Seismic sequence stratigraphy of the Tertiary sediments, offshore Sarawak deepwater area, Malaysia

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Abstract: A seismic sequence stratigraphic interpretation was carried out in the Sarawak deepwater area with the main objective of developing a workable chronostratigraphic chart that defines stratigraphic boundaries within which depositional systems and lithofacies can be identified, mapped and interpreted. The dataset includes 8,000 km of seismic lines and well data from four drilled locations.

The study has resulted in the identification and correlation of eight seismic horizons representing the tops of eight depositional sequences which are grouped into four mega/supersequences (A, B, C and D) based on regional tectonic events of the South China Sea. Six of the seismic horizons have been tied to the four wells and dated based on paleontologic data. Two other older horizons are dated based on correlation to the global sea-level chart. Higher order sequences are also interpreted from paleontologic, lithologic, paleofacies data and GR-logs from the four wells.

Seismic facies analysis have also been carried out in the study area where four main seismic facies (Facies I–IV) ranging from non-marine to deepmarine facies are interpreted. Seismic facies maps constructed for lower and upper portions of Oligocene-Lower Miocene Supersequence C indicate that it contains all four main facies. This supersequence is overall transgressive and its paleoshoreline runs in a NW-SE direction. A seismic facies map generated for Middle Miocene-Recent Supersequence D suggests that it contains mainly outer shelf to deepmarine facies (Facies III–IV) and its paleoshoreline runs in an East-West direction.

A workable chronostratigraphic chart has been developed where second to fourth-order sequences can be correlated within the study area. The chart is able to correlate the episodic rifting of Ru and Pigott (1986), the local structural history and Shell's sedimentary Cycles I–VIII (Ho, 1978) to the global sea-level curve (Haq *et al.*, 1988).

This study also assisted in identifying potential play-types. Structural traps of non-marine to shallow marine facies are mainly confined to Supersequence C while stratigraphic traps of basin floor fans are located mainly in Supersequence D.

INTRODUCTION

The study area is located within the Sarawak Basin in the South China Sea. It lies approximately 200 to 400 km from the present coastline of Sarawak and covers an area of approximately 40,000 sq km (Fig. 1).

Water depths in the study area ranges from about 100 m to more than 2,000 m (Fig. 2). In general, the bathymetric depth increases towards the northeast but occasionally is interrupted by seamounts that reach up to less than 1,000 m of water depths. At the western part of the study area, a very smooth seafloor topography with gentle northeast gradient is observed, due to clastic sedimentation during Late Miocene to Pliocene. However, the shelf edge in central area forms a steep slope and is associated with oblique shelf progradation during the Upper Miocene to Recent period. Meanwhile, a protrusion at the eastern shelf edge is related to a carbonate growth which is Middle Miocene.

The seismic sequence stratigraphic study was performed with the following objectives:-

- To develop a workable chronostratigraphic correlation chart that defines main stratigraphic boundaries within which deposition systems and lithofacies can be defined, mapped and interpreted. The correlation takes into consideration the regional tectonics, local structural history and the global sea-level curve;
- To determine the different types of paleoenvironment under which the sequences were deposited; and;
- To assist in identifying potential play-types which include both structural and stratigraphic traps.

DATA AVAILABILITY

The seismic sequence stratigraphic study was conducted based on the available geophysical and geological data.

The geophysical database comprises

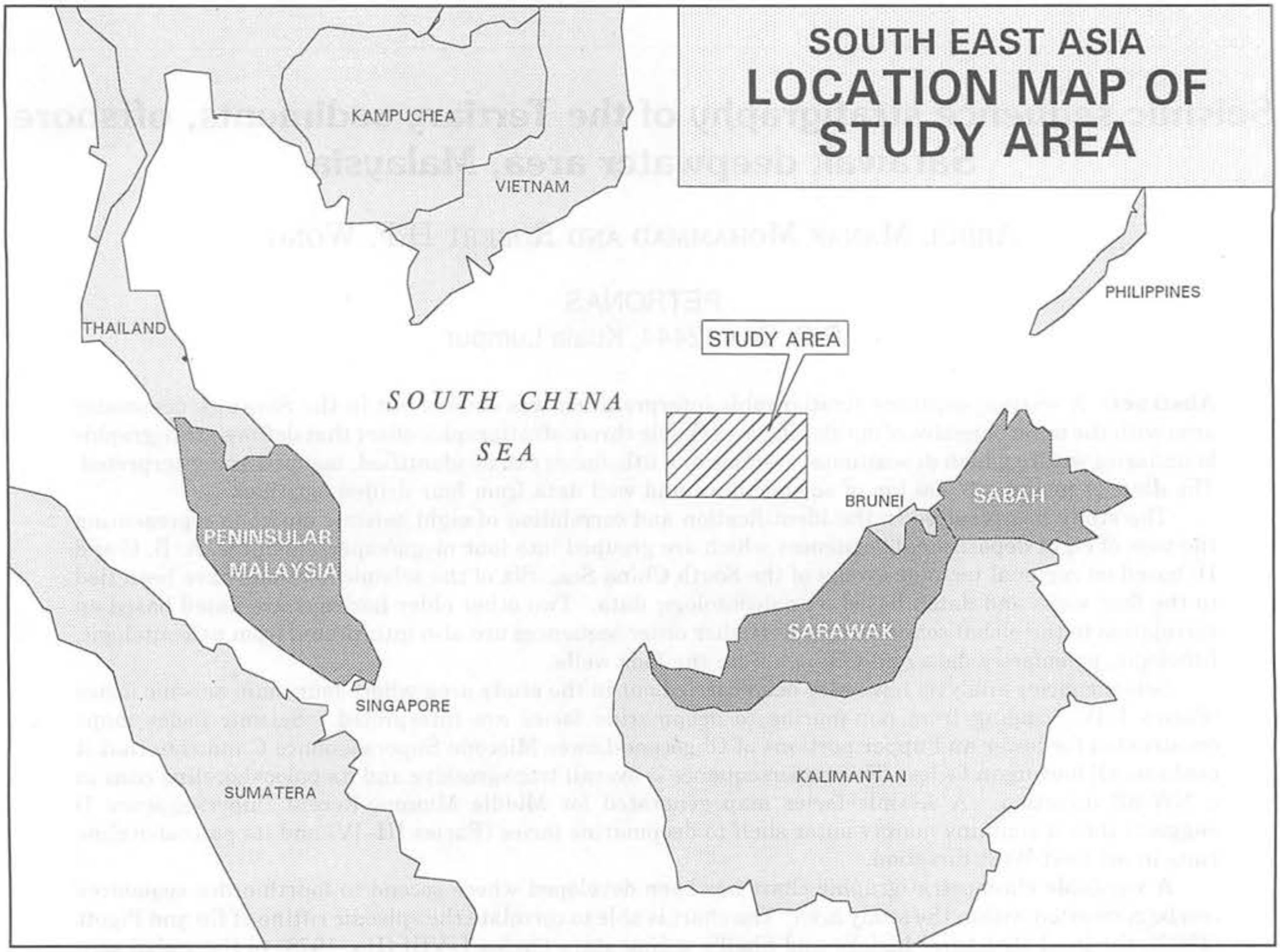

Figure 1. Location map of the study area.

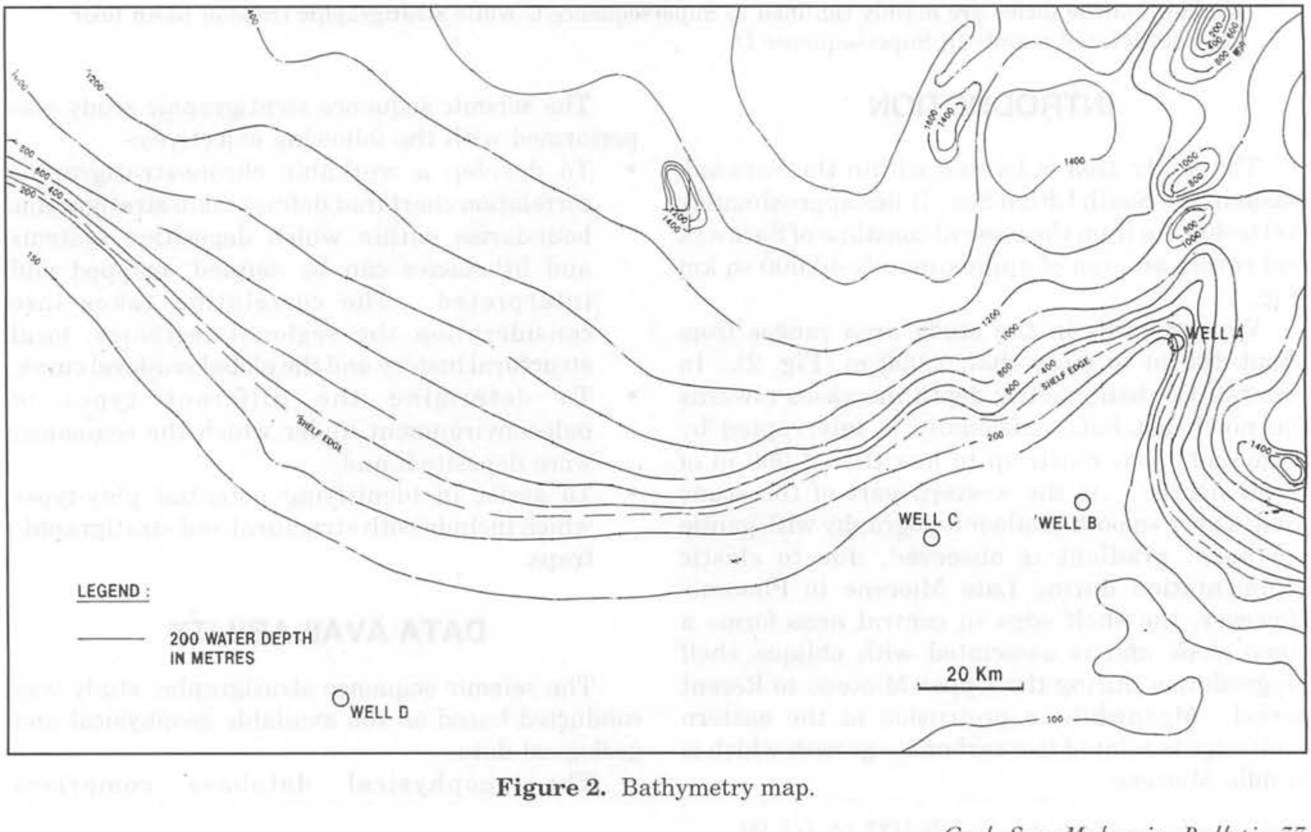

Figure 2. Bathymetry map.

approximately 8,000 line-km of high-quality seismic data of 1989 vintage and reprocessed seismic data of 1969–1973 vintages. The seismic coverage provides a grid spacing of 5 x 10 km^2 in the east and 15 x 15 km^2 in the west. The lines are orientated mainly in NE-SW and NW-SE directions.

The well database for this study includes four wells — A, B, C and D that were drilled in the shelfal part of the study area.

The seismic and well location map is shown in Figure 3.

GEOLOGICAL SETTING

Based on structural trends and styles observed, the study area can be subdivided into three provinces: West Luconia, North Luconia and Central Luconia platform (Fig. 4).

The West Luconia Province is characterized by thrust imbricates and asymmetrical anticlines associated with zones of large expansion towards the landward side. The province contains very thick Miocene-Pliocene sections.

The North Luconia Province represents a deep Cenozoic rift basin. It is characterised by mainly N-S trending fault-bounded structures and listric faulted graben complexes.

The Central Luconia Platform is a stable province where very little clastics influx reached the area at least up to Mid-Miocene, allowing deposition of a carbonate bank which locally developed into shelfal buildups.

SEISMIC INTERPRETATION

Altogether, eight seismic horizons were correlated using regional lines in the study area. They represent tops of depositional sequences which are grouped into four Mega/Supersequences based on correlation of regional tectonic events i.e. the rifting episodes of the South China Sea (Ru and Pigott, 1986) to the global sea-level chart (Haq *et al.*, 1988) (Fig. 5). They range from Megasequence A (Late Cretaceous-Middle Eocene), Supersequence B (Late Eocene-Late Oligocene), Supersequence C (late Oligocene-Early Miocene) and Supersequence D (Early Miocene-Recent).

The ages of the Blue, Purple, Dark Green, Orange, Brown and Light Green horizons have been dated based on seismic ties to the four wells located on the shelfal area which penetrated down to Lower Oligocene sediments. The Red and Pink horizons have been tentatively dated based on the ages of the regional tectonic events in the South China Sea and their comparison with the eustatic chart (Fig. 5).

An example of interpreted mega/supersequences within a listric-faulted graben complex is shown Figure 6. The boundaries are clearly distinguished by their angular relationship and/or regionally mappable horizons, usually associated with high amplitudes. Figure 7 is another example where the four mega/supersequences are identified and the onlapping of the overlying sediments of Supersequence B against the Red Horizon is clearly evident. The Red Horizon also truncates the upper part of Megasequence A.

In these examples, other simple sequence boundaries related to local structural history are also interpreted. One of them is the Purple Horizon which is interpreted to separate two major seismic facies — a lower continuous high amplitude parallel events and an upper weak reflectors to reflection free zone (Fig. 6).

WELL-LOG INTERPRETATION

Second order mega/supersequence and third-order simple sequence boundaries (Vail *et al.*, 1990) can be readily identified on seismic data. Well logs are able to resolve up to fifth or sixth order of cyclicity (Van Wagoner *et at.*, 1990). Hence, in this study, mega/supersequence, simple sequence and parasequence boundaries are also interpreted by utilizing well-logs combined with paleontologic, lithologic and paleofacies data.

The stratigraphy was previously interpreted by Shell using the sedimentary cycle concept (Ho, 1978). Altogether there are eight cycles with ages ranging from Early Oligocene to Recent. Cycle I (early Oligocene-Early Miocene is the oldest cycle whilst Cycle VIII (Pleistocene) is the youngest cycle (Fig. 5). Systems tract interpretation was conducted on the well sections and the intervals crossing major stratigraphic boundaries are depicted (Fig. 8 to Fig. 15).

The 30 Ma Supersequence Boundary (Blue Horizon) separating Supersequences B and C is recognised within Cycle I which was penetrated by Well A. Although there is no variation in the interpreted paleofacies, the coarsening upward sandy section is easily differentiated from the overlying thick, shaly interval, suggesting a drastic change from low to high accommodation space (Fig. 8). The coarsening upward section below the Blue Horizon is interpreted to be highstand systems tract and the shaly interval above it is interpreted to be a transgressive systems tract.

The third-order 22 Ma sequence boundary (Purple Horizon) within Supersequence C was interpreted to be the boundary dividing Cycle I and Cycle II (Fig. 9). The boundary is marked by a sudden change in lithology (sand prone below to shales and carbonate above) and depositional

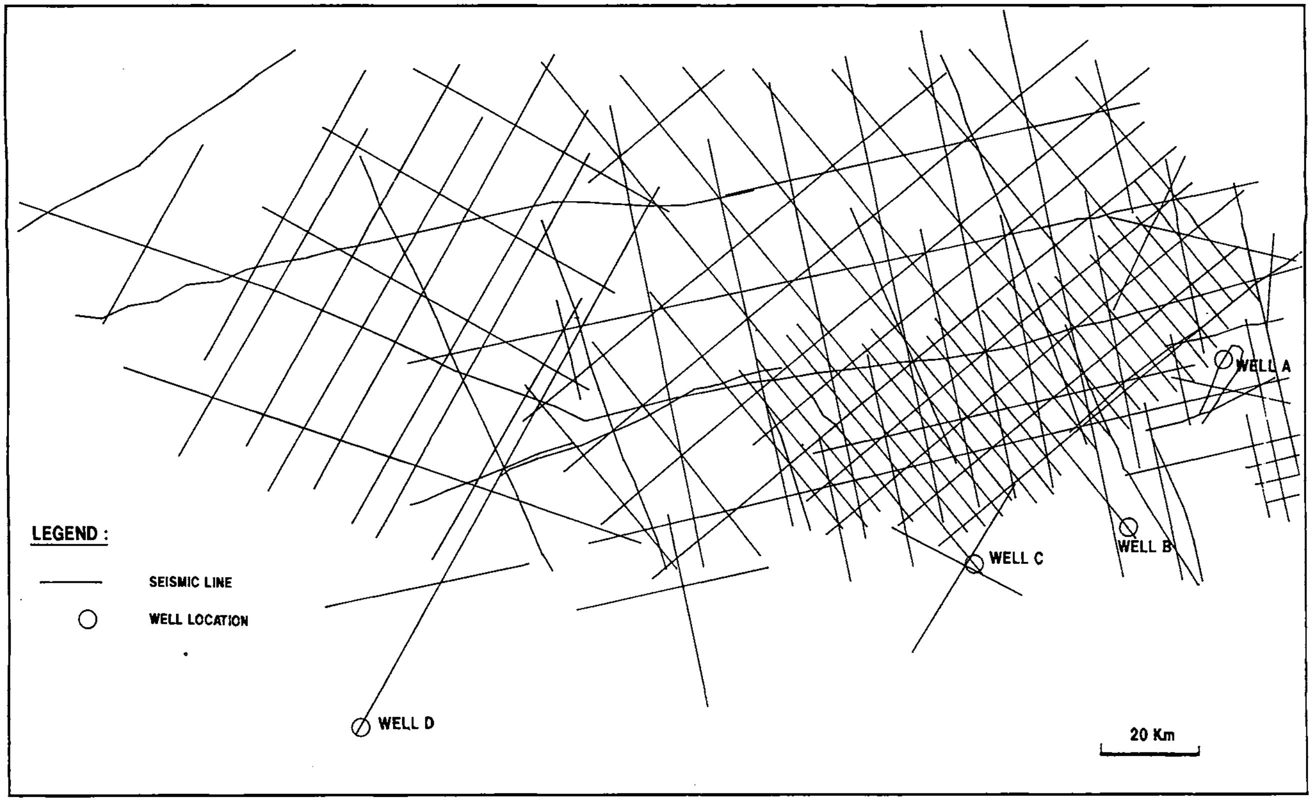

Figure 3. Seismic and well location map.

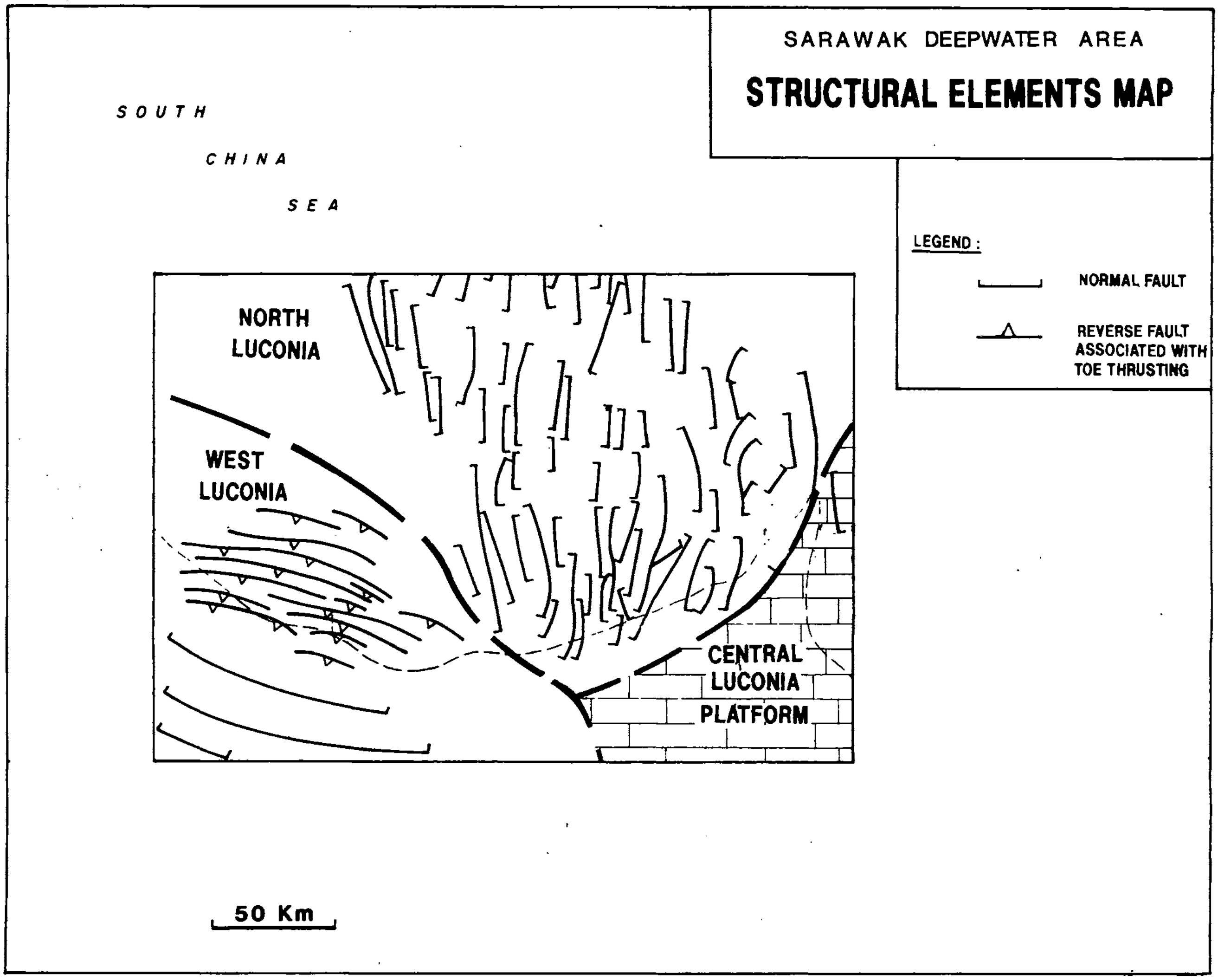

Figure 4. Structural elements map.

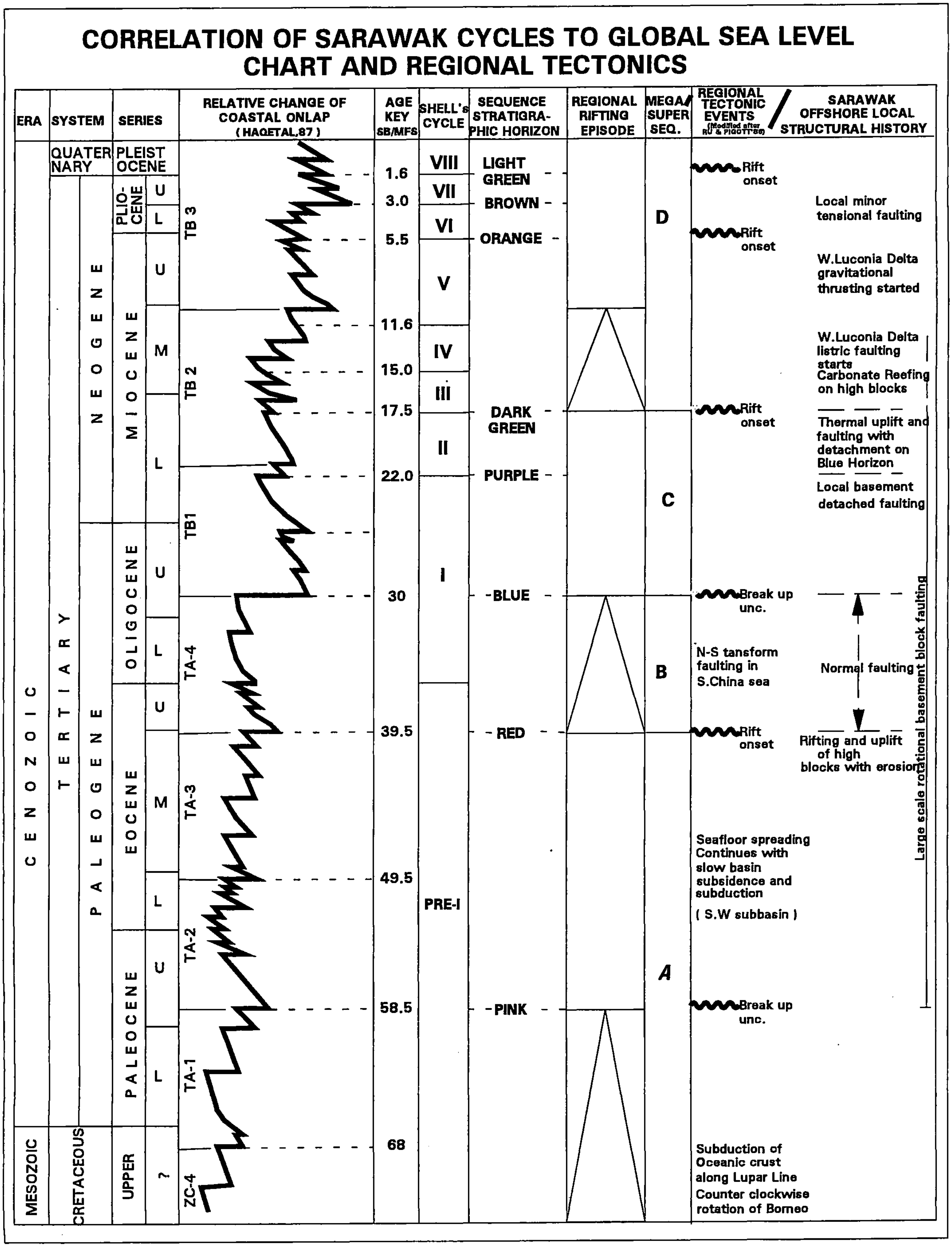

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Figure 5. Correlation of Sarawak cycles to global sea-level chart and regional tectonics.

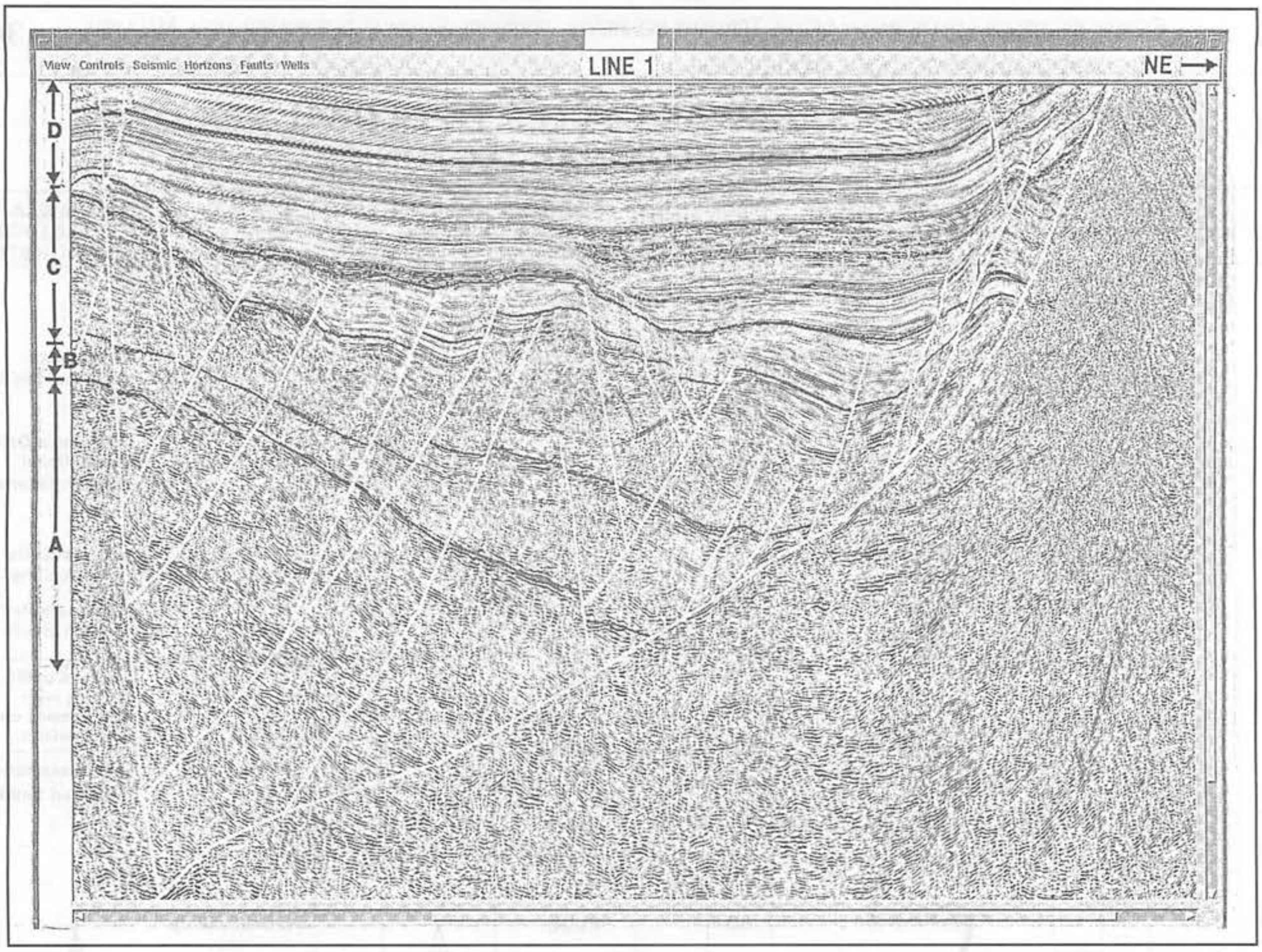

Figure 6. Interpreted Line 1 crossing a listric-faulted graben complex.

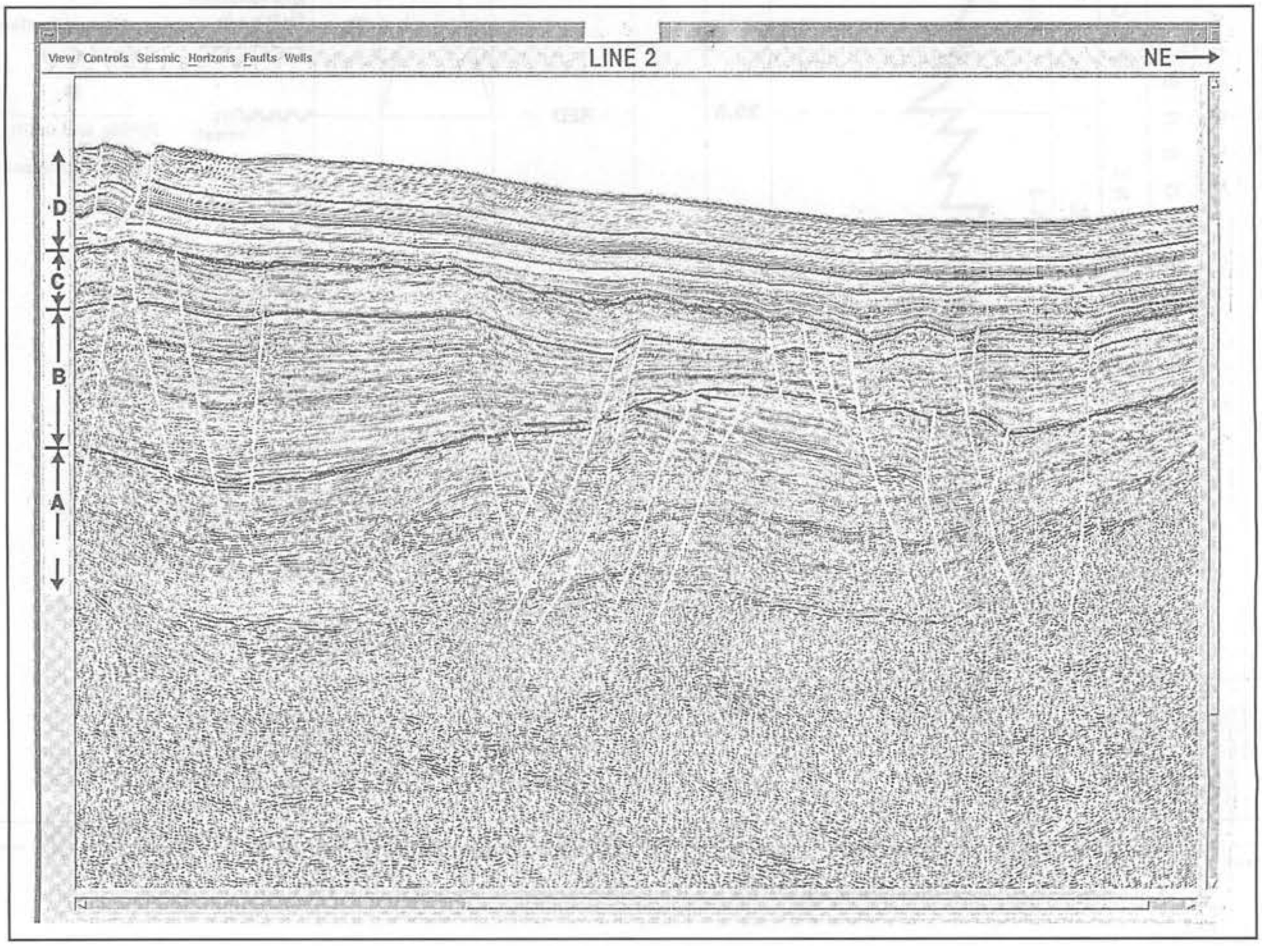

Figure 7. Interpreted Line 2 showing major truncation by red horizon.

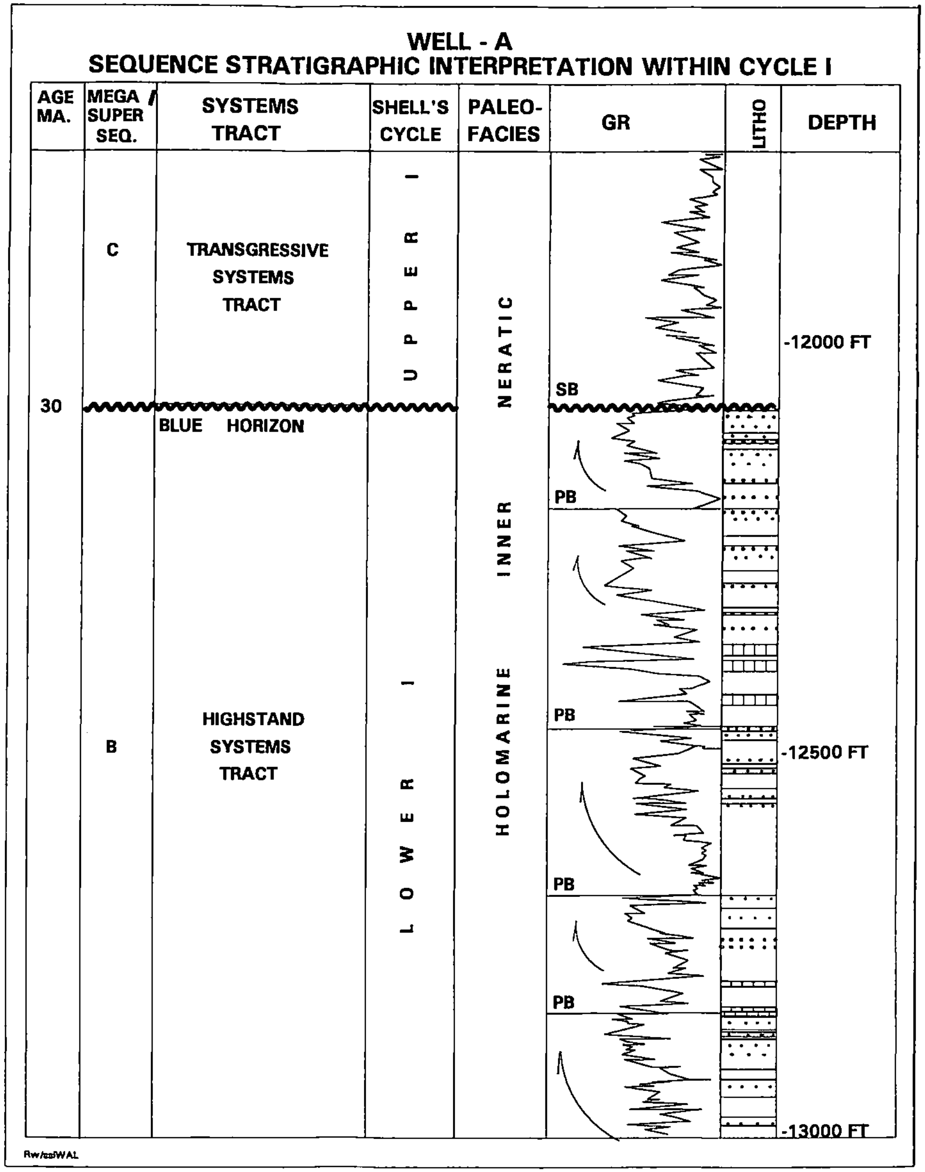

Figure 8. Well-A: sequence stratigraphic interpretation within Cycle I.

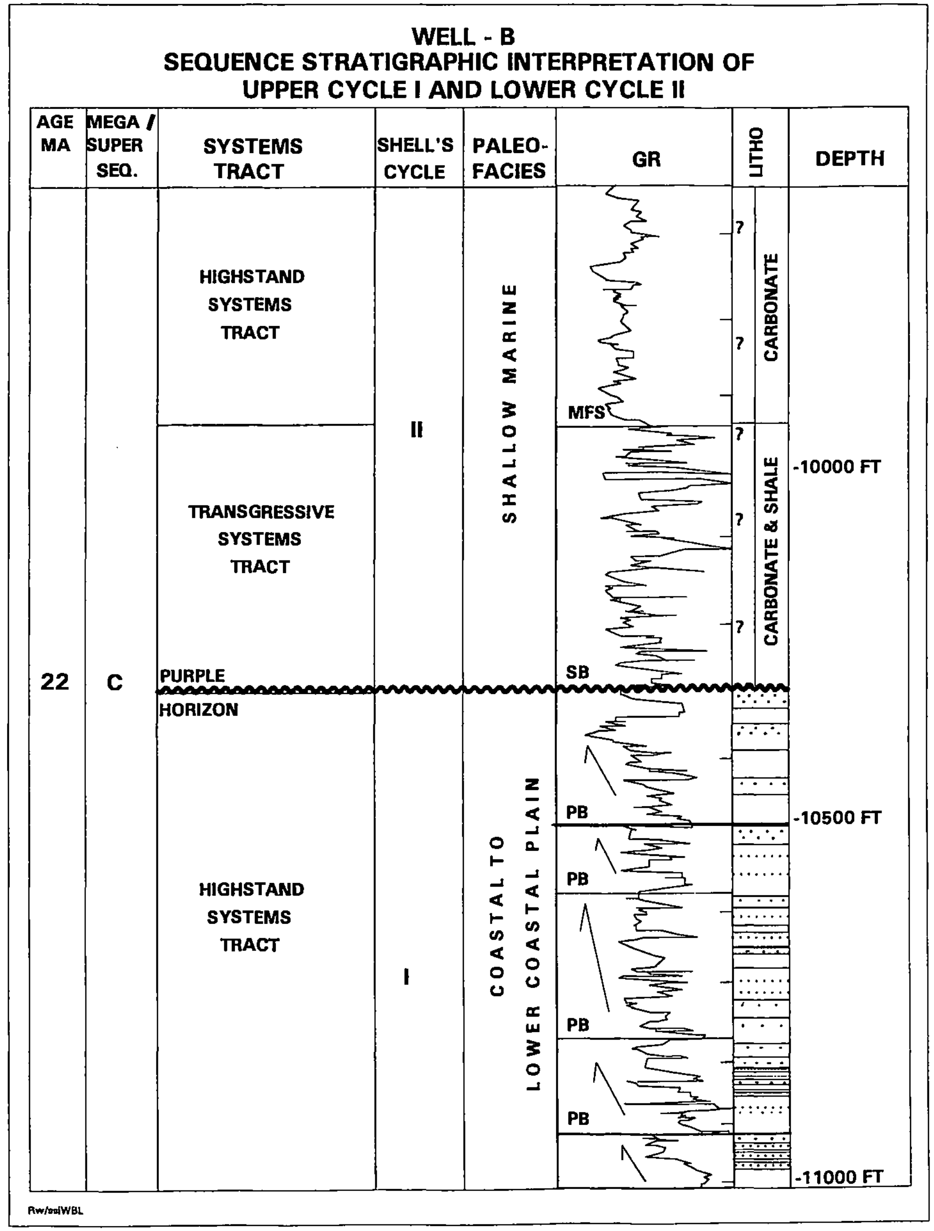

Figure 9. Well-B: sequence stratigraphic interpretation of Upper Cycle I and Lower Cycle II.

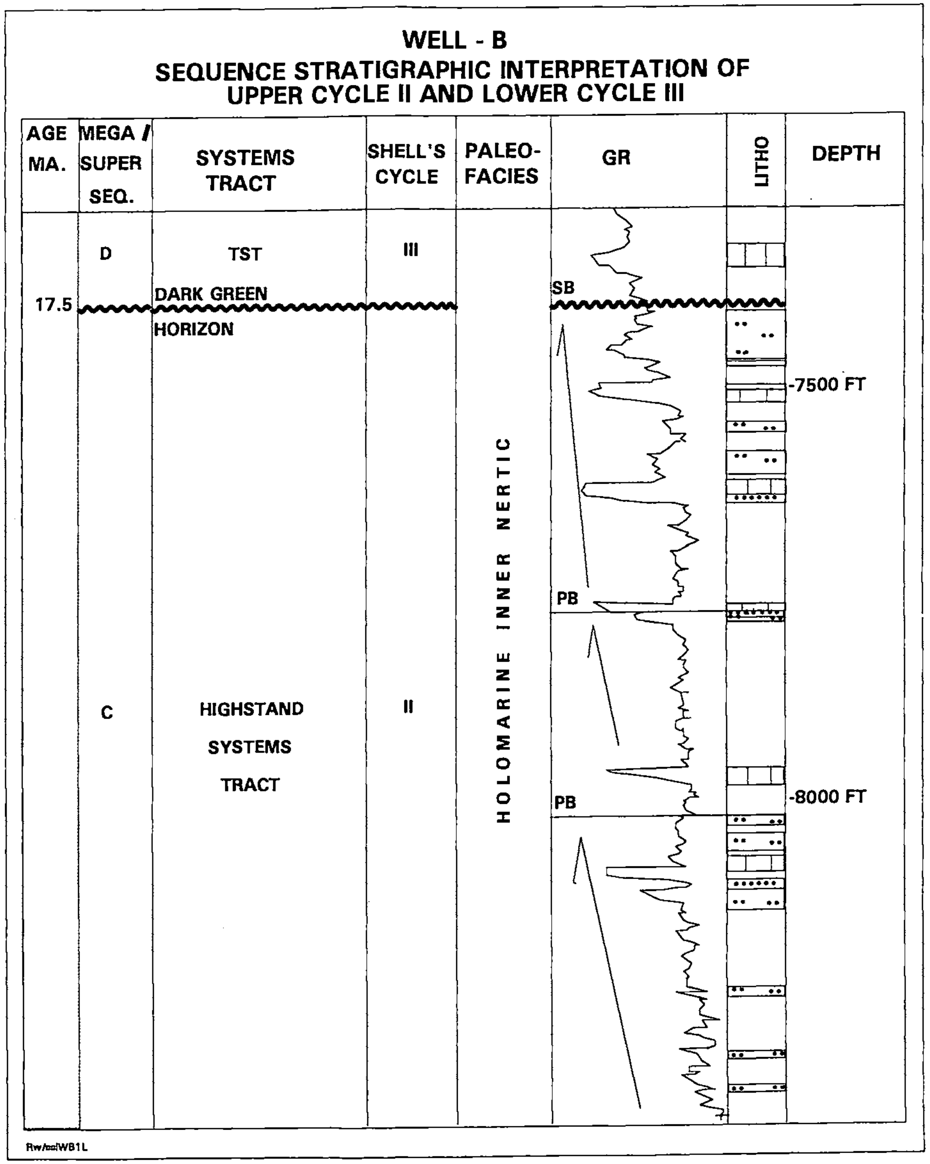

Figure 10. Well-B: sequence stratigraphic interpretation of Upper Cycle II and Lower Cycle III.

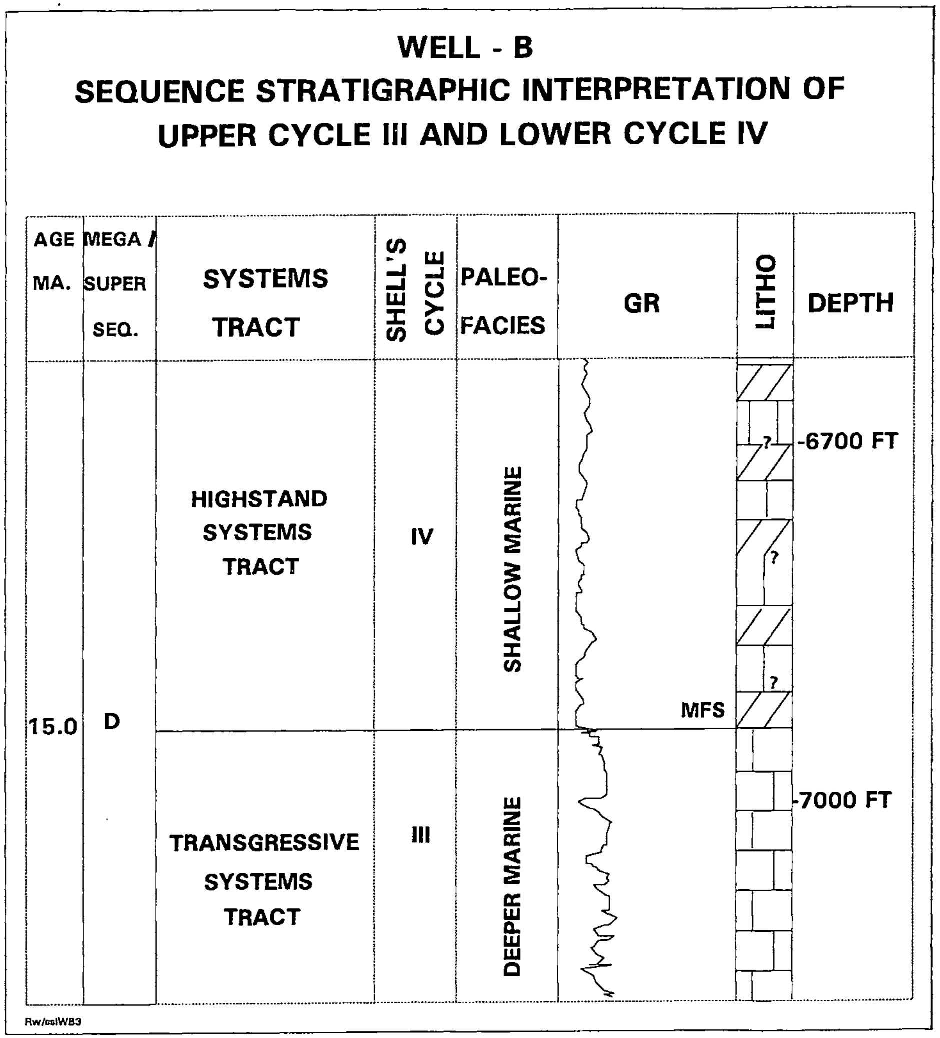

Figure 11. Well-B: sequence stratigraphic interpretation of Upper Cycle III and Lower Cycle IV.

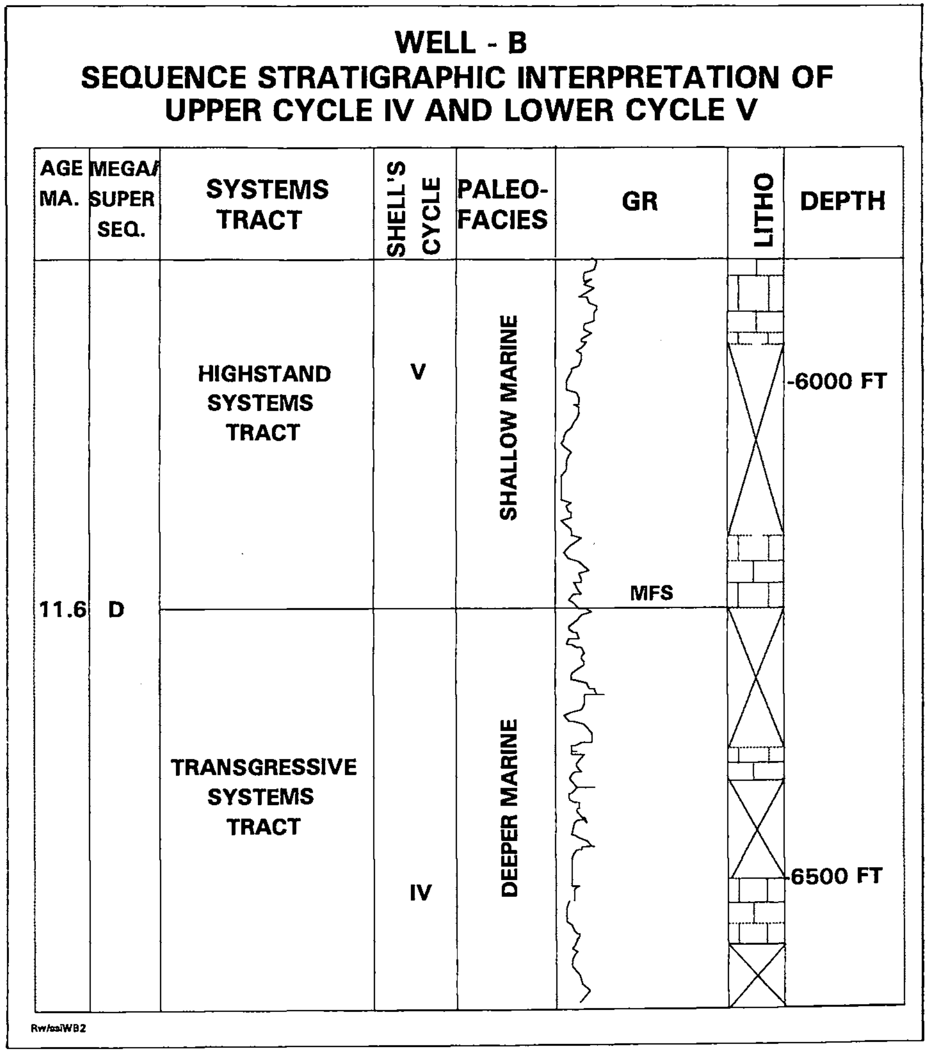

Figure 12. Well-B: sequence stratigraphic interpretation of Upper Cycle IV and Lower Cycle V.

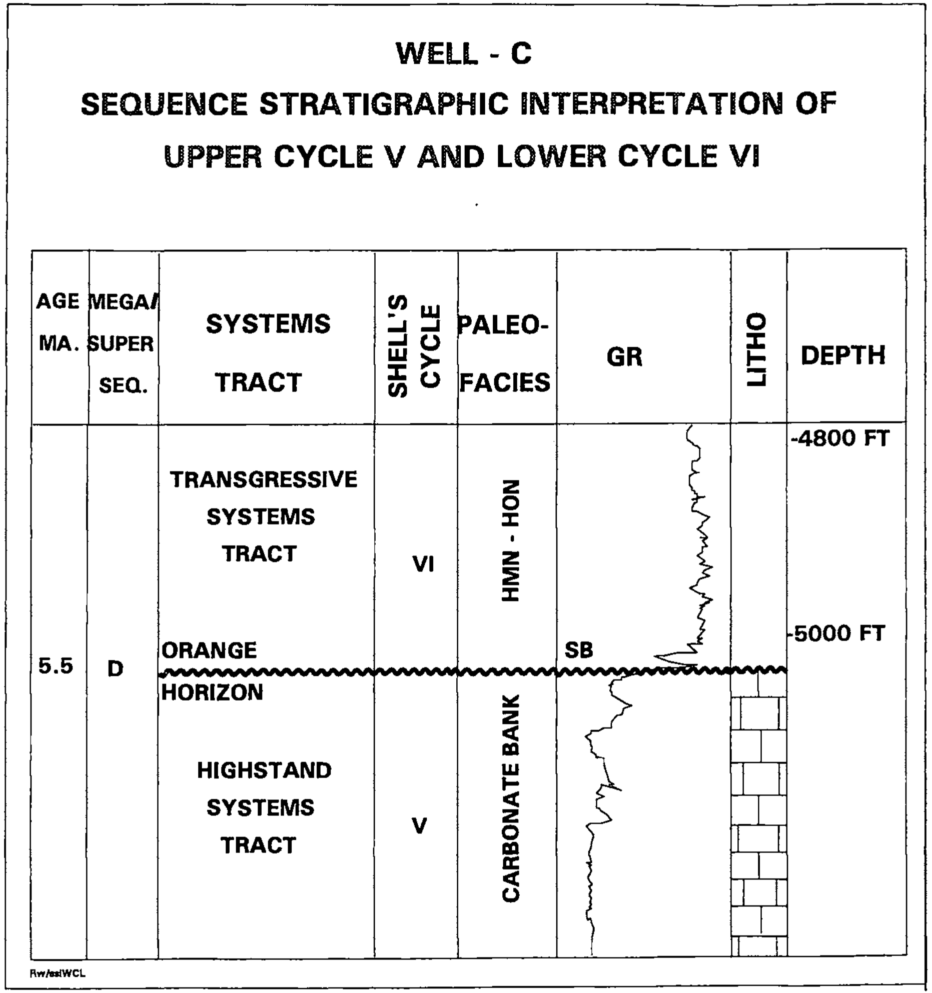

Figure 13. Well-B: sequence stratigraphic interpretation of Upper Cycle V and Lower Cycle VI.

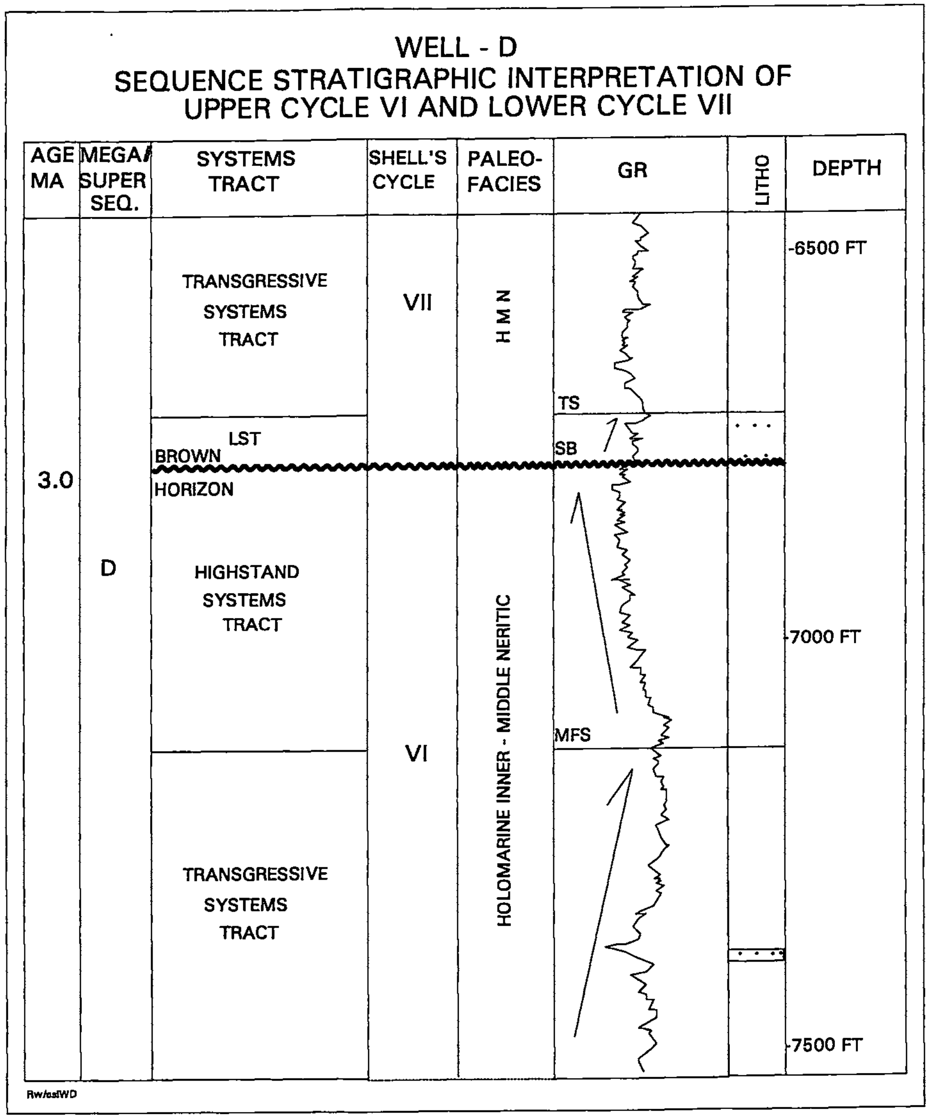

Figure 14. Well-D: sequence stratigraphic interpretation of Upper Cycle VI and Lower Cycle VII.

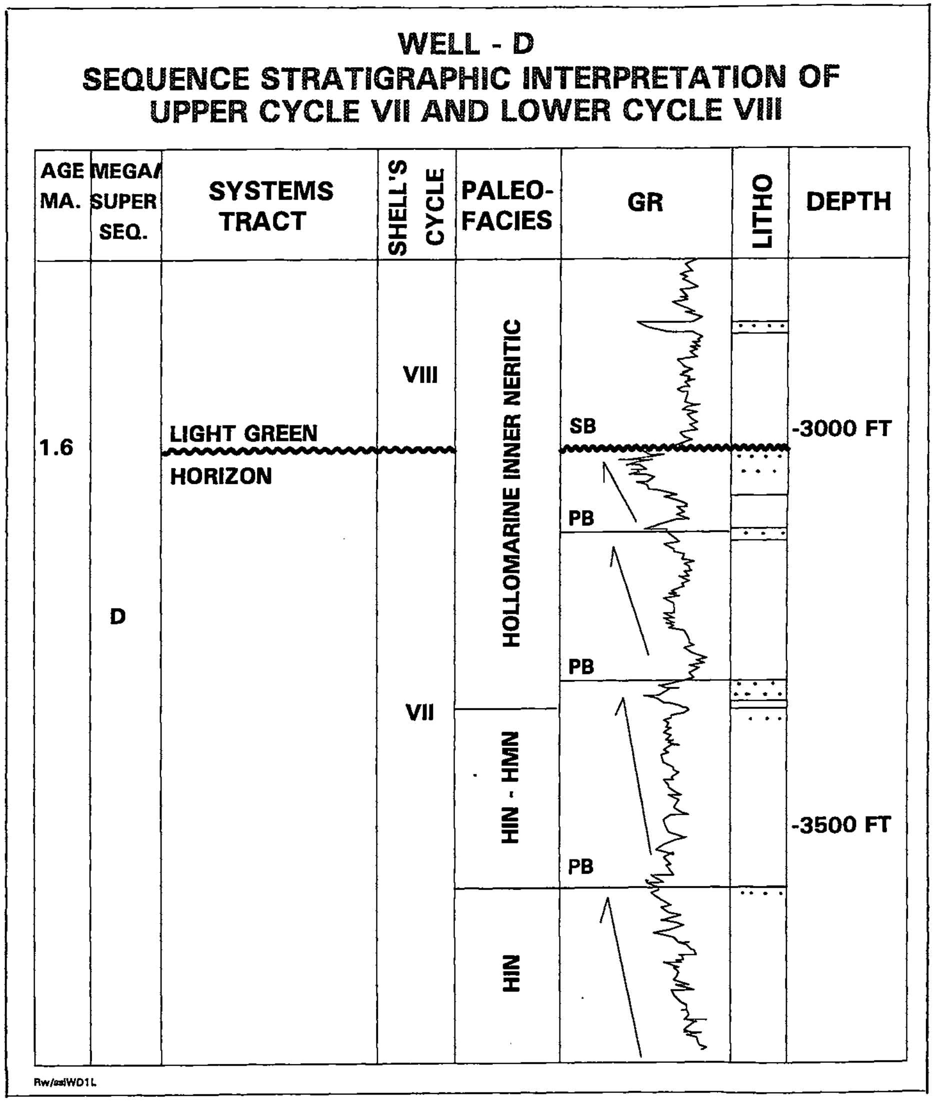

Figure 15. Well-D: sequence stratigraphic interpretation of Upper Cycle VII and Lower cycle VIII.

environment (coastal to lower coastal plain below to shallow marine above). A transgressive systems tract and a highstand systems tract are interpreted to lie immediately above and below the Purple Horizon respectively.

On the well-log, the second-order 17.5 Ma Supersequence Boundary (Dark Green Horizon) is interpreted to separate Cycle II from Cycle III (Fig. 10) and coincides with the end of an overall coarsening upward clastics belonging to the highstand systems tract. Although no change of paleofacies is detected across this boundary the overlying sediments are more argillaceous with intercalations of thin carbonates, which are referred to the transgressive systems tract.

Well-B encountered carbonate sediments during Cycles III–IV (Middle-Upper Miocene). The Cycle III/IV and Cycle IV/V boundaries are interpreted to be maximum flooding surfaces as shown in Figure 11 and Figure 12 respectively. The boundaries demarcate the change from transgressive systems tract to highstand systems tract as suggested by a change from finer grain, deeper marine facies to coarser grain shallow marine facies. The transgressive period signifies a time of build-in phase due to high accommodation space while the highstand period implies a build-out phase due to low accommodation phase (Epting, 1980).

The interface between Cycle V carbonates and Cycle VI clastics encountered by Well-C is shown in Figure 13. The change in lithology and paleofacies indicates a highstand deposition of carbonates followed by a fall in sea-level and erosion at 5.5 Ma. Subsequently, outer shelf shaly sediments were deposited during the ensuing rise in sea-level.

Well-D encountered a thick section of Cycles VI, VII and VIII clastic sediments. The lower part of the well portrays a shaly to silty Upper Cycle VI and Lower Cycle VII. The change in stacking patterns and paleofacies enables the sequence boundary to be recognized (Fig. 14). The underlying highstand systems tract exhibits a coarsening upward pattern whereas the overlying thin, lowstand systems tract reveals a fining upward pattern.

The upper part of Well-D shows a more sandy, shallower marine environment. The boundary between Cycles VII and VIII is suggested by a change from an overall coarsening upward highstand systems tract to thick, shaly sediments of the transgressive systems tract of the next sequence (Fig. 15).

Hence, by interpreting the systems tracts at the four drilled locations, second order supersequence boundaries, third-order simple boundaries and fourth-order maximum flooding surfaces are distinguished. One supersequence boundary falls within Cycle I and another is located at the top of Cycle II. Four third-order simple boundaries differentiated the Cycles I/II, V/VI, VI/VII and VII/VIII boundaries and two maximum flooding surfaces define the Cycles III/IV and IV/V boundaries.

SEISMIC FACIES ANALYSIS

Based on the seismic facies analysis (Mitchum *et al.*, 1977) carried out in the study area incorporating well control in the shelf area, the paleoenvironments were interpreted for Supersequence C and D. As no well has been drilled in the deeper waters, the predicted facies distribution is based mainly on the observation and interpretation of seismic data.

Four main seismic facies are interpreted in the study area (Fig. 16). Facies I includes subparallel to wedging, discontinuous to continuous, irregular to wavy reflections representing upper to lower coastal plain sediments. Fluvial fans and lacustrine shales are confined to this facies. Facies II comprises parallel to subparallel to wedging, continuous high amplitude reflections. They are interpreted as mainly coastal to inner neritic sediments comprising sand/shale interbeds. Facies III contains transitional parallel events overlying transparent to chaotic data and some mounded facies indicating shale-prone marine facies with some carbonates. Facies IV encompasses transparent to chaotic reflectors mimicking outer shelf to bathyal shales with some slightly mounded facies suggesting deposition of some turbidite fans.

Based on this analysis, seismic facies maps were generated for various zones within Supersequences C and D. Figure 17 displays the seismic map for the lower part of Supersequence C (between Purple and Blue Horizons) illustrating the deposition environments from non-marine in the southwest (Facies I) to marine in the northeast (Facies III). The variation of the various seismic facies is exhibited by Line 3 and Line 4 which portrays Facies I and Facies II respectively (Fig. 18).

A seismic facies map constructed for the Upper Supersequence C (between Dark Green and Purple Horizons) shows that the paleoshoreline continues to trend in a NW-SE direction (Fig. 19). This map also indicates a backstepping in the paleoenvironments as compared with the Figure 17 and implies an overall rise in sea-level within Supersequence C, which agrees with the Haq's curve (Fig. 5). Line 5 and Line 6 depict Facies II and Facies III/IV respectively (Fig. 20) of the Upper Supersequence C.

Another seismic facies map was produced for

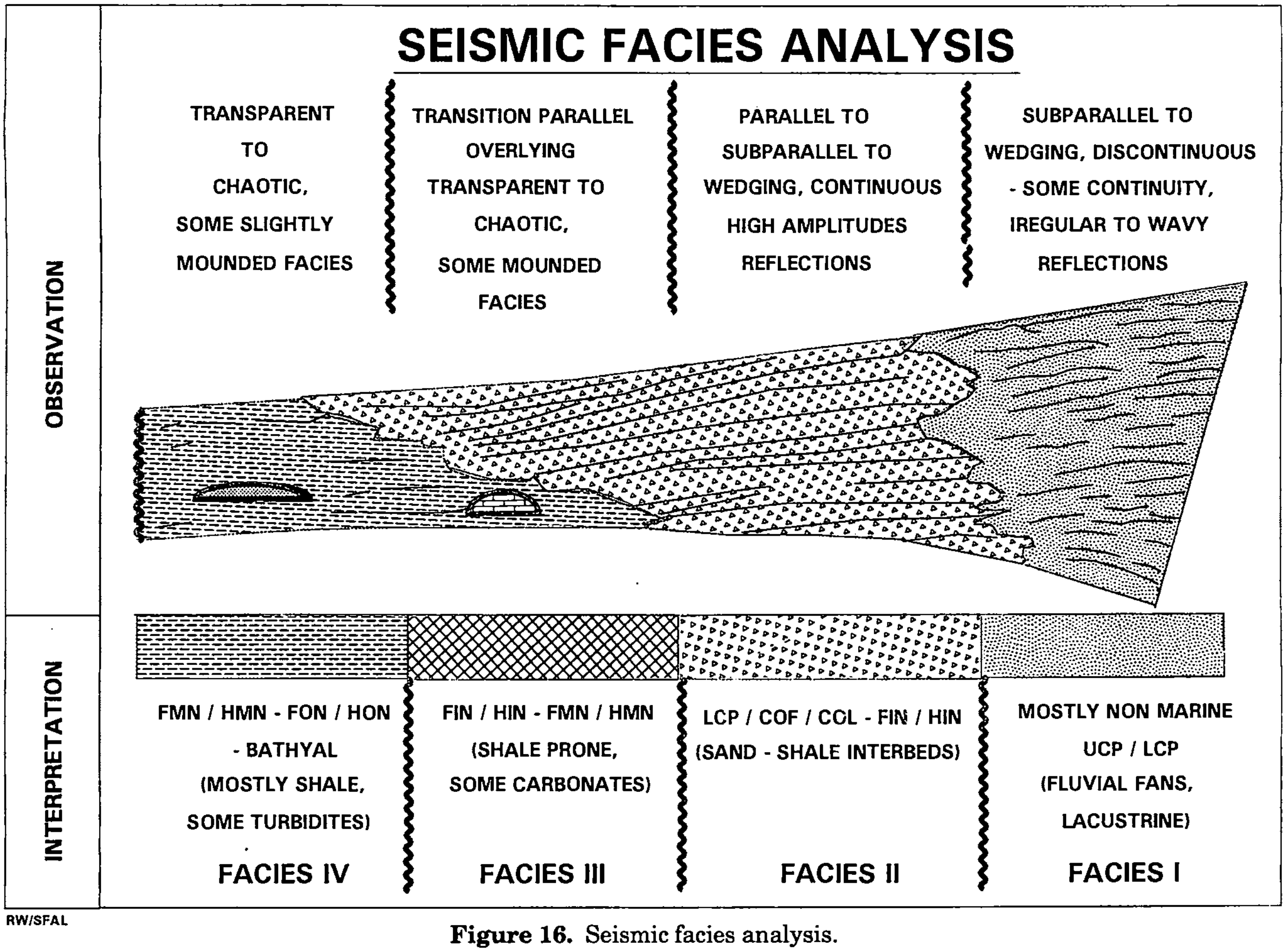

Figure 16. Seismic facies analysis.

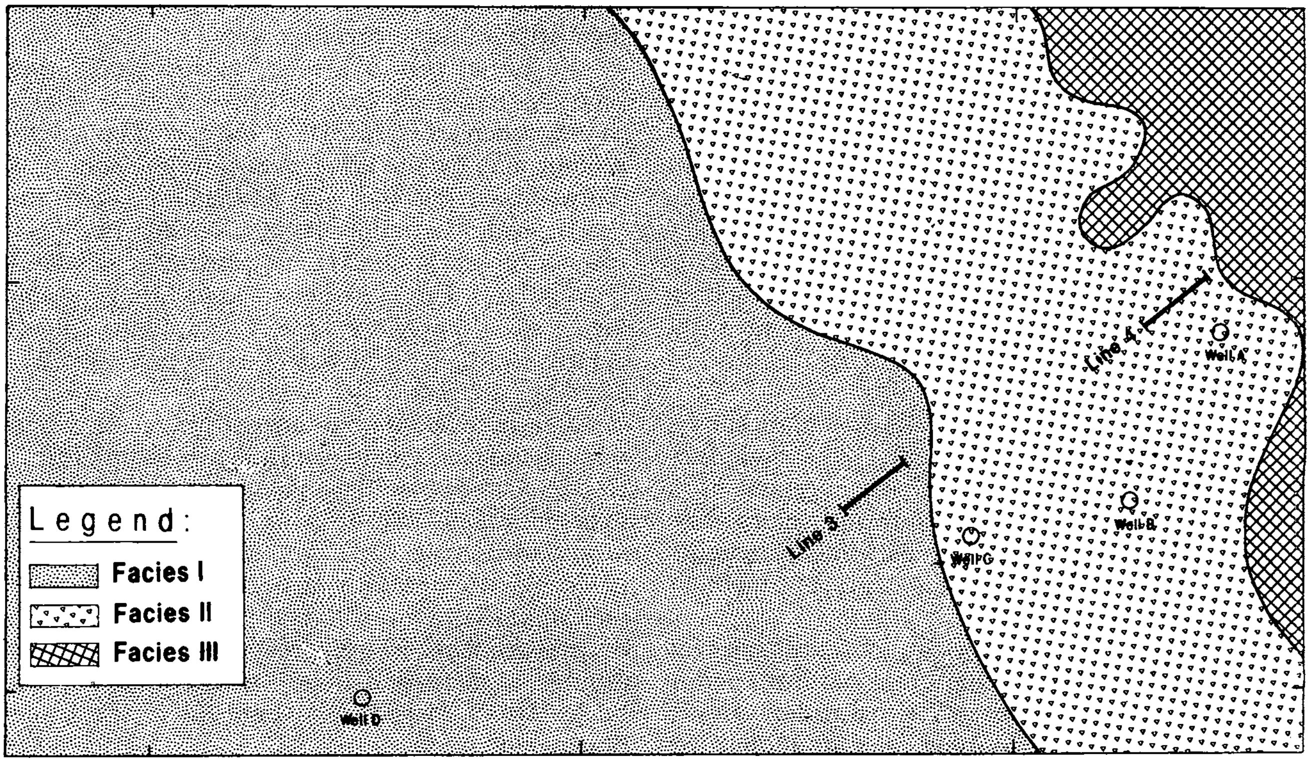

Figure 17. Seismic facies map, lower mega/supersequence C (between purple and blue).

the Supersequence D. A major uplift at about 17.5 Ma (Dark Green horizon) shifted the paleoshoreline to a position running roughly parallel to the present day coastline (Fig. 21). Within the study area, only Facies III and IV are recognised, representing outer shelf to bathyal environments. The seismic facies map also shows locations of ponded turbidites and turbiditic fans located within Facies IV. Ponded turbidites are interpreted as high amplitude events encased by low amplitude data located within a depressed areas (Fig. 22).

POTENTIAL PLAY-TYPES

Once the seismic facies of the two important supersequences are mapped and the chronostratigraphic boundaries correlated, the study can then assist in identifying potential play-types. Structural traps as well as stratigraphic traps containing the various seismic facies can be mapped, and their seal, reservoir and source rock characteristics assessed.

Figure 23 displays a structural trap of Upper Supersequence C containing reservoir rock of Seismics Facies II sealed by Seismics Facies IV of Supersequence D. Source rocks are believed to be derived from underlying Seismics Facies I/II of Lower Supersequence C. Two stratigraphic traps of interpreted basin floor fans within Seismics Facies IV of Supersequence D are demonstrated in Figure 24. Overlying deepwater shales provide the seal. Source rocks for this play are thought to be derived from deeper Seismics Facies I/II of Upper Supersequence C.

CONCLUSIONS

Four second-order mega/supersequences have been identified and correlated with the regional tectonic events of the South China Sea. Within the second order supersequences, third-order sequences are also recognised and they are related to the local

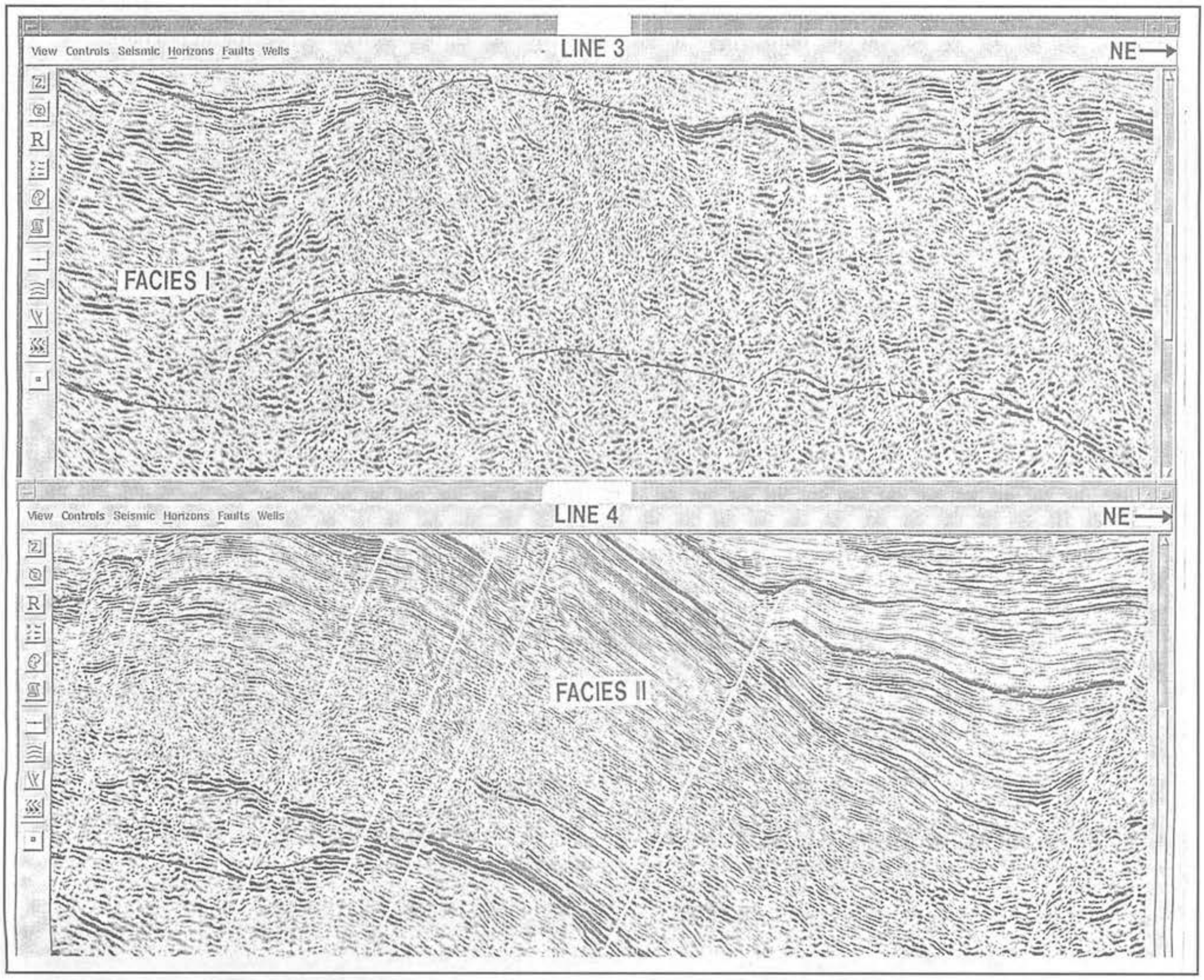

Figure 18. Line 3 (Facies I) and Line 4 (Facies II).

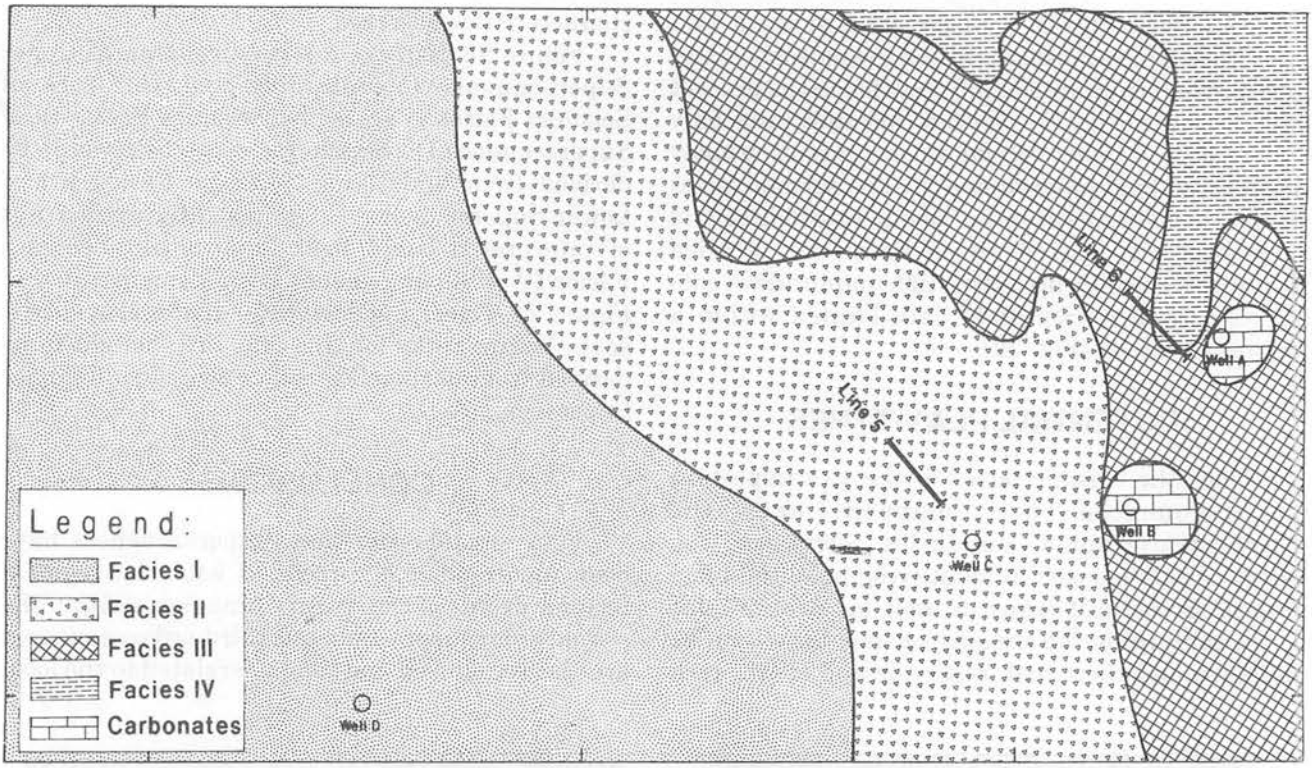

Figure 19. Seismic facies map, upper mega/supersequence C (between dark green and purple).

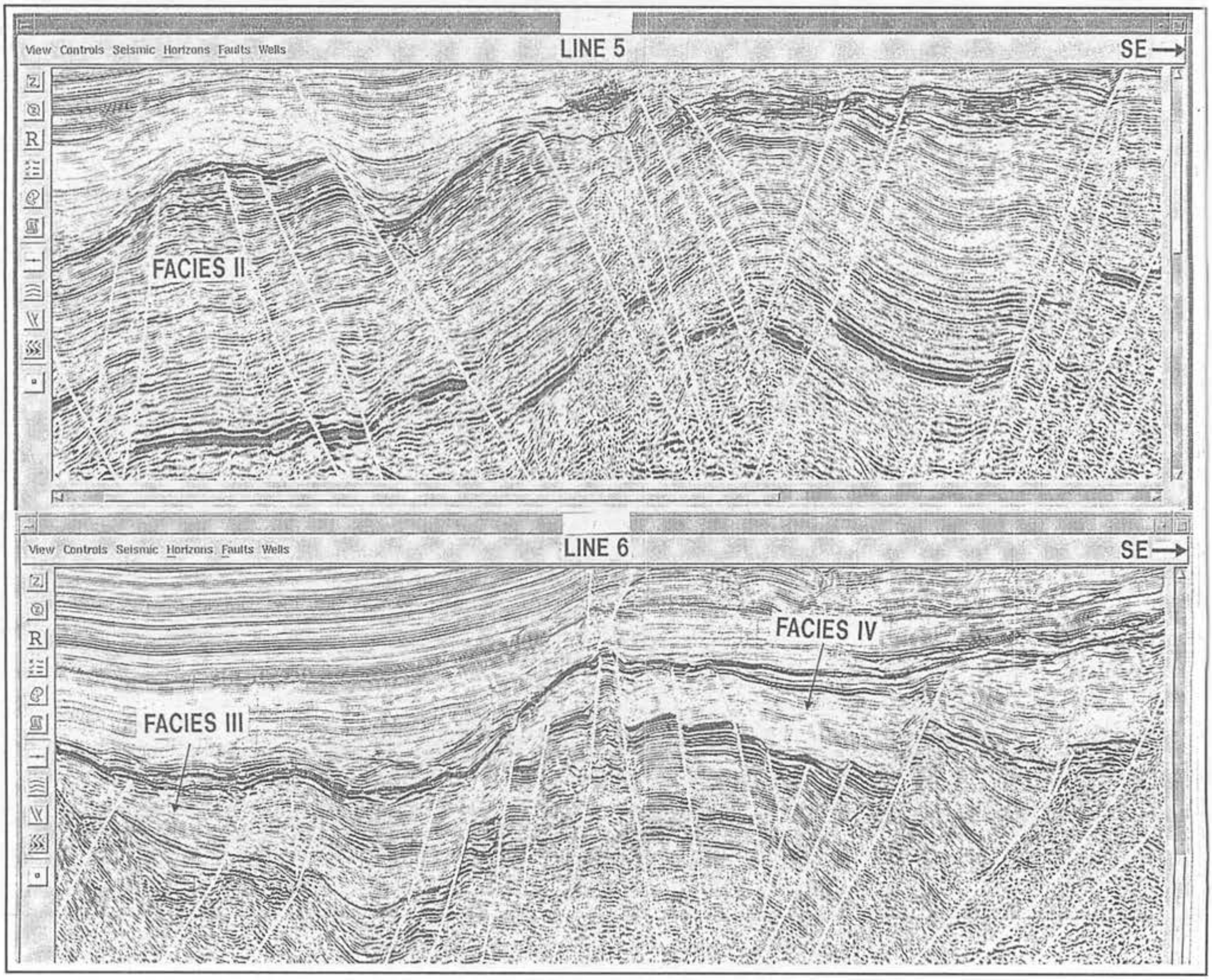

Figure 20. Line 5 (Facies II) and Line 6 (Facies III/IV).

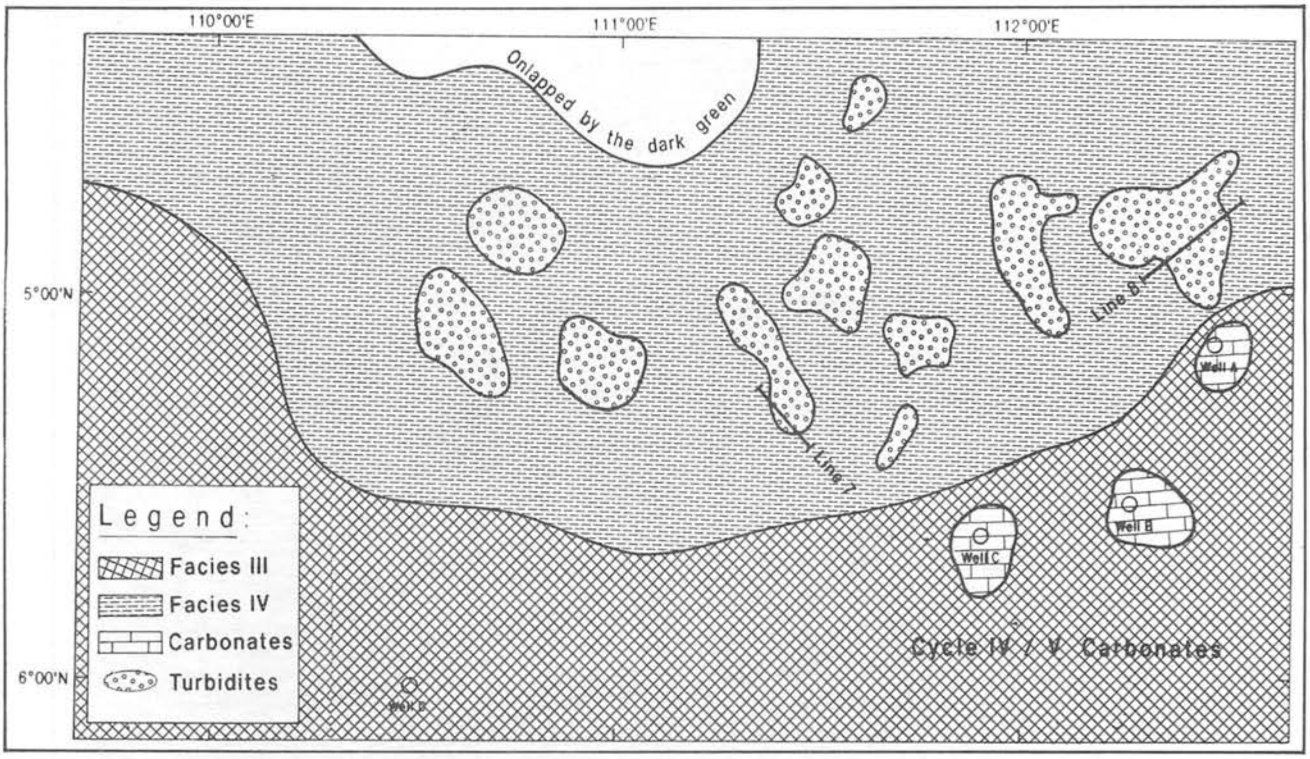

Figure 21. Seismic facies map, mega/super sequence D (post dark green).

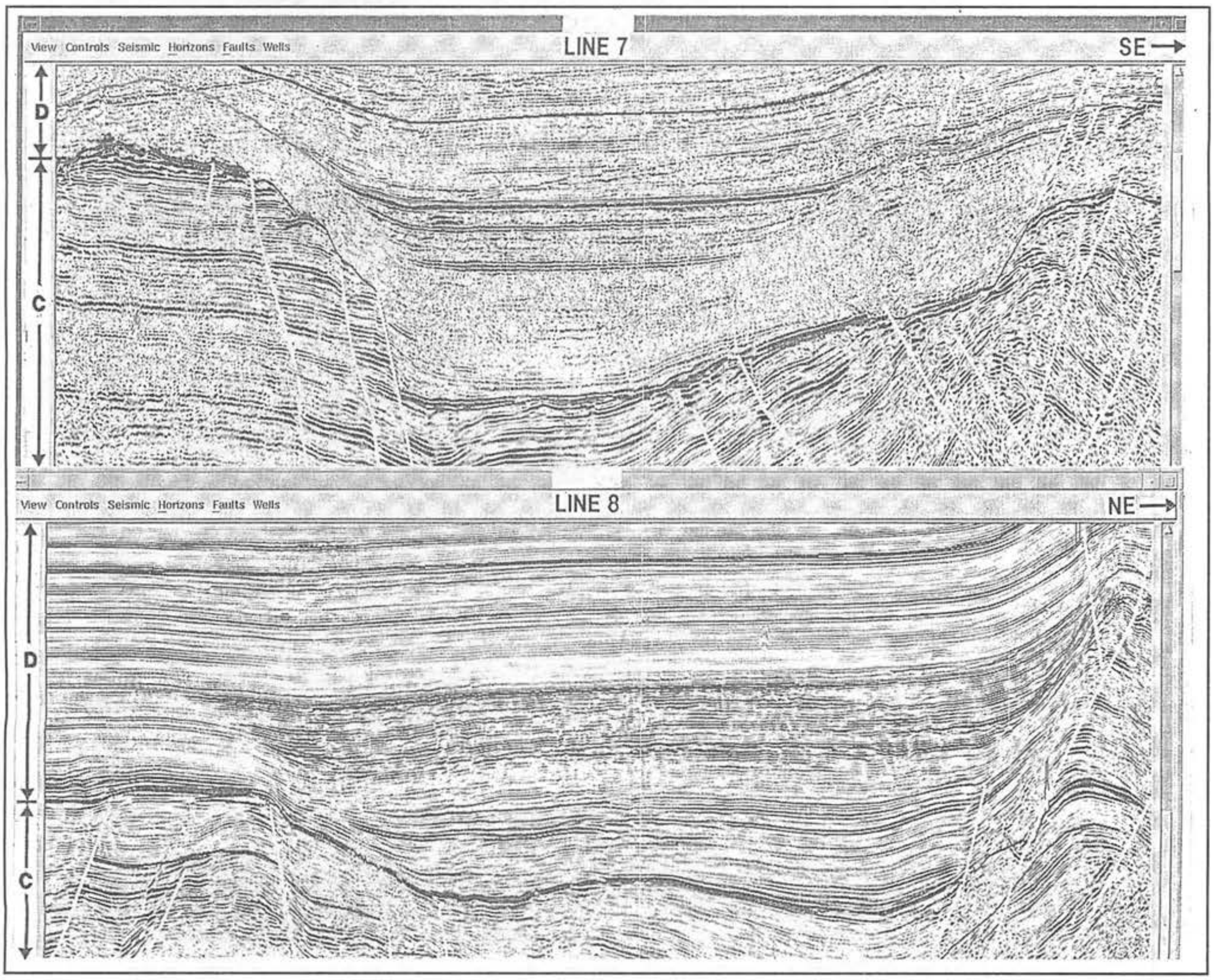

Figure 22. Line 7 and Line 8 showing ponded turbidites.

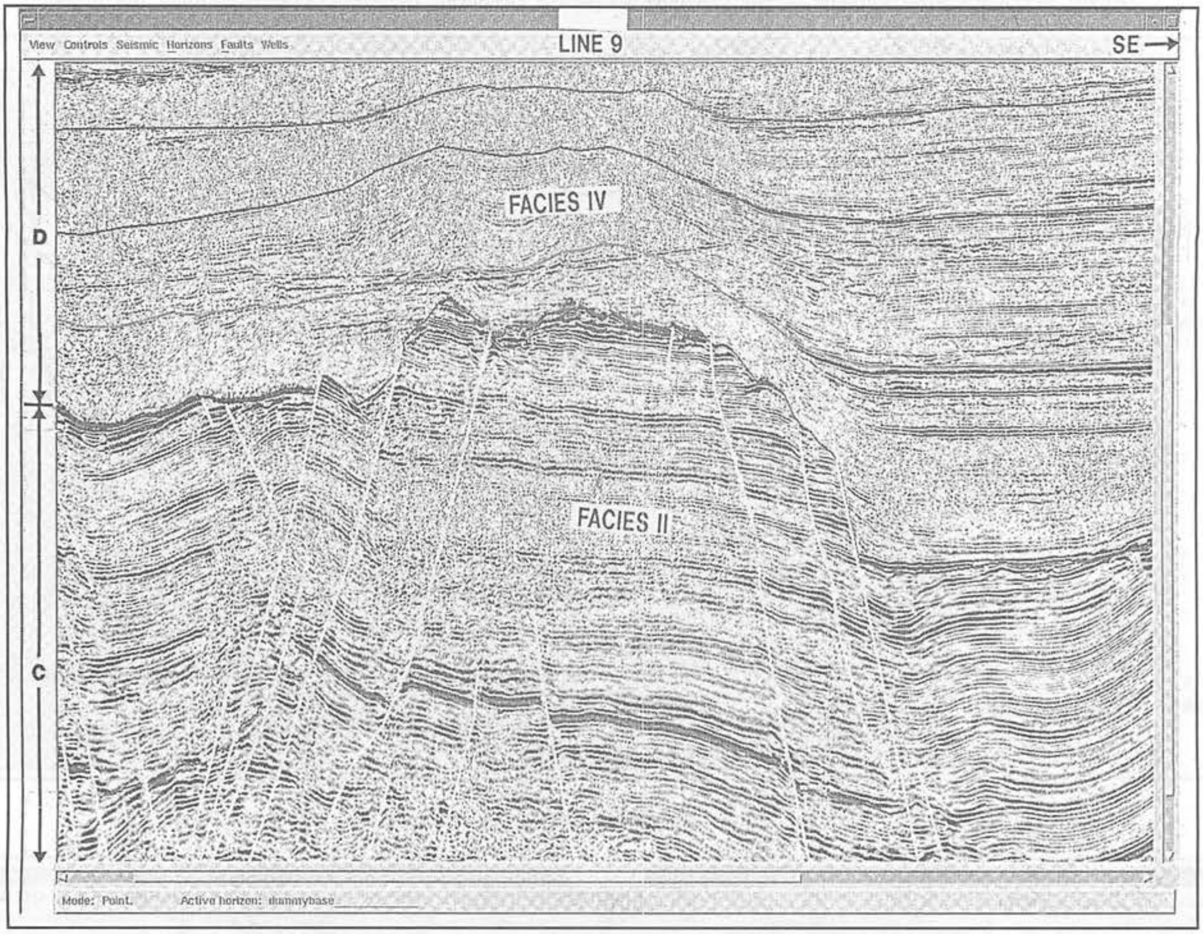

Figure 23. Structural play in supersequence C.

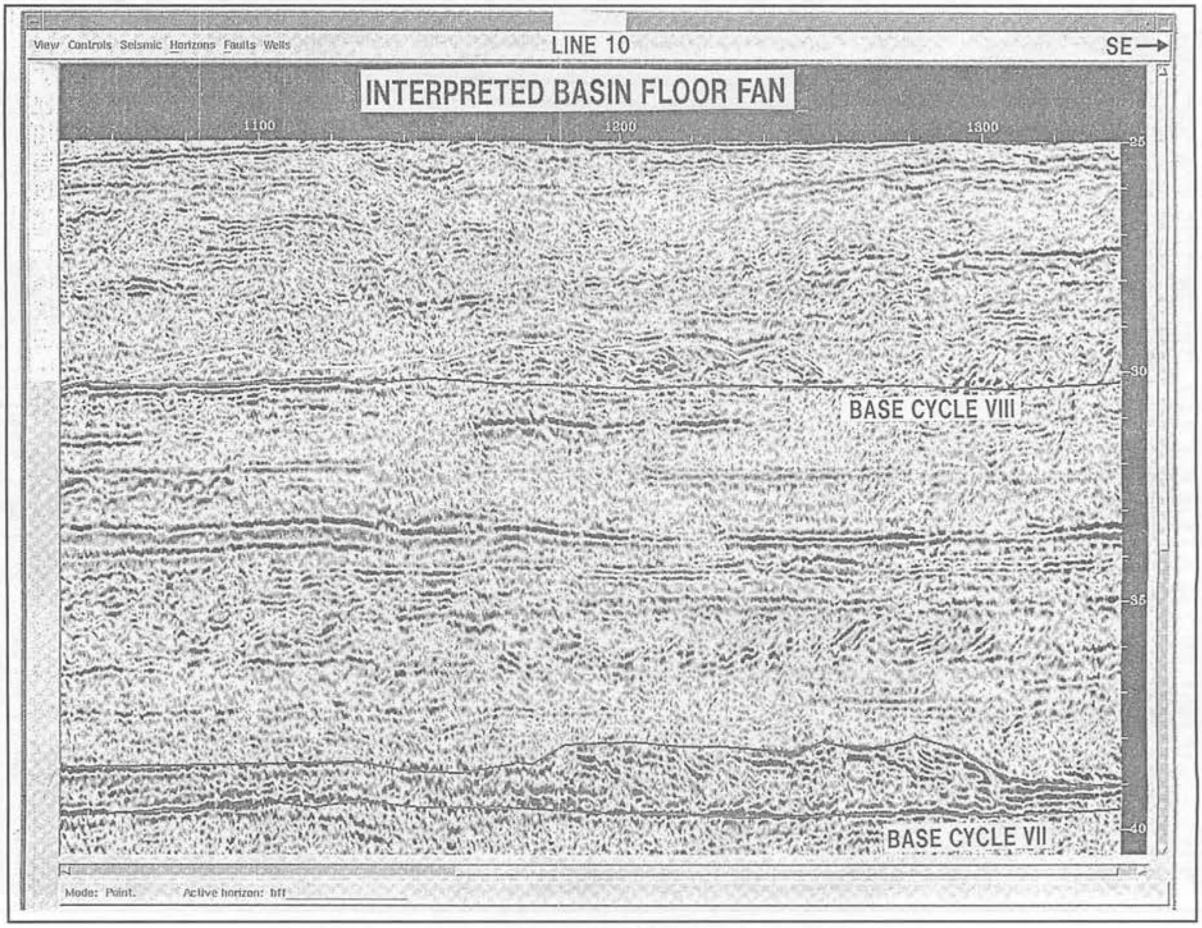

Figure 24. Interpreted basin floor fan.

structural history. Fourth-order sequences linked to the sea-level fluctuations are also distinguished within the third-order sequences.

A workable chronostratigraphic chart has been developed where the second to fourth-order sequences can be correlated. The chart is able to correlate the episodic rifting of the South China Sea (Ru and Pigott., 1986), local structural history and Shell's sedimentary Cycles I–VIII (Ho, 1978) to the global sea-level chart (Haq *et al.*, 1988).

Four seismic facies (Facies I, II, III and IV) have been identified in the study area. The interpreted facies range from non-marine to deep marine facies. Seismic maps generated for the supersequence C indicates its overall transgressive deposition which agrees with the global sea-level curve of Hag *et al.* (1988).

Potential play-types within Supersequence C and D are also derived from this study. The main play type in Supersequence C is a structural trap of Seismic Facies I/II, whereas stratigraphic traps of basin floor fans are found mainly in Supersequence D.

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