combined with seismic information.
2. The scheme improves our ability to unravel the competing influences of tectonics and eustatic sea level change on the evolution of the sedimentary section.
3. By tying shelf and deepwater TB sequence boundaries, our understanding of turbidite sand distribution is improved.
4. They allow the erection of a chrono-stratigraphic framework for the NW Borneo margin that is critical for basin modeling studies.
5. Correlation to other basins in the Asia Pacific region is simplified.

BUILDING THE TB SEQUENCE FRAMEWORK

The key controls on sequence development in NW Borneo are:
1. Eustatic sea level changes.
2. Regional tectonics, in particular the series of compressional episodes that have affected the NW Borneo margin from the Early Miocene to the present day.
3. Localized effects that include the re-activation of pre-existing trends and shale diapirism.

In some cases control can be shown to result from a combination of all the above three processes. The key to building an effective sequence stratigraphic framework is the development of a high-resolution biostratigraphic scheme through the analysis of palynomorphs, nannofossils and foraminifera to enable correlation from well data and seismic data to the TB sequences (Fig. 3). Palynology is also used to establish palaeo-climate curves based on the occurrence of climatically sensitive groups (Fig. 4). This information is used as one of the criteria for defining sequence boundaries. For example, major eustatic sea level falls which define the TB 3.4 sb (sequence boundary) and TB 3.1 sb are coincident with strong climatic shifts from "Everwet" to "Seasonal".

APPLICATION ON A TECTONICALLY, ACTIVE MARGIN

An argument raised against the application of the TB scheme to the NW Borneo margin is that tectonics have had a much more significant impact on sedimentation than have eustatic sea level changes. We certainly accept that major tectonic uplift, as well as more localised effects, has produced marked unconformities. However we believe we have demonstrated through successful application of the scheme in recent years that it works well despite this tectonic overprint. A key reason for this is that in many cases, a fall in eustatic sea level and tectonically driven uplift event will tend to coincide.

During a period of uplift and erosion, any synchronous eustatic fall in sea level will serve to enhance the resultant unconformity (Fig. 5). There are also of course, major uplift events which do not coincide with global sea level falls. In such cases, flexibility in the use of the TB nomenclature is required with an intermediate horizon (i.e. TB 2.6.2 sb) defined. Understanding the genesis and timing of such structural events is important as they may result in deposition of turbidite reservoirs that would not be predicted by the eustatic sea level chart.

There is also an argument that the rapid subsidence that occurs in Sabah to accommodate the thick sedimentary section negates the role of eustatic seal level falls in producing basin wide unconformities (van Vliet and Schwaner, 1987). We accept rapid deposition may make identifying sequence boundaries associated with eustatic sea level falls more difficult than in gently subsiding environments. However, detailed interpretation (identification of channeling, onlap geometries etc.), combined with high-resolution biostratigraphy generally allows recognition of correct TB sequence boundaries.

Time transgressive events

An interesting issue concerns use of the TB stratigraphic horizons in mapping possible time transgressive events. In the case of truly time transgresssive event, such as the readily mapped top carbonate horizon in Central Luconia, it is appropriate to remain flexible and have an additional event (i.e. "Top Carbonate") outside of the TB sequence nomenclature. Despite this it should be noted identification and mapping sequence boundaries through limestone buildup is useful and provides important exploration insights. In reality, limitation of age dating and lack of clear seismic signature of sequence boundaries within carbonates often make this difficult or impractical.

Dealing with major unconformities in the region within the TB nomenclature also raises some interesting issues. We accept conceptually the TB sequence boundary nomenclature has problems dealing with time transgressive unconformities, that is, events that are caused by a tectonic pulse manifest in different areas at different times. However, while it is difficult to resolve categorically, it is our contention that tectonic events within the main structural events that impact the NW Borneo

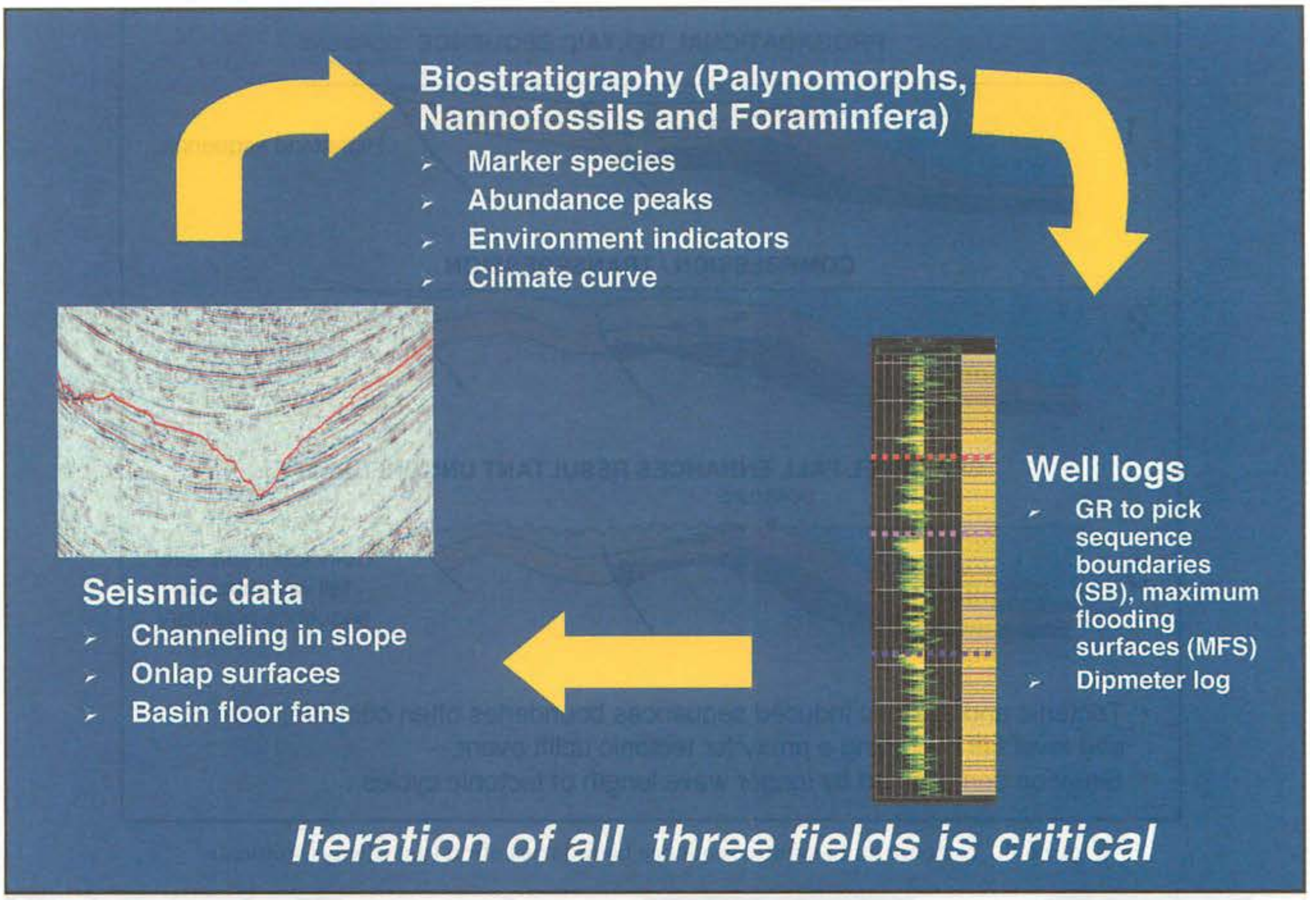

Figure 3. Building the TB sequence framework.

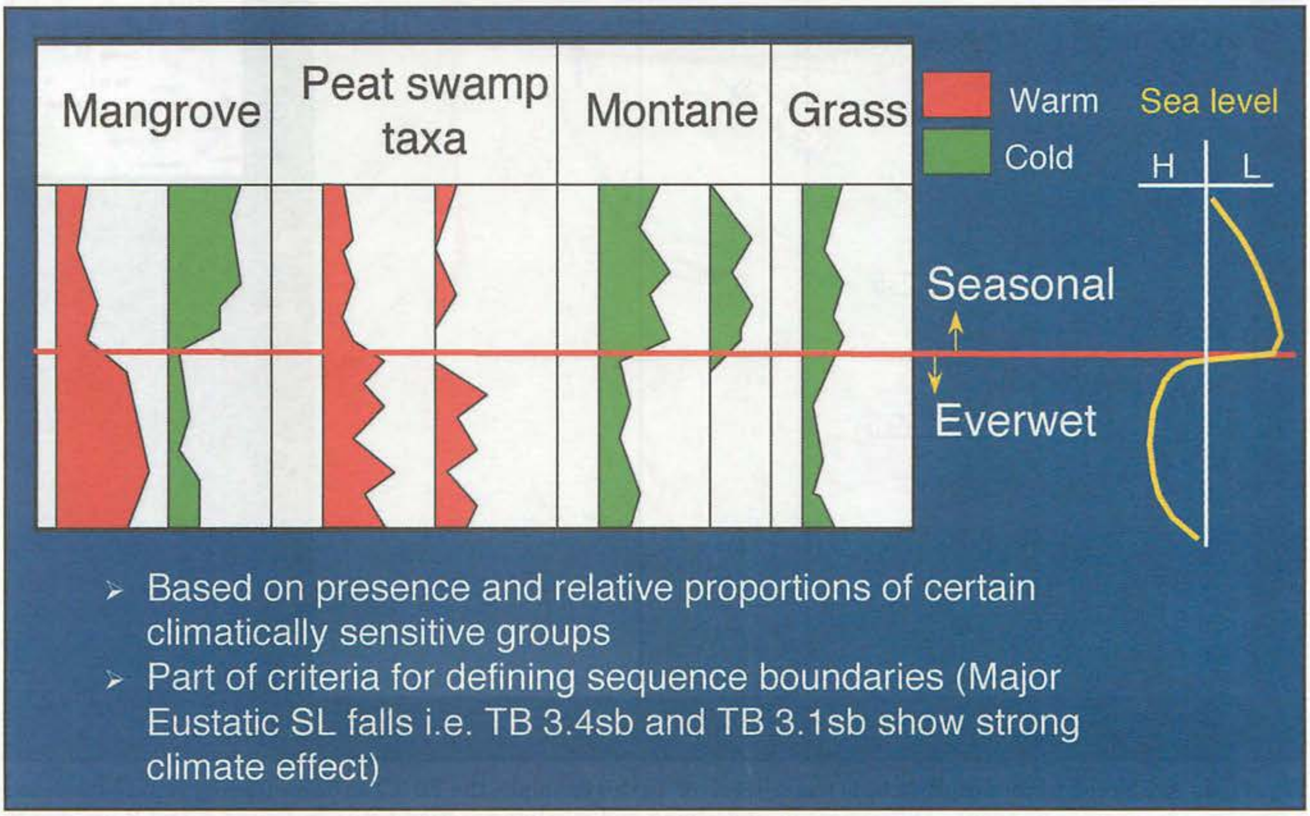

Figure 4. Use of palynology to develop climate curve.

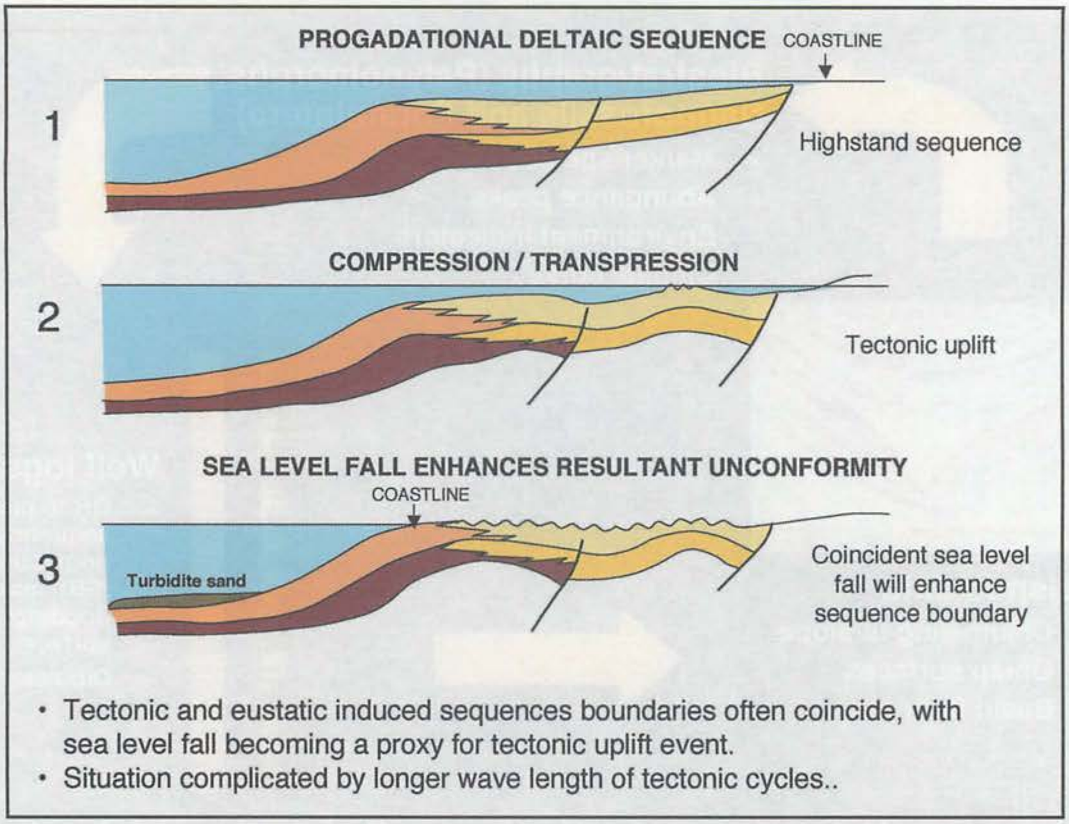

Figure 5. Tectonic and eustatic sequence boundaries often (not always) coincide.

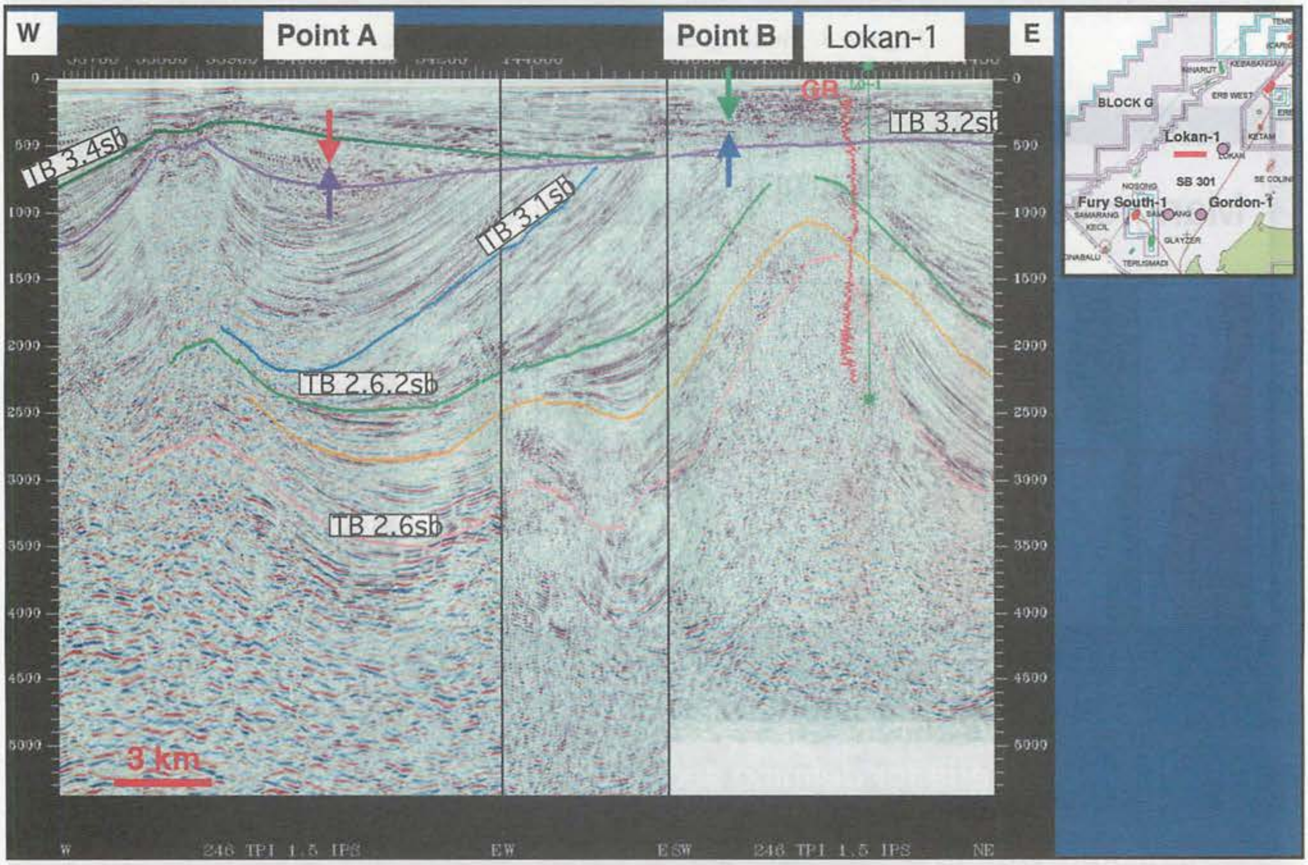

Figure 6. Are Sabah unconformities time transgressive? In this example, the TB 3.2 sb unconformity is not considered a true time transgressive event. Differences in underlying and overlying section between Points A and B are due to varying amounts of erosion and subsequent gradual onlap.

margin are essentially coeval and thus TB nomenclature can be successfully applied. Figure 6, a composite seismic line through the Lokan-1 well in central offshore Sabah shows how difference in overlying and underlying sections between Point A and Point B are due to differential erosion and gradual onlap onto the uplifted surface and the event can be mapped as a single TB sequence boundary, in this case the TB 3.2 sb. Further work is recommended to improve our understanding of the timing and relationship of the main unconformities along the margin.

In summary, the ongoing exploration effort by Shell has shown it is possible to apply the TB nomenclature successfully to even the most tectonically active portions of the margin. The scheme provides a critical baseline for discriminating between eustatic and tectonic components. Careful mapping and integration of all available biostratigraphy data is required, particularly in areas where one or more sequence boundary has been eroded, to fully determine the structural evolution of an area.

APPLICATION OF TB SEQUENCE FRAMEWORK

The next few figures illustrate how a consistent scheme allows some of the key elements of the major NW Borneo geological provinces (Fig. 1) to be linked. This section is not intended as an exhaustive discussion on the structural and stratigraphic evolution of these areas. It is intended to demonstrate some of the benefits of application of the TB nomenclature.

Balingian Province

This NE-SW trending regional line is a tie from the Temana Field in the southeastern part of the Balingian Province to the West Baram Delta (Fig. 7). Key elements are:

- TB1.1–1.4 (Late Oligocene) comprises coastal plain facies in Temana area with some limestone and deeper marine deposits in East Balingian.
- The TB 1.5 sb unconformity (Base Miocene) is subtly represented on this line although elsewhere it is more marked with evidence for major erosion.
- TB 2.2–2.3 (late Early to early Middle Miocene) coastal plain sediments in Balingian are the main commercial reservoir section. Laterally, outer shelf and bathyal conditions prevailed in the Baram Delta at this time.
- TB 2.3 (early Middle Miocene) represents a period of extension with block faulting.
- TB 2.4–TB 2.6 (Middle Miocene) is a period of localised carbonate growth on fault blocks.
- TB 3.1–TB 3.3 (Late Miocene) is a time of progradation of shelf facies over the area.
- TB 3.4 sb Unconformity (Upper Miocene) results from major compression and uplift with subsequent erosion of the older section. This has implications for turbidite sand distribution in distal locations.
- Regressive sequences above the TB 3.4 sb (Late Miocene) consist of shallow marine sands.
- Late compression is evident in the area from TB 3.8 (Late Pliocene) and younger.

Central Luconia

This line trends roughly N-S through the province and shows the relationship with the Balingian Province to the south (Fig. 8).

- TB 1.3–2.3 (Late Oligocene–early Middle Miocene) consists of distal, shelf facies.
- Normal faulting of the section occurs around TB 2.4 sb (early Middle Miocene).
- TB 2.4–2.6 (Middle Miocene) carbonates typically grow on fault block highs in response to eustatic sea level rise and subsidence of the Luconia block.
- Subsequently, the carbonates were overwhelmed by a TB 3.4 (Late Miocene) prograding clastic wedge in response to both eustatic sea level fall and uplift and erosion of the hinterland.
- TB 3.4–3.7 (latest Late Miocene-Late Pliocene) shallow marine sands form exploration objectives.

West Baram Delta

This is a NW-SE trending line showing compressional anticlines in the inboard portion of the Baram Delta with growth faulting over much of present day shelf (Fig. 9). The Baram Delta zone contains a significantly thicker TB 2.4–TB 3.9 (Late Miocene to Pleistocene) section than does the Luconia Province because of greater subsidence to the east of the West Baram line, coupled with major deposition from the Baram Delta.

- The Baram Delta began progradation in the Middle Miocene (TB 2.4).
- Major growth faulting began in TB 3.1 (early Late Miocene) times. Structures related to this growth faulting form the most successful hydrocarbon play in the West Baram Delta.
- Rapid deltaic deposition continued throughout Late Miocene (TB 3.1) to Pleistocene (TB 3.8). Eustatic Sea level falls during this period are the primary trigger for lowstand sand deposition in deepwater regions.
- Inversion is evident in Pleistocene times (TB 3.8) leading to the formation of major anticlines.

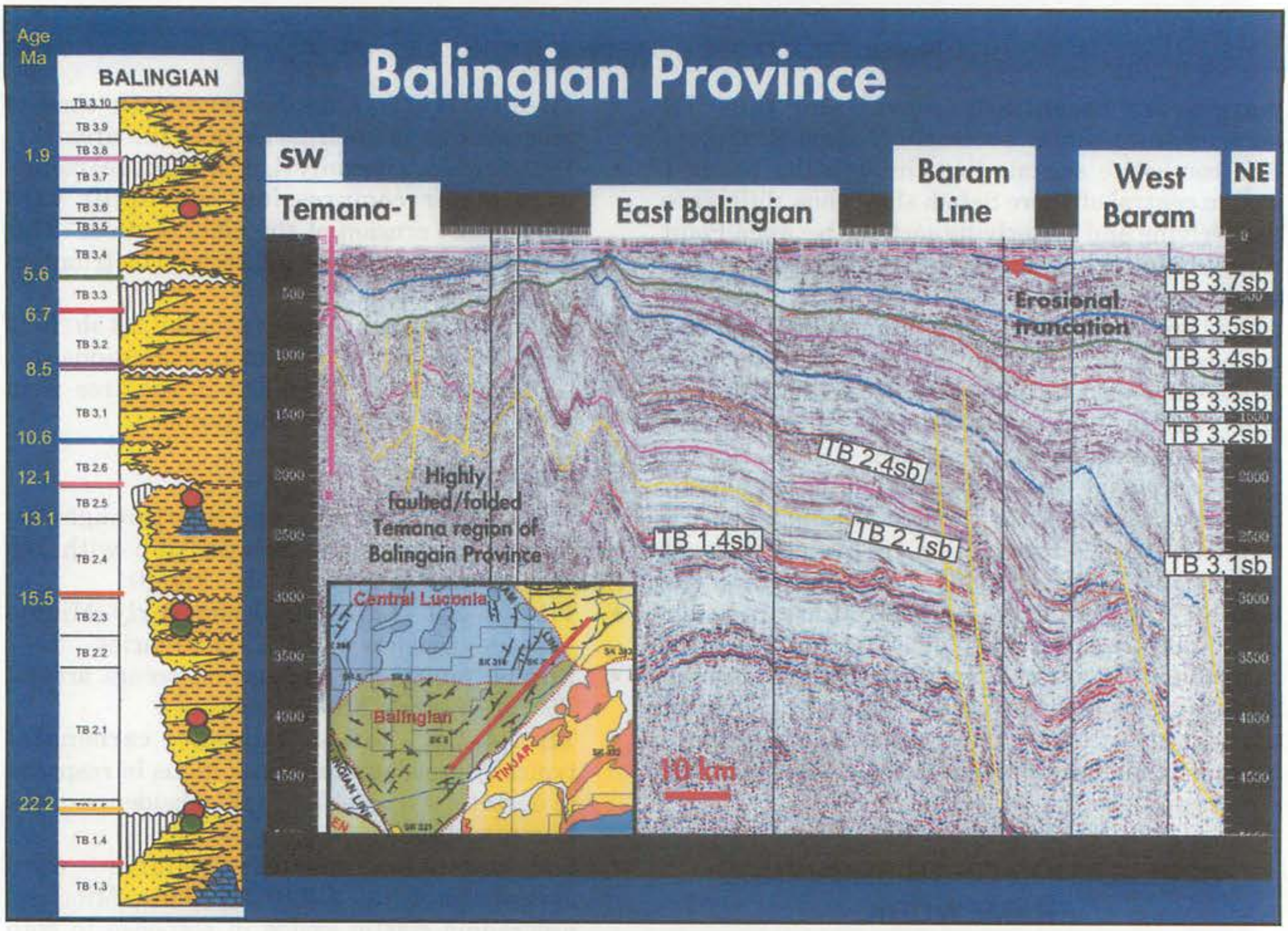

Figure 7. Application of TB sequence framework in Balingian Province.

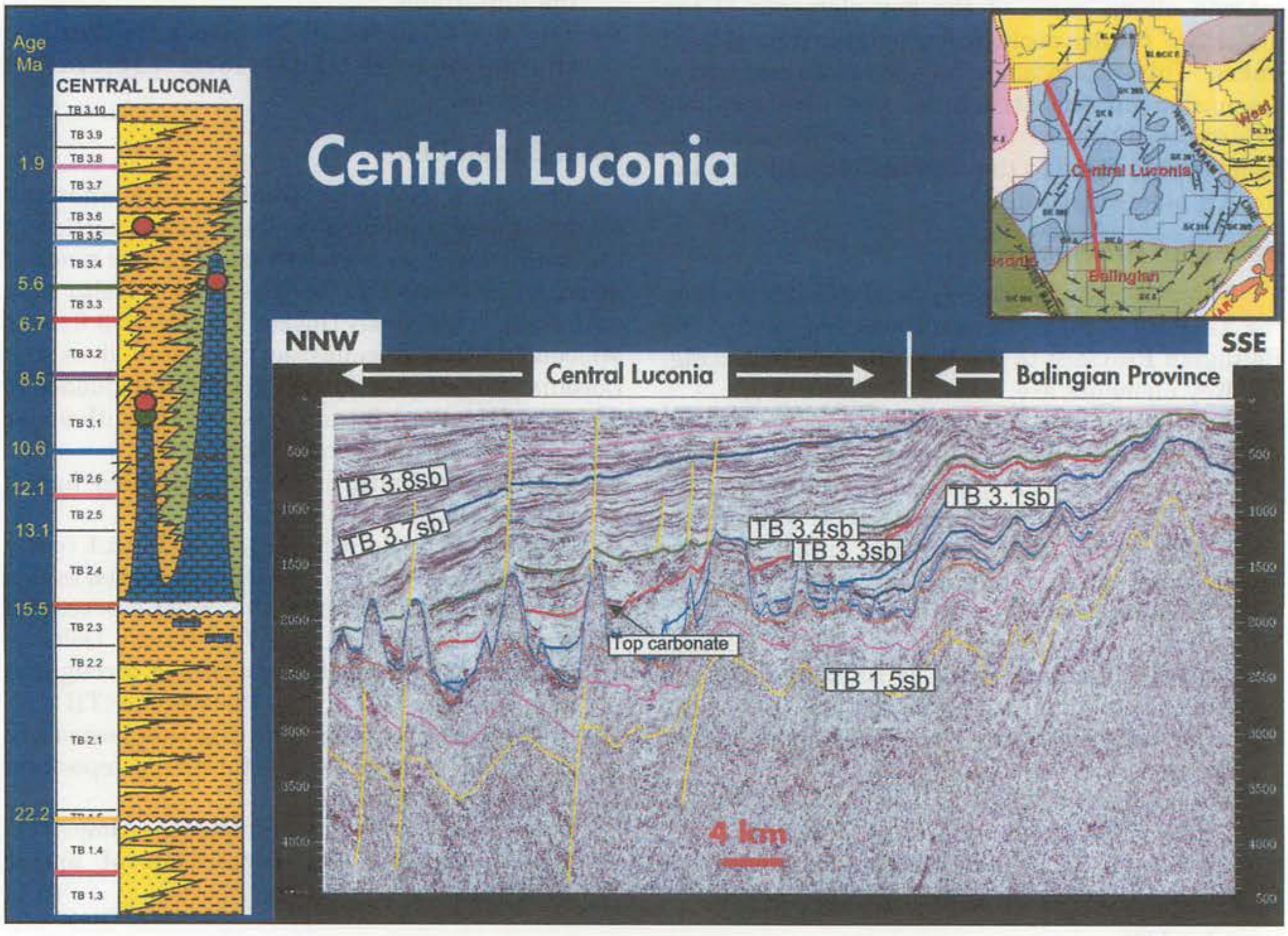

Figure 8. Application of TB sequence framework in Central Luconia Province.

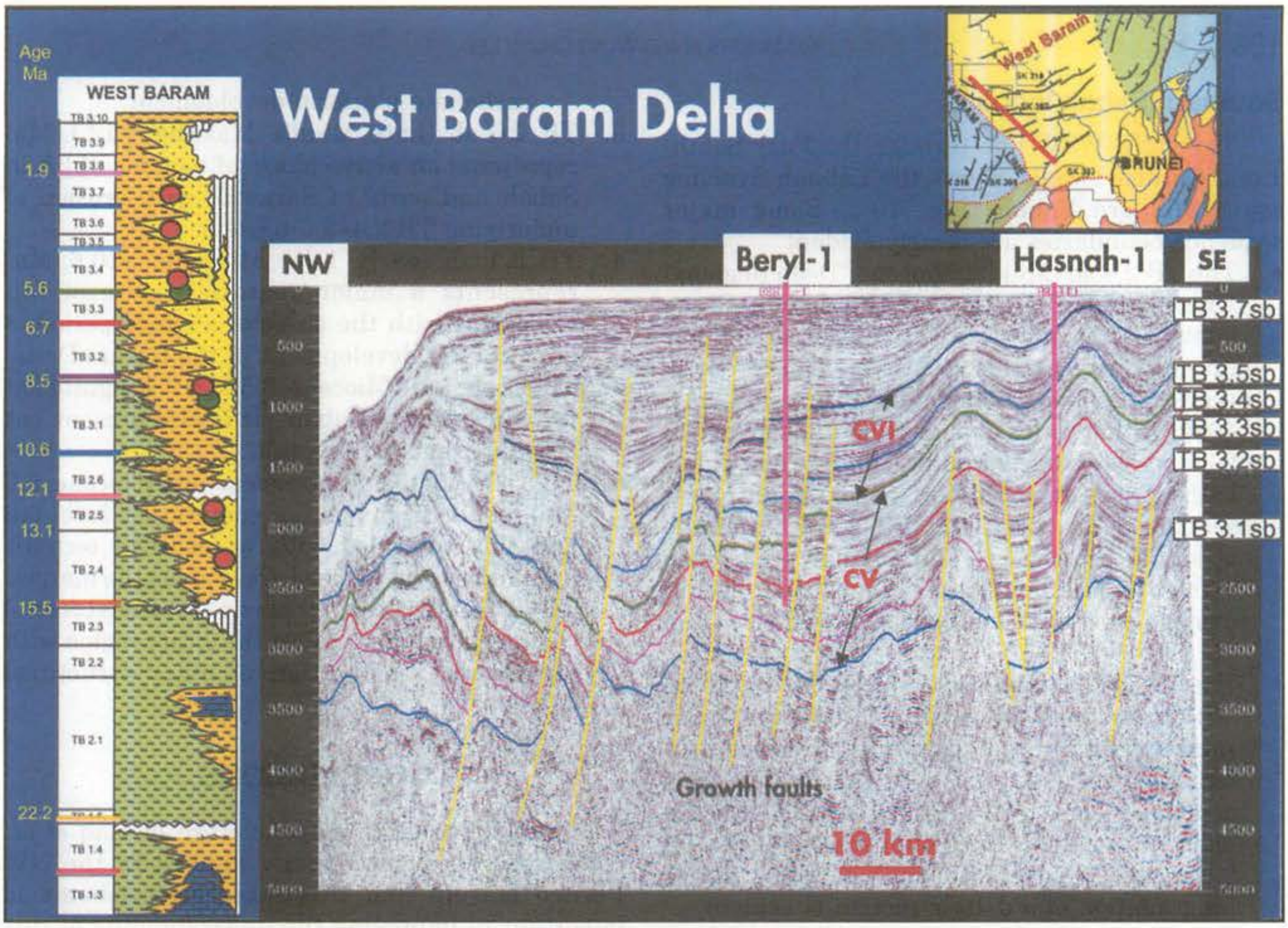

Figure 9. Application of TB sequence framework in West Baram Delta.

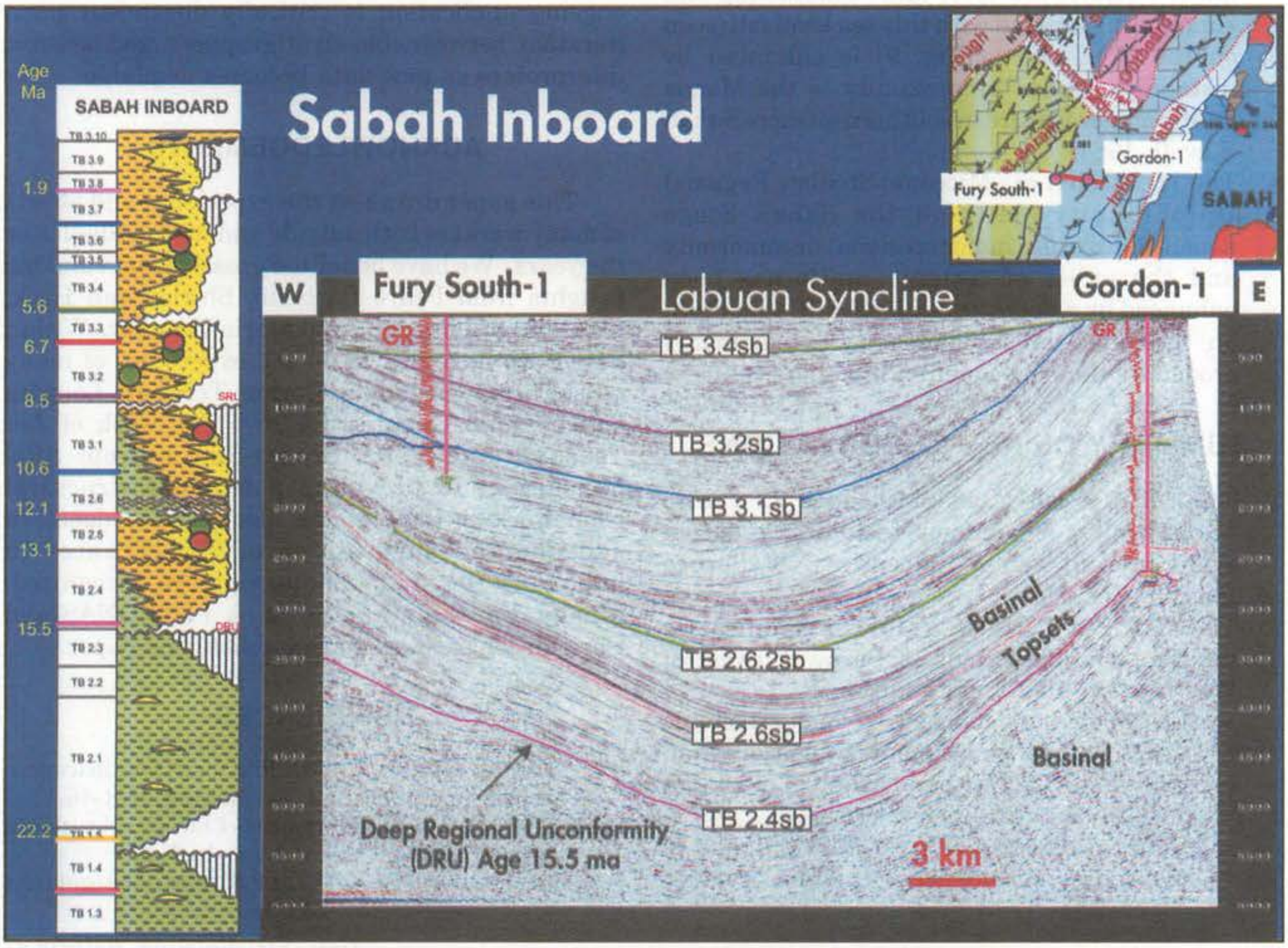

Figure 10. Application of TB sequence framework in Sabah Inboard.

Southern Sabah Inboard

This ENE-WSW line through the Fury South-1 and Gordon-1 wells, shows the Labuan Syncline south offshore Sabah (Fig. 10). Some major sequence boundaries are clearly evident.

- The TB 2.4 sb (Middle Miocene "Deep Regional Unconformity" (DRU)) of the Sabah Stage nomenclature shows a relatively minor angular unconformity at this location. This event is related to major tectonic uplift (Tan and Lamy, 1990) with a facies change from underlying TB 2.3 and older (early Middle Miocene and older) bathyal deposits to shallow marine sandy topset section of the overlying TB 2.4–2.5 (Middle Miocene) sequence. This change from deep water to shallow water deposition occurs despite an overall eustatic sea level rise (Fig. 2).
- The TB 2.6 sb (late Middle Miocene) marks an initial sea level fall with potential for major sand bypass into the deepwater, followed by a major transgression with bathyal shales deposited on top of the TB 2.4–2.5 (Middle Miocene) section. In the upper part of the TB 2.6 (late Middle Miocene) section, major progradation of a deltaic section is evident.
- The TB 3.1 sb (Late Miocene) is a result of major eustatic sea level fall. Channeling and slumping associated with this sea level fall (seen on the ENE end of Fig. 9) is enhanced by instability caused by proximity to the Morris fault, a major feature in southern offshore Sabah (Levell, 1987).
- The TB 3.2 sb (Late Miocene) Shallow Regional Unconformity (SRU) of the Sabah Stage nomenclature) is a major erosional unconformity and the effect of tectonic uplift has been enhanced by a eustatic sea level fall. As shown on the line, the unconformity is commonly eroded by the subsequent TB 3.4 sb event.

SUMMARY OF KEY OBSERVATIONS

1. The TB 1.5 sb (Base Miocene, 22.2 Ma) unconformity is a major tectonically driven event present across the entire NW Borneo margin (Fig. 11).
2. The TB 2.4 sb (DRU, 15.5 Ma) has significantly different manifestations in Sarawak (west of West Baram line) and Sabah.
   ⇒ In Sabah it is marked by major tectonic uplift with a consequent transition from bathyal (TB 2.3) to sandy shelf (TB 2.4/2.5) despite eustatic sea level rise.
   ⇒ In Sarawak (west of West Baram line) it is marked by subsidence with start of major carbonate platform development.
3. TB 2.6 sb (Late Middle Miocene: 12.1 Ma) represents an active phase of tectonic uplift in Sabah and parts of Sarawak with erosion of underlying TB 2.4–2.5 topsets.
4. TB 3.1 sb (early Late Miocene: 10.6 Ma) represents a major eustatic sea level fall coincident with the onset of a major period of growth fault development in the Baram Delta.
5. TB 3.2 sb (Late Miocene, 8.5 Ma) is a significant tectonic event in Sabah. It is also present but less apparent in Sarawak.
6. TB 3.4 sb (Latest Miocene/earliest Pliocene, 5.6 Ma) results from a major eustatic sea level fall and this coincides with widespread tectonic uplift/erosion in inboard areas along the margin.
7. TB 3.7–3.8 (Late Pliocene to Pleistocene) compressive phases affect the entire region with significant reactivation of older structural trends.

CONCLUSIONS

The TB sequence nomenclature of Haq *et al.* (1988) has been successfully applied to the NW Borneo margin and this integrated scheme is important to improving the understanding of this complex region. Successful implementation and ongoing application is critically dependent upon iteration between bio-stratigraphers and seismic interpreters as new data becomes available.

ACKNOWLEDGEMENTS

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REFERENCES

BOL, A.J. AND VAN HOORN, B., 1980. Structural styles in western Sabah offshore. *Bull. Geol. Soc. Malaysia*, 12, 1–16.

HO, K.F., 1978. Stratigraphic framework for oil exploration in Sarawak. *Bull. Geol. Soc. Malaysia*, 10, 1–13.

HAQ, B.U., HARDENBOL, J. AND VAIL, P.R., 1988. Mesozoic and

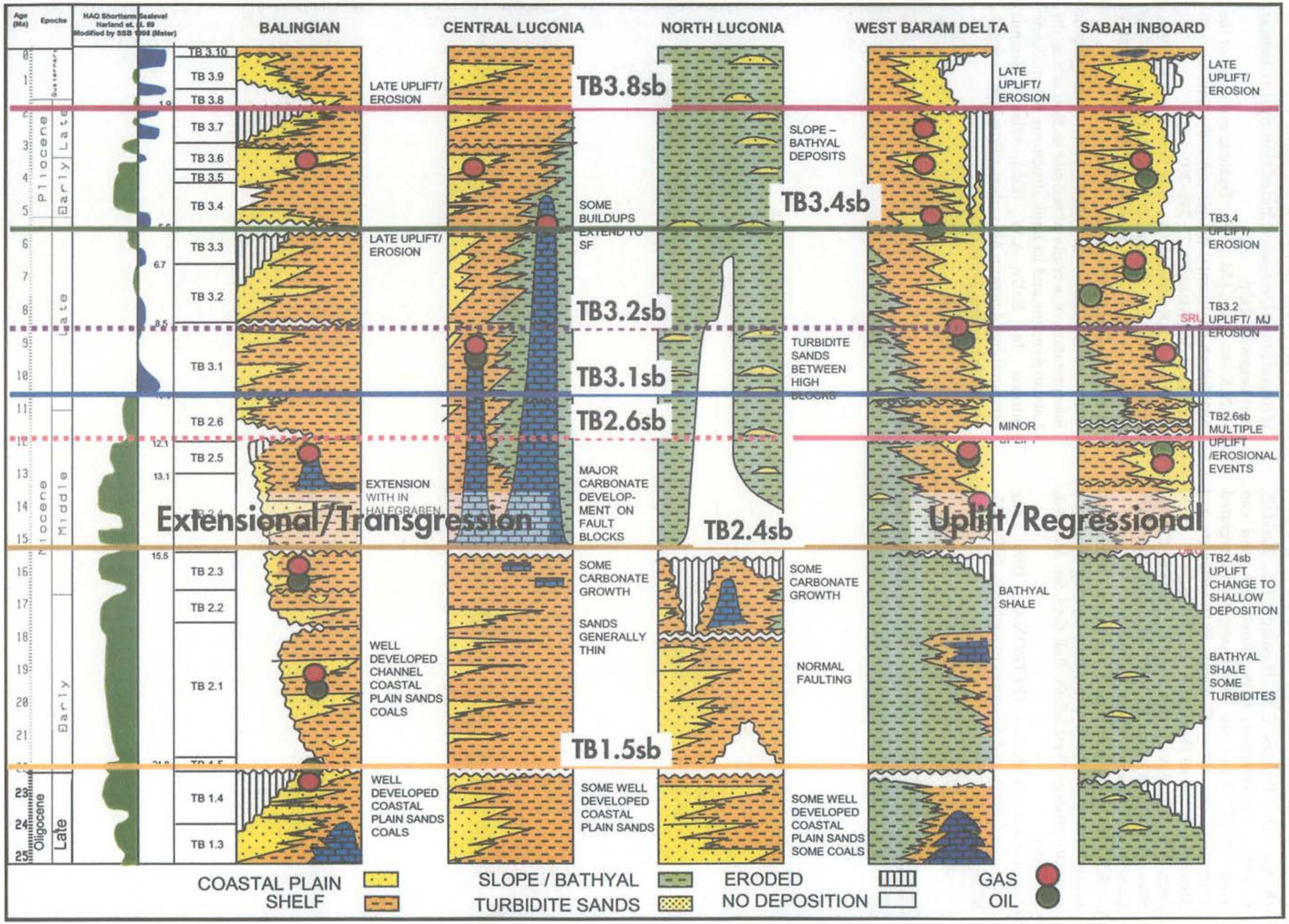

Figure 11. Summary NW Borneo geological provinces.

Cenozoic chronostratigraphy and cycles of sea level change. *In:* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and van Wagoner, J.C. (Eds.), Sea level change: an integrated approach. *Society of Economic Paleontologists and Mineralogists Special Publication*, 42, 71–108.

HARLAND, W.B., COX, A.V., LLEWELLYN, P.G., PICKTON. C.A.G., SMITH, A.G. AND WALTERS, R., 1989. *A Geologic Time Scale.* Cambridge University Press, Cambridge.

LEVELL, B.K., 1987. The nature and significance of regional unconformity in the hydrocarbon-bearing Neogene sequence offshore West Sabah. *Bull. Geol. Soc. Malaysia, 21,* 55–90.

PETROLEUM NASIONAL BERHAD (PETRONAS), 1999. The *Petroleum Geology and Resources of Malaysia,* ISBN 983-9738-10-0, 665p.

SANDAL, S.T. (Ed.), 1996. *The Geology and Hydrocarbon Resources of Negara Brunei Darussalam,* 2nd edition. Syabas, Bandar Seri Begawan, 243p.

TAN, D.N.K AND LAMY, J.M., 1990. Tectonic evolution of the NW Sabah continental margin since the Late Eocene. *Bull. Geol. Soc. Malaysia, 27,* 241–260.

VAN BORREN, L., KOOPMAN, A. AND SCHREURS, J., 1996. Stratigraphy. *In:* Sandal, D.T. (Ed.), *The geology and hydrocarbon resources of Negara Brunei Darussalam,* 2nd Ed. Syabas, Bandar Seri Begawan, 81–128.

VAN VLIET, A. AND SCHWANER, M.M., 1987. Stratigraphic interpretation of a regional seismic section across the Labuan Syncline and its flank structures, Sabah, North Borneo. *In:* Bally, A.W., (Ed.), Atlas of Seismic Stratigraphy. *American Association of Petroleum Geologist, Studies in Geology, 27,* 163–167.

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