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3D Seismic Interpretation and Development of Sequence Stratigraphic Model of a Carbonate Buildup in Central Luconia, Offshore Sarawak

By

Mohamad Faizal Bin Idris

A THESIS
SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME
AS A REQUIREMENT FOR THE
DEGREE OF MSc. in PETROLEUM GEOSCIENCE

JANUARY, 2008

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CERTIFICATION OF APPROVAL

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Date : 2nd January 2008

Signature :

Supervisor : Mohd Razali Che Kob

Date : 2nd January 2008

CERTIFICATION OF ORIGINALITY

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or currently submitted for any other degree at UTP or other institutions.

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ABSTRACT

The calibrated 3D seismic data were studied to characterize the carbonate facies in a carbonate buildup located in southeast Central Luconia Province. The sequence stratigraphy and seismic attributes analyses were carried on the carbonate bearing intervals to characterize the facies, understand the evolution and map-out their distribution. The carbonate bearing intervals, which is defined by Top Carbonate and Base Carbonate horizons were accumulated in Early Miocene to Middle Miocene time in two major sequences. These sequences were developed in response to the changes of relative sea level, with well defined associated system tracts. The stacking pattern of the system tracts and stratigraphic unit reveal the growth architecture and the evolution of the buildup. Three main factors have been identified in controlling the growth, evolution and architecture of the buildup; which are tectonics (faulting and subsidence), relative sea level and also paleowind direction in addition to the rate of carbonate production. Using seismic facies approach, the mounded reefal and progradational facies are potentially associated with good reservoir properties. They are extensive in peripheral area of the buildups, whereas the tight lagoonal facies is commonly found in the central of the buildup. The porosity and permeability enhancement through secondary processes such as karstification and late leaching has been identified as one of the main contribution to the reservoir formation. These facies is distributed in association with the formation of the sequence boundaries during lowstand sea levels. The findings from the study could contribute in lowering the future exploration and development risks and also to maximize the returns.

ACKNOWLEDGEMENT

Thanks to the Petronas Research (PRSB) for permission of using the data for this project. Special thanks to supervisor, Mohd Razali Che Kob, also thanks to lecturers from University Teknologi Petronas (UTP) and Institute Francais du Petrole (IFP) for providing excellent review on this paper. To all Msc. Petroleum Geoscience colleagues, thank you for the support.

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1.0 CHAPTER ONE: INTRODUCTION

1.1 Overview

The Central Luconia Province is one of the structural provinces located in the offshore Sarawak. It lies at the present water depth of 250 ft and is characterised by extensive development of Late Miocene carbonates. This province is a prolific gas producer from carbonate reservoirs in Sarawak and has been actively explored since 1970's. It is separated from Baram Delta and Tatau Province by the West Baram Line and West Balingian Line respectively. The northern extent of the province is bordered by North Luconia Province and to the south by Balingian Province.

The study area (Figure 1.1) located at the south-eastern part of the Central Luconia Province and one of the carbonate gas fields in Sarawak.

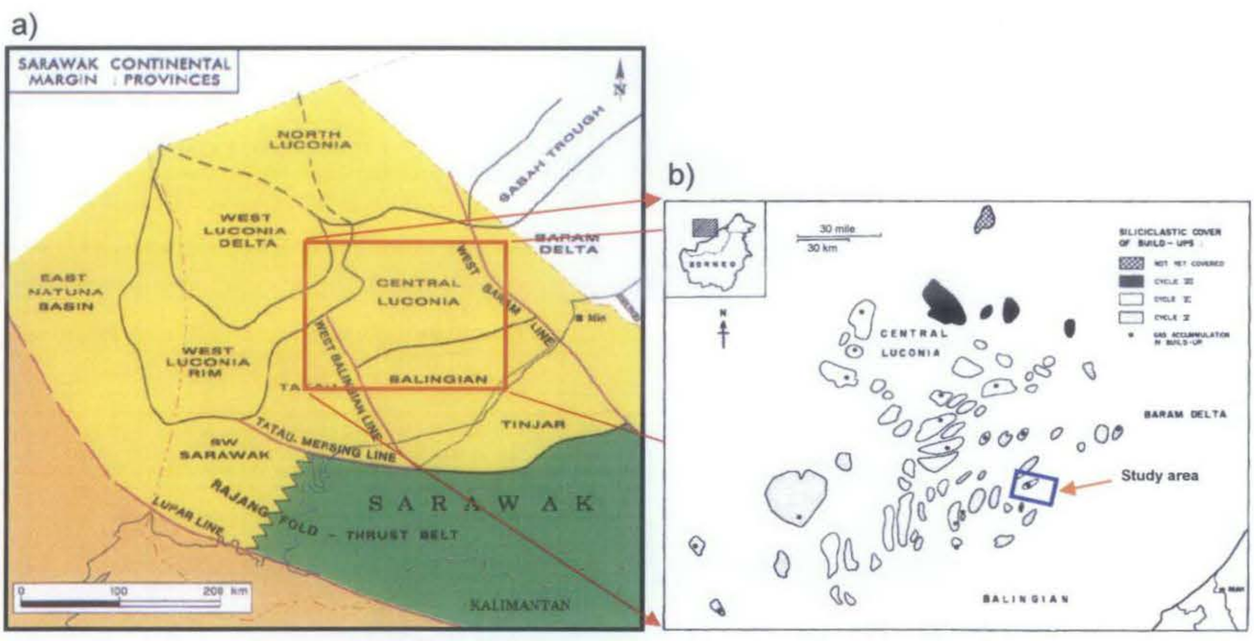


Figure 1.1 (a). Structural provinces of Sarawak Basin (modified after Mazlan, 1999a). (b) Distribution of the carbonate platforms in Central Luconia (modified after Epting, 1980).

1.2 Problem Statement

The application of sequence stratigraphic concept in characterizing carbonate facies in Central Luconia Province has been under utilized. Hence, their potential contribution to the understanding of the carbonate reservoirs in the area has not been used. Through the understanding of the stratigraphy and the development of buildups, prediction of reservoirs distribution can be made through understanding of systems tract and their related facies.

1.3 Objective

The project objectives are to:-

1. Understand the carbonate buildups development and their evolution.
2. Describe and illustrate various facies type within buildups using sequence stratigraphy.
3. Obtain the reservoir facies distribution and better facies prediction.

The main work scopes for this project are 3D seismic interpretation, seismic attributes analysis and seismic sequence stratigraphy.

1.4 Scope of work / Methodology

The study will include:

1. Well log correlation
2. Seismic to well tie
3. 3D seismic interpretation
4. Seismic attributes analysis
5. Generation of geo-seismic sections
6. Seismic facies and stratigraphy
7. Sequence stratigraphic interpretation

2.0 CHAPTER TWO: REGIONAL GEOLOGY

2.1 Geological Setting

The Central Luconia Province is a part of the Luconia Block that has been interpreted to be drifted from the South China during Oligocene South China Sea spreading. The Luconia Block is therefore a continental terrain, thought to underlie the Central Sarawak shelf. The collision of this terrain with the West Borneo Basement caused the uplift and deformation of the subduction accretionary prism to form the Rajang Fold Thrust Belt. This event also caused the closure of the Proto South China Sea (PSCS) in oblique direction from west to the east (Mazlan, 1999a).

Sea floor spreading in the South China Sea Basin during the Oligocene to Middle Eocene affected the continental crust, caused the deepening and opening of the basin towards southwest and the marine influx allowed the carbonate growth during Miocene time (M. Yamin & Abolins, 1999). Carbonate deposition in Luconia Province started in Early Miocene, but was most prolific during the Middle-Late Miocene (Epting, 1980). Contemporaneous crustal extension in this province resulted in the development of a horst-graben pattern, which controls the size and distribution of these carbonate build-ups (M. Yamin & Abolins, 1999). Two types of carbonate build-ups are common in this area; the platform and pinnacle types.

Structurally, the Central Luconia province located in between an extensional area in the north and a compressional realm in south. Epting (1980) suggested that the province evolved through two phases of faulting; Oligocene-Early Miocene and Early-Middle Miocene (when Balingian province in compressional phase). The growth of the carbonates was interrupted by a major marine transgression that had resulted in deposition of the overlying shale sequences.

2.2 Stratigraphy and Sedimentation History

M. Yamin and Abolins (1999) had summarized the regional sedimentation history of the Central Luconia Province. Several episodes of sedimentation were recorded. The deposition of deepwater argillaceous and shallow marine silisiclastic occurred during early synrift phase of Cycle I times (Late Oligocene). This event was followed by a late phase of synrift sedimentation during Cycle II and III (Early Miocene-Early Middle Miocene) consistent with the opening of the South China Sea.

Carbonate deposition started in Cycle III (Figure 2.1 & 2.2) and widespread during Cycle IV and V times (Early Miocene - Late Miocene); controlled mainly by continuous subsidence and formation of half graben. These carbonates deposition were terminated by the clastic influx from uplifted Rajang Fold-Thrust Belt from Cycle V times onward.

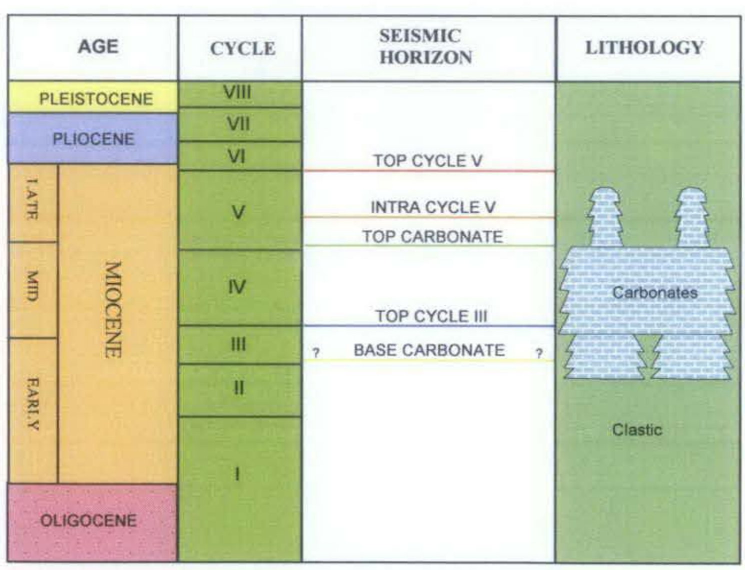


Figure 2.1. Stratigraphic scheme of the study area.

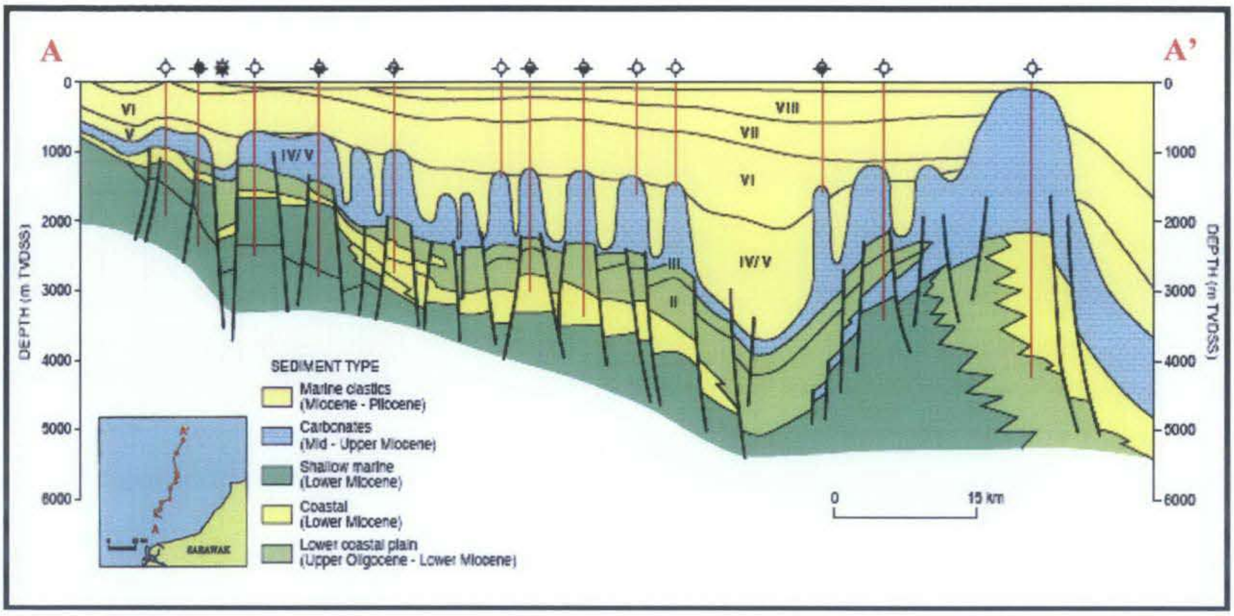


Figure 2.2. Schematic cross section across Central Luconia Province. Map shows location of profile. Modified after Mazlan (1999b).

2.3 Dataset

The 3D seismic reflection dataset for this study had been acquired in 1997, and was processed in 1998. The survey has a total areal extent of 393 km² with inline/crossline spacing of 12.5m (Figure 2.3). This data was recorded with four second record length, where the main carbonate section located at approximately two second two way time (TWT).

This dataset fully covered 'W' structure (central area) and partially covered another 'X' structure to the south. Data quality ranging from fair to good with the central part of dataset remain poorly imaged due to wipe out zone with poor seismic quality – (Figure 2.4). This central wipe out zone is caused by strong signal absorption by a very shallow event, probably a recent reef and also effects from shallow gas clastic reservoir above the main carbonate section. The pull-up effects can be detected below the recent reef (at sea bottom) and below the main carbonate section. There is also a pull down effect from the gas clastic reservoir.

The study area has been penetrated by seven wells; six wells on structure 'W' and one well in the vicinity of 'X' structure to the south. The locations of W-1 and W-3 wells were displayed in single location as these wells only located 100 ft apart. The first well (W-1) was drilled in 1970. For fluid sampling and production test, the W-3 well was drilled in the same structure in late 1974. Due to data availability, only five wells were used for this project which is W-1, W-2, W-3, W-4 and W-5 well. The Seismic 3D data and wells were loaded in Landmark's Openwork workstation for seismic interactive interpretation.

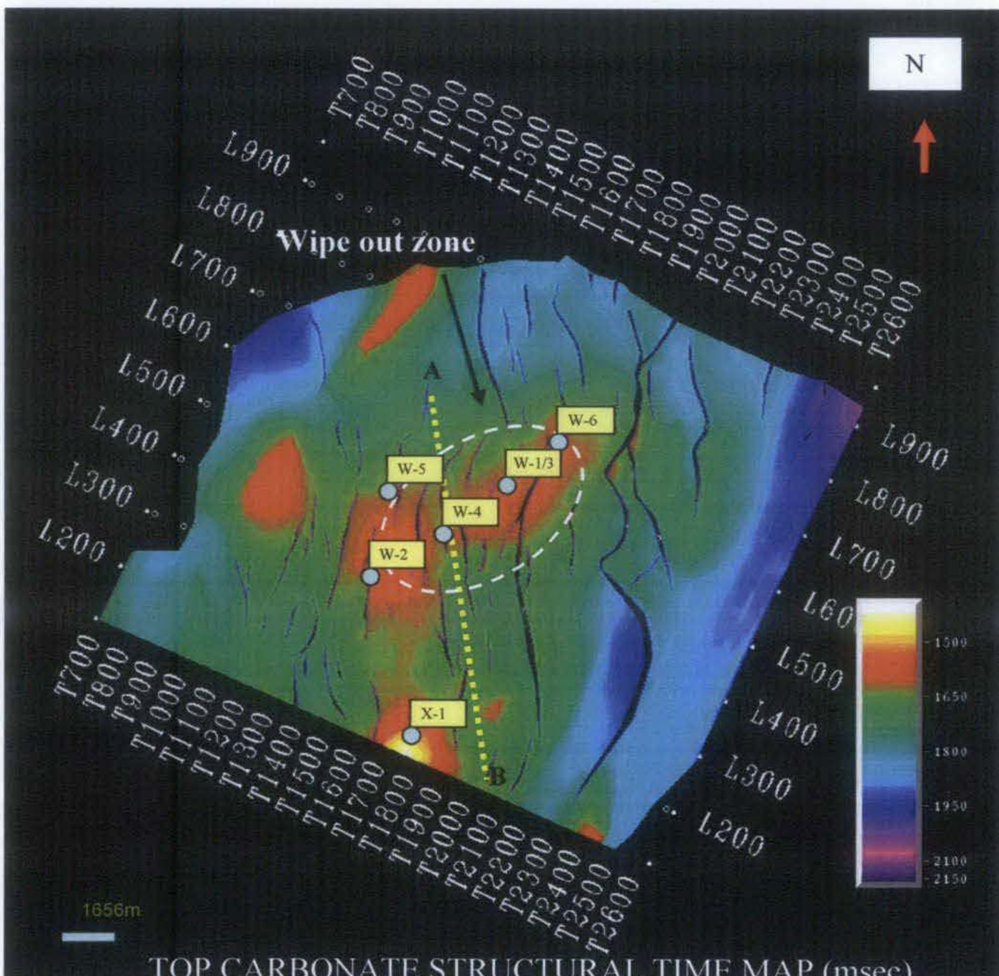


Figure 2.3. Well location, 3D seismic data and wipe out zone outline.

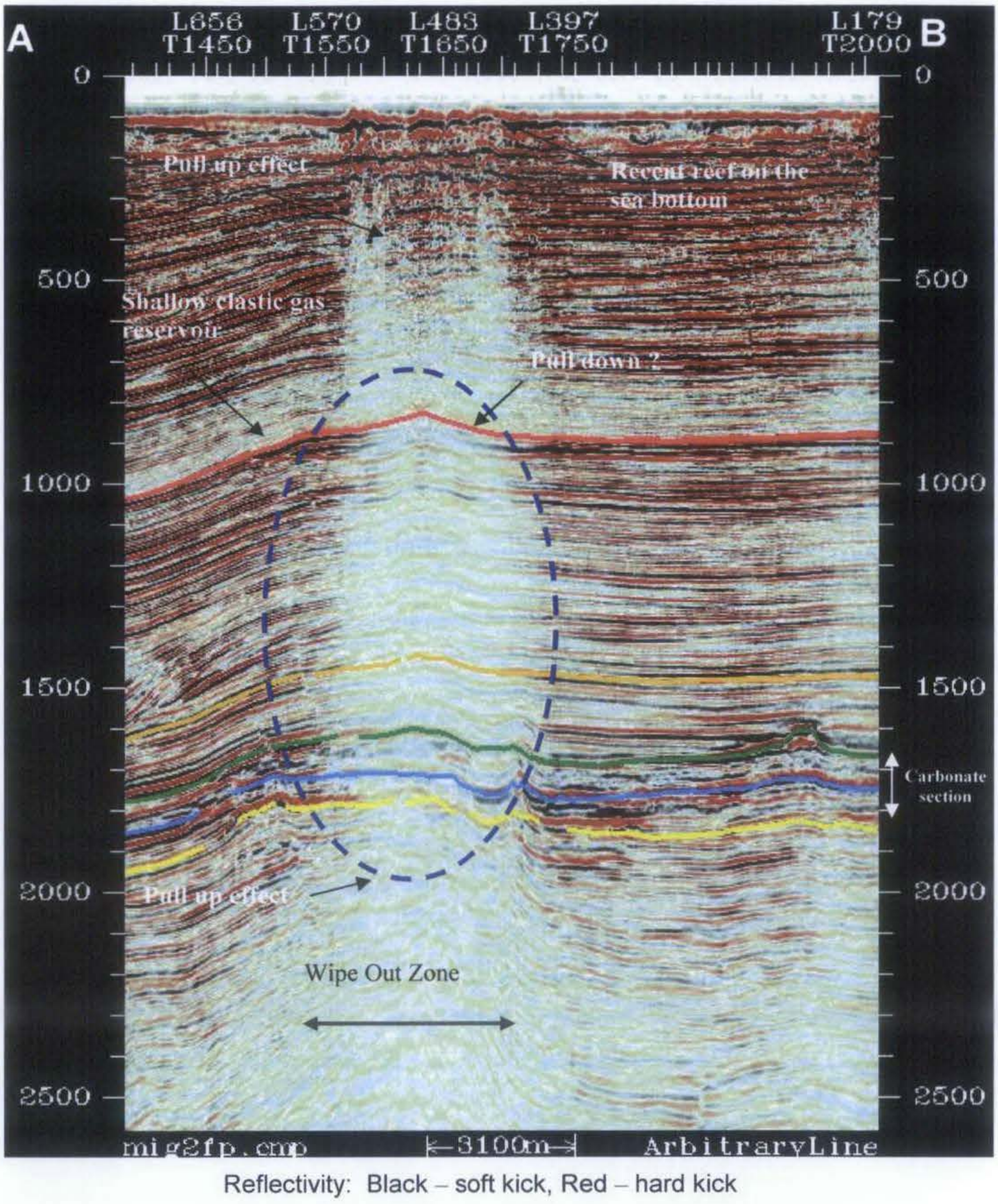


Figure 2.4. Arbitrary seismic section along NW (A) –SE (B) with interpreted horizons. Note: The central part of dataset is characterized by poor data quality – wipe out zone; this image is captured from 0-2.5 second. Data quality is deteriorating with depth.

2.4 Well Summary

Analysis on wells W-1, W-2, W-3, W-4 and W-5 indicate that the carbonate sections in this study area consist of Cycle III, IV and V carbonates. Result from W-2 well (Figure 2.5) indicates the occurrence of Cycle III shallow water carbonate facies which is defined by interval between Top Cycle III and Base Carbonate markers. This well was selected as a key well for this study, other wells only penetrates the Cycle IV and V carbonates. The results from W-4 well also indicate the presence of deeper marine carbonate facies.

The Cycle IV and V carbonates are more widespread as compared to Cycle III carbonate. The thick Cycle IV carbonates could be associated to the period of prolific carbonate growth during Middle Miocene times as a consequence of rising relative sea level. This thick sequence is covered by thin Cycle V carbonate layer which indicates the transition period of carbonate growth before extensive clastic deposition took place during Late Miocene times. The Cycle V sequence is mostly dominated by clastic sediments, showing progradational and shallowing upward with environment of deposition ranges from the holomarine neritic to coastal.

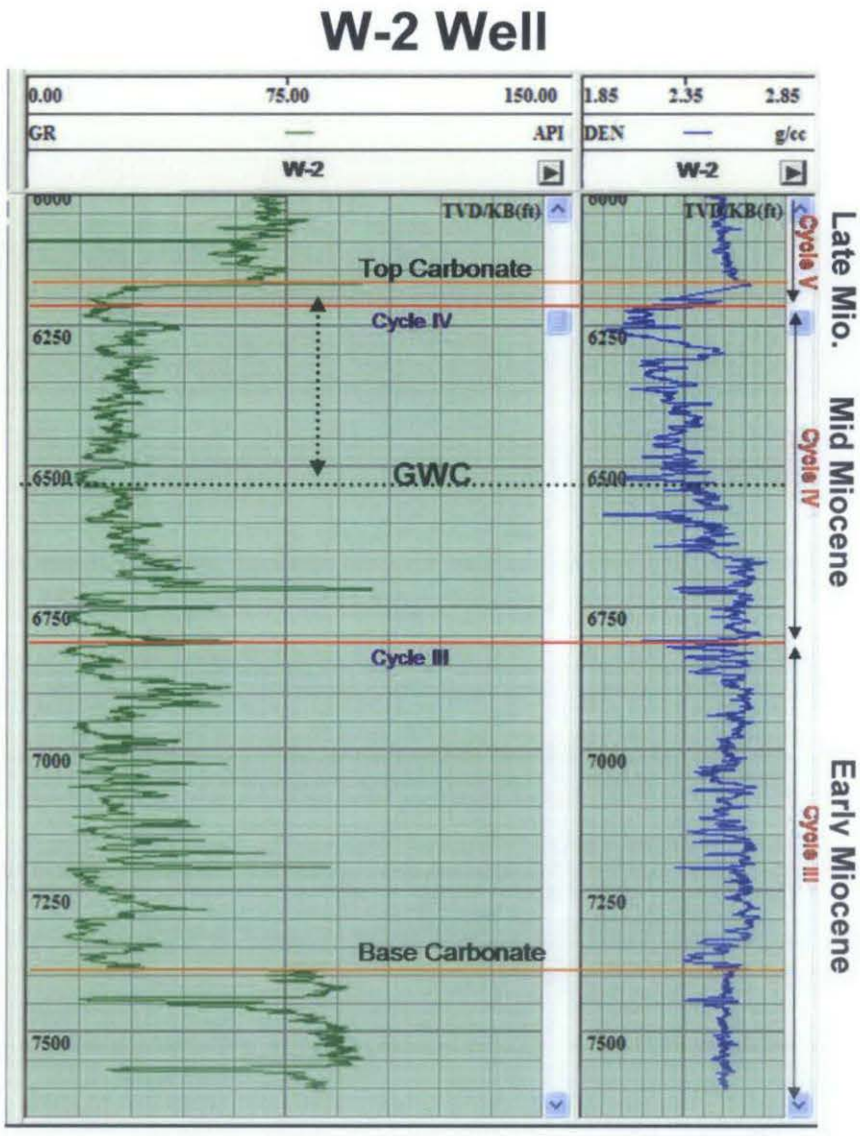


Figure 2.5. Well log of W-2 well. Thick Cycle IV carbonate is covered by thin Cycle V carbonate sequence. Note : Gamma Ray – green curve, Density – blue curve, GWC (Gas Water Contact).

3.0 CHAPTER THREE: 3D SEISMIC INTERPRETATION

3.1 Seismic to Well Tie

Due to limitation of well data and variation in seismic data quality, only five wells were used for generation of synthetic seismogram. The wells are W-1, W-2, W-3 W-4 and W-5. The synthetic seismograms were constructed using Landmark's Syntool software (Figure 3.2 and Appendix 1-4).

Density, checkshot and sonic velocity data from well were used in calculation and calibration with the seismic dataset. Synthetic curve was generated using extracted wavelet, with 30Hz dominant frequency, zero phase and normal SEG polarity convention (reversed to Petronas polarity standard). The seismic reflectivity is displayed in variable density colour using red (negative number-trough) indicating hard kicks (e.g sea bottom reflector) whereas black colour (positive number-peak) indicating a soft kicks.

Result from seismic to well tie analysis shows a poor correlation between synthetic and seismic data in wipe out zone. Comparatively, wells (W-2 and W-5) which were drilled outside of this zone shows a good match (Figure 3.1).

The horizons for seismic interpretation were selected according to available markers from W-2 well (Figure 3.2) and were picked accordingly; peak (Top Cycle V – Clastic gas reservoir), trough (Top Carbonate), peak-zero crossing (Top Cycle III) and peak (Base Carbonate). The Intra Cycle V horizon was picked directly from seismic data, displayed by trough, strong and good reflector continuity.

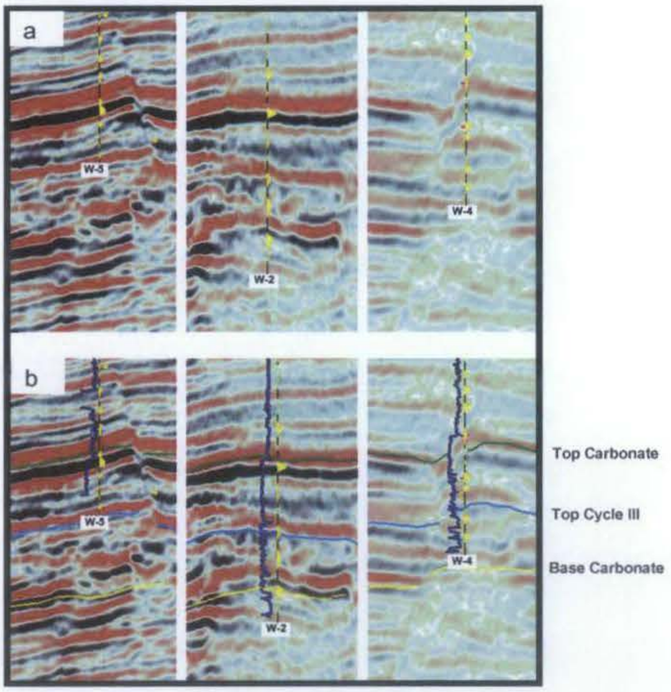


Figure 3.1 (a) Uninterpreted seismic sections. (b) Interpreted seismic sections at W-2, W-4 and W-5 wells with Gamma Ray (blue) and synthetic curve (yellow). The Top Carbonate was picked at red trough, Top Cycle III at zero crossing and Base Carbonate at black peak.

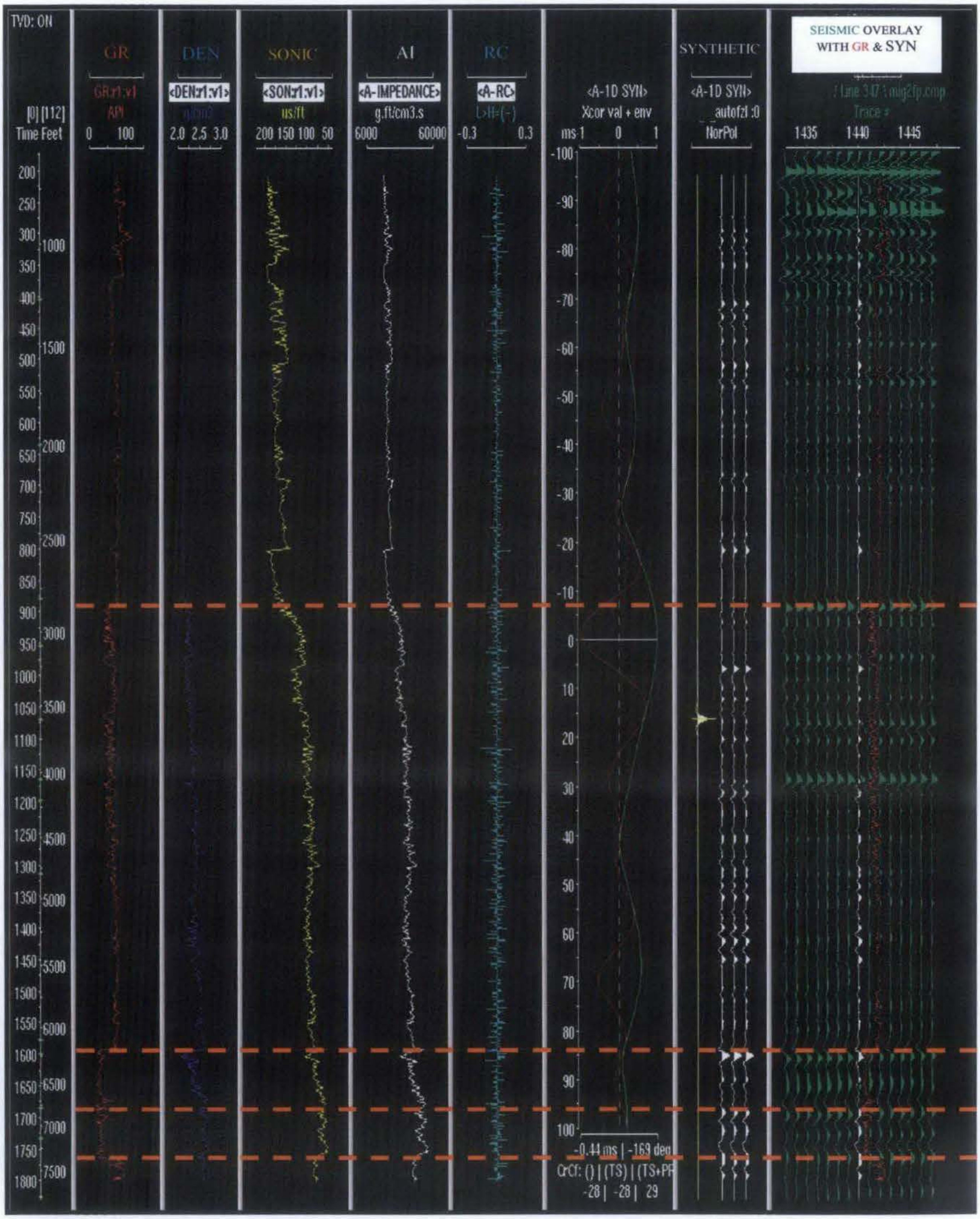


Figure 3.2. Synthetic seismogram of W-2 well. Dashed lines indicated the selected markers; Top Cycle V, Top Carbonate, Top Cycle III and Base Carbonate respectively from top to bottom.

3.2 3D Structural Mapping

The 3D seismic interpretation was conducted on Landmark's work-station using Seiswork 3D software. Five horizons were traced and mapped; three horizons within carbonate section (Top Carbonate, Top Cycle III, and Base Carbonate) and additional two horizons from Cycle V interval (Top Cycle V and Intra Cycle V). Even though the focus is on carbonate section, the additional horizons within the clastic sequence were interpreted to get a better understanding of the overlying sequence in the study area. The results from the horizon interpretations were used for attributes analysis in the next chapter.

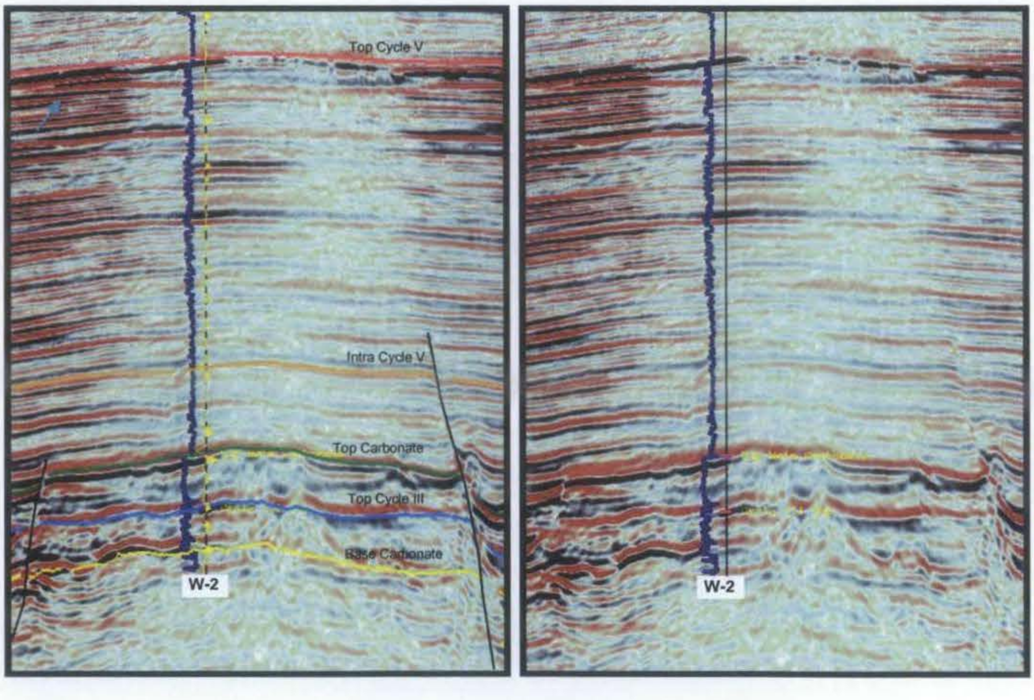


Figure 3.3. Seismic section at W-2 well location, with Gamma Ray, interpreted horizons and synthetic display. Blue arrow indicates flat spot (DHI), gas water contact within Cycle V sand reservoir. Five horizons were selected for the mapping.

3.2.1 Top Cycle V

The Top Cycle V horizon is characterized by strong and continuous reflector; corresponded to a proven Cycle V clastic gas reservoir. The results from wells indicated that this sand rich reservoir was deposited in coastal environment with thick and laterally continuous. The presence of gas in this reservoir indicates the existence of active petroleum system in the studied interval. Thick trangressive shale (homogenous, weak amplitude on seismic sections) overlying this sand provides a good seals for hydrocarbon accumulation. The difference of impedance contrast between gas and water had induced a "flat spot"- seismic phenomenon that indicates a surface of gas water contact.

The RMS (Root Mean Square) attributes from this horizon show the outline of the gas-water contact that extends southward toward the X-1 well (Figure 3.4). The results from the structural mapping show the amplitude deduced by gas is conformable to the structure. A late tectonic compression might have been responsible for creating this folded structure with the axis in NE-SW direction.

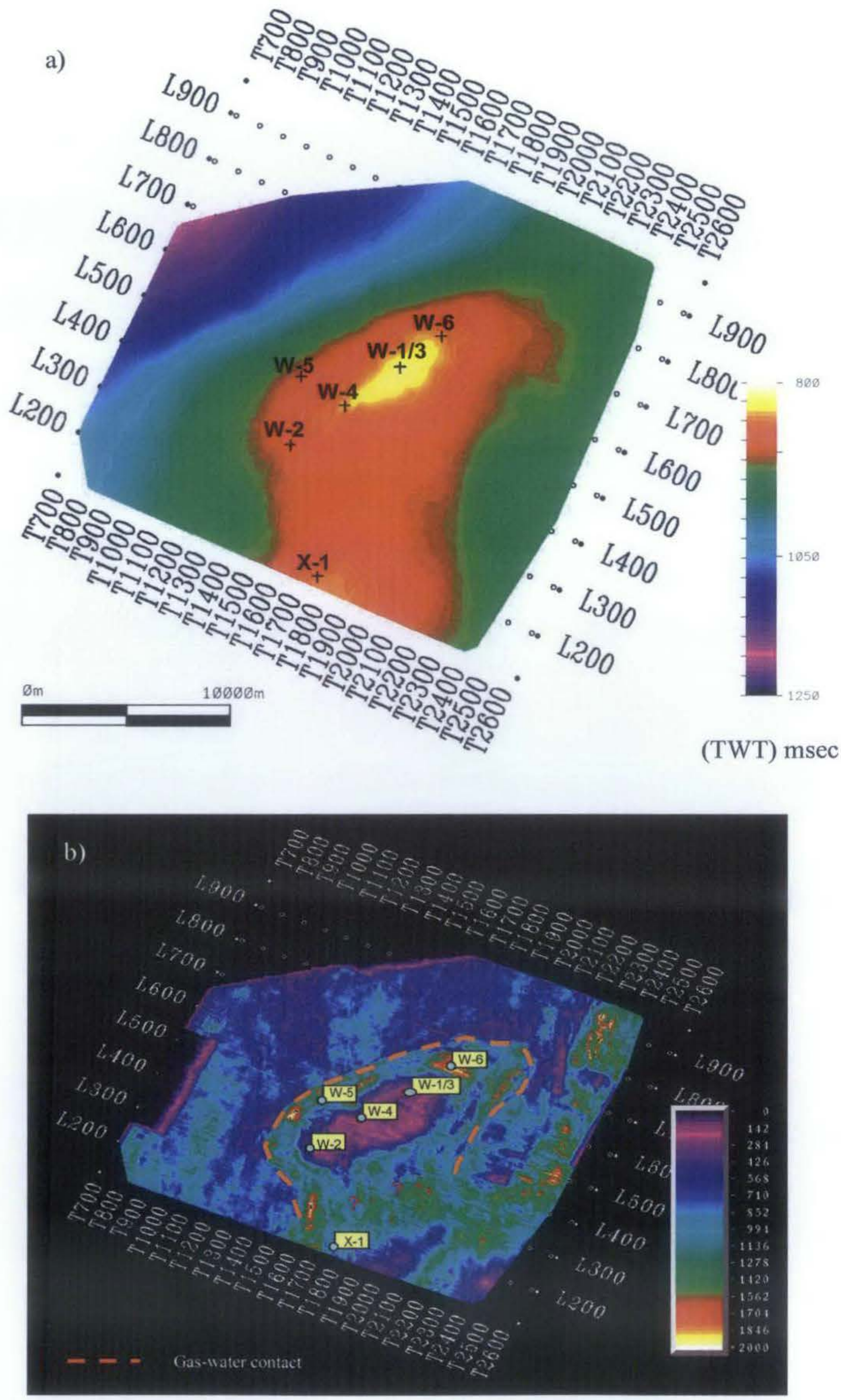


Figure 3.4 a) Top Cycle V Time structure map. b) Top Cycle V RMS attribute (-20 to +50 msec window).

3.2.2 Intra Cycle V

This horizon was picked based on a continuous reflector throughout the study area. It is located at approximately 200msec above the Top Carbonate horizon. This horizon is believed to be part of the outer neritic silty-clay rich zone that formed an efficient seal for underlying carbonate reservoirs.

The structural map of this horizon shows the presence of faults which oriented in almost north-south direction (Figure 3.5). The seismic sections on Figure 3.3 and 3.6 illustrate the faults were formed during early Late Miocene time.

The flattened seismic section at the Intra Cycle V horizon (Figure 3.6) shows the original condition of the underlying sequences. It indicates that the faults were reactivated during Late Miocene, probably before the compression took place during the end of Late Miocene-Pliocene.

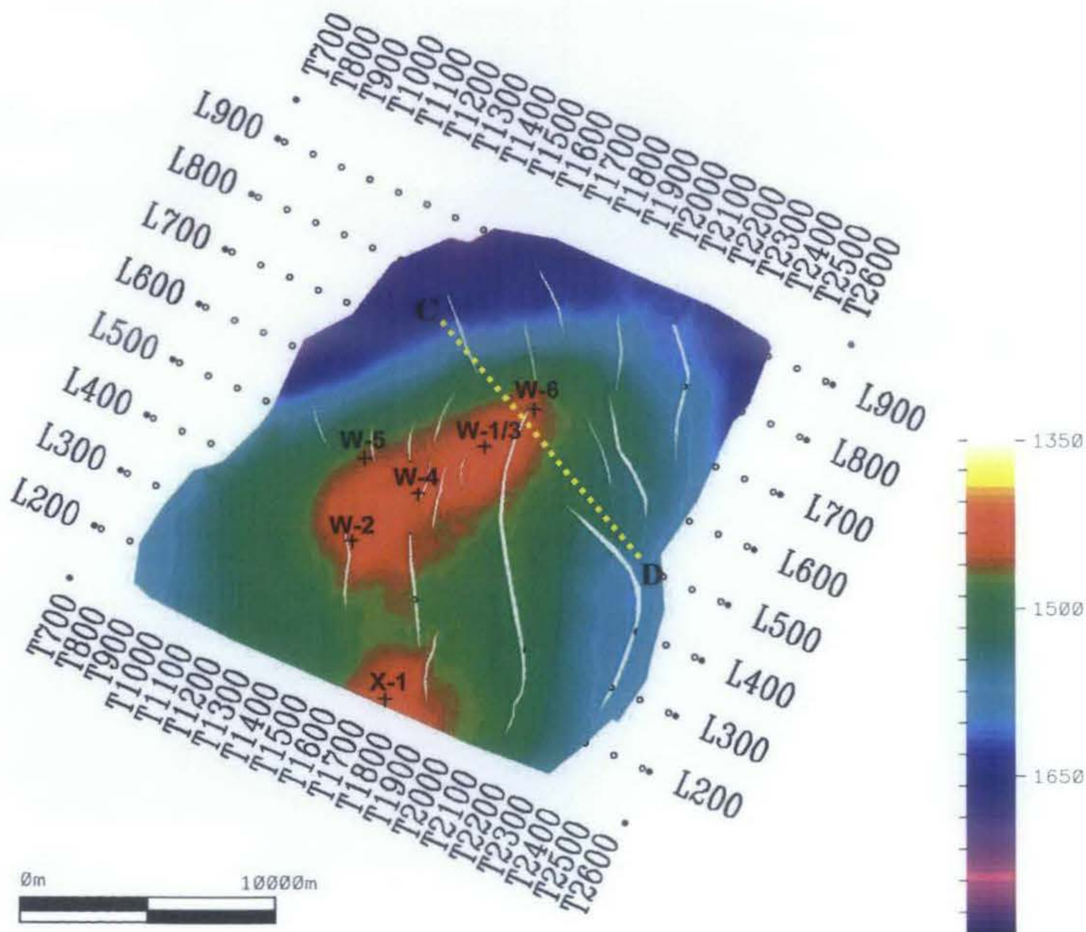


Figure 3.5. Intra Cycle V time structure map.

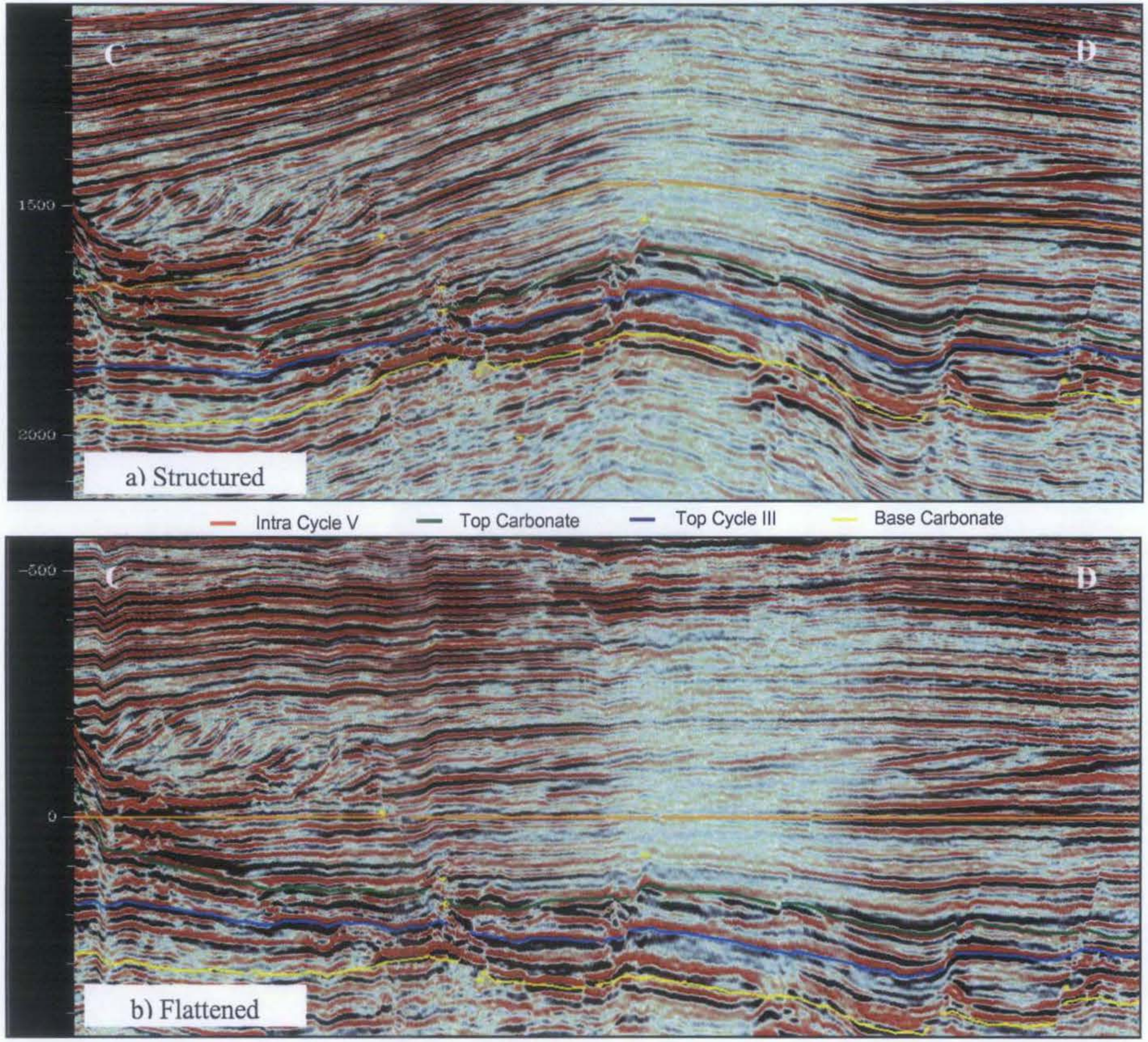


Figure 3.6. Seismic section, flattened at Intra Cycle V horizon.

3.2.3 Top Carbonate

The Top carbonate horizon is characterized by strong and continuous reflector, highly faulted and associated with series of low relief buildups. These buildups were extensively dissected by numerous normal faults with north-south trend. The fault displacement decreases to the west.

Picking the horizon within carbonate sections is a difficult process compared to clastic intervals; the seismic pull-up of the buildups, low frequency interval, gas effect, highly faulted structure and lateral facies variation had contributed to the uncertainties in interpretation, in an addition to that is the deterioration seismic energy with depth make things worst. Time slices and semblances attribute were used in mapping process of the faults (Figure 4.8).

The carbonate interval has been proven as gas reservoirs, attributed to the combination of structural and stratigraphic traps. Information from wells confirmed the connectivity reservoirs between W-2, W-5 and X-1 well (west compartment), and in the eastern compartment between W-1, W-3 and W-6 wells. These two compartments are separated by impermeable layer detected at W-4 well location.

Regionally, the carbonate growth is associated with high topography area such as folding or uplifted fault blocks in this area. Horst and graben topography controlled the lateral facies variation, whereas the high elevated horst blocks provides a suitable site for shallow water carbonate and the deeper water carbonate facies accumulated in the much lower position in the grabens.

The carbonates continue to grow until Middle Cycle V time, but restricted only in the western area; with isolated pinnacle type of geometry (Figure 3.8). The growth of these pinnacles started after the low relief buildups of Cycle IV buried by prograding clastic sediments from east.

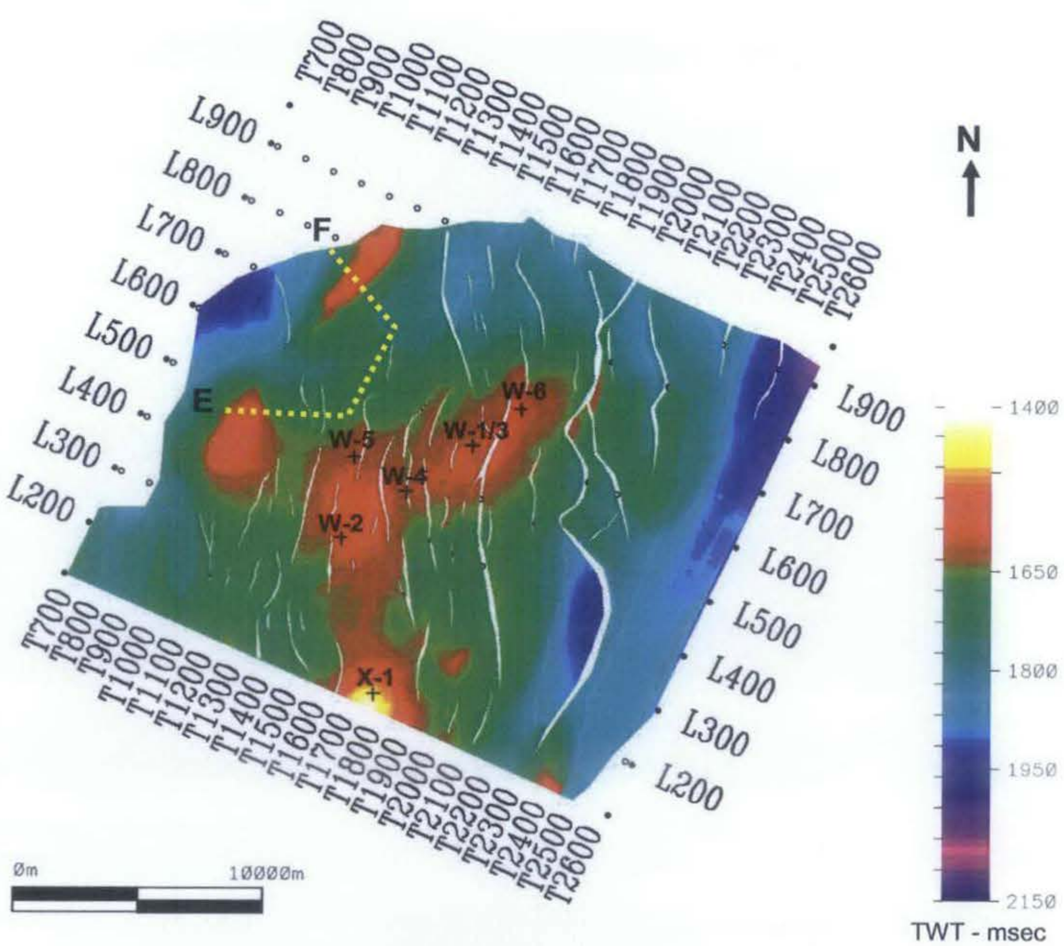


Figure 3.7. Top Carbonate time structure map.

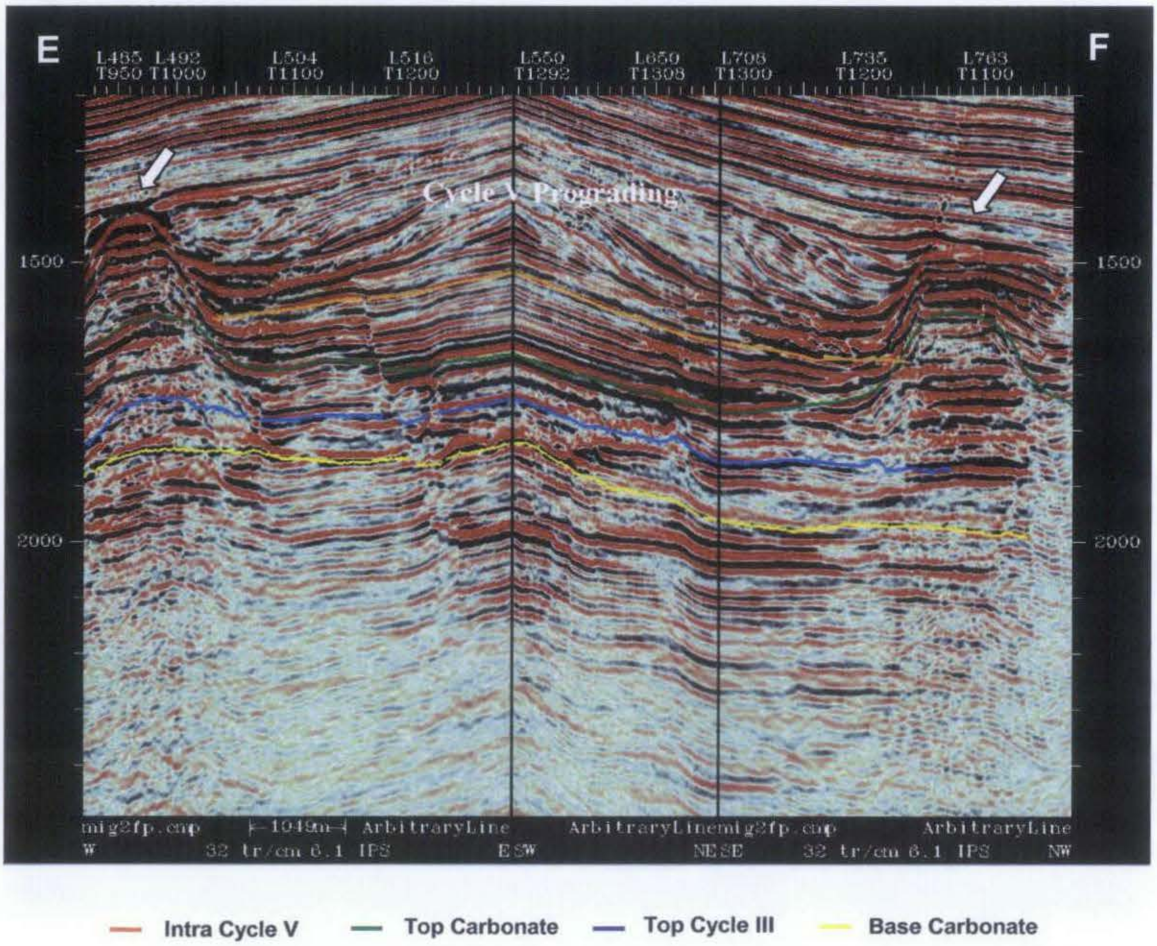


Figure 3.8. Arbitrary line through two pinnacles (high relief) carbonates (arrow). These carbonates were developed during Late Miocene (Cycle V) time, after termination of low relief (Cycle IV) buildups.

3.2.4 <u>Top Cycle III</u>

The Top Cycle III horizon is an intermediate horizon between Top Carbonate and Base Carbonate. In well W-2, the Cycle III sequence is characterized by shallow water carbonate, whereas in the well W-4 a typical interbuildup (deeper water) facies demonstrated by siliclastic intercalation between tight argillaceous and muddy limestone. Since the position of this horizon is only 100 msec below the Top Carbonate, there is a similarity in the structural style with the Top Carbonate map, clearly depicts by the horizon map.

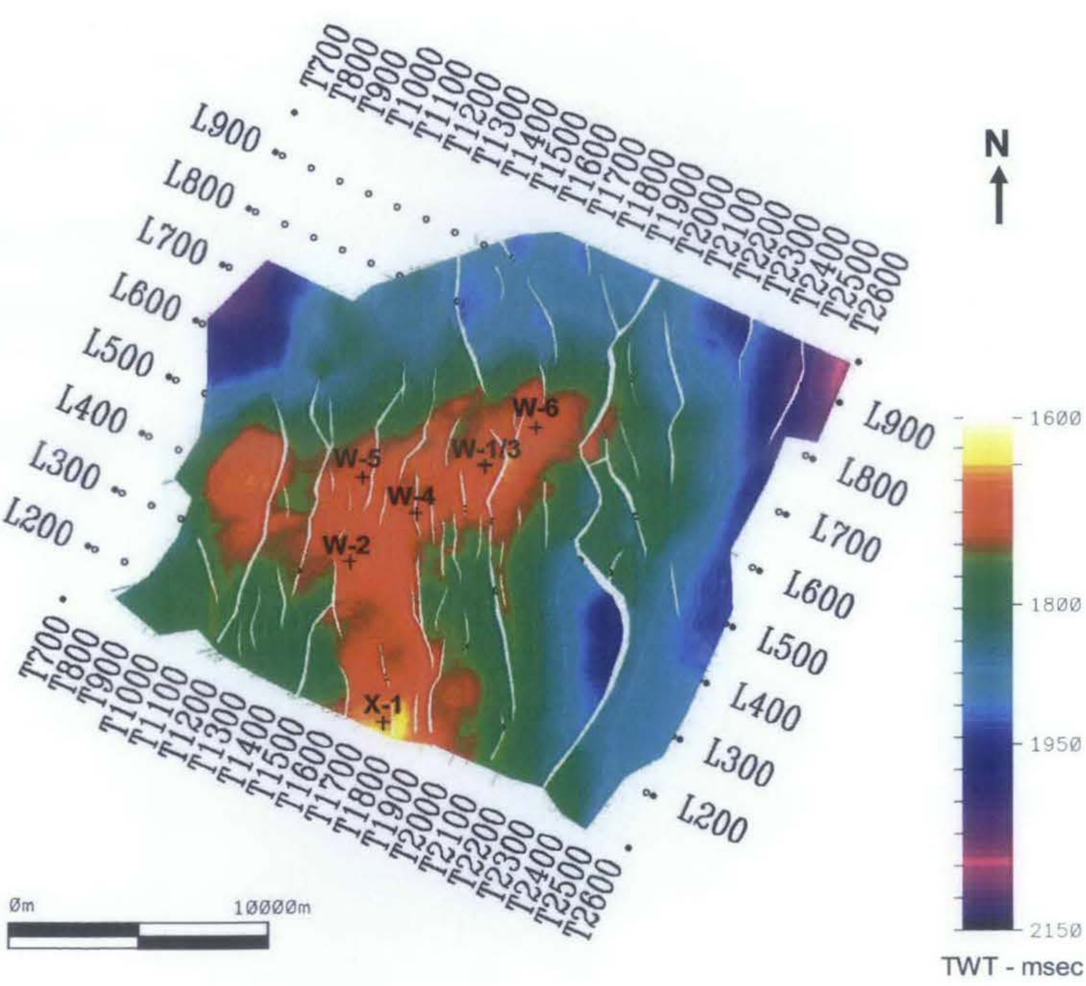


Figure 3.9. Top Cycle III time structure map.

3.2.5 Base Carbonate

The deepest carbonate sections from W-2 well is corresponded to the Base Carbonate marker. The structural time map of this horizon shows high intensity of faultings, with numerous small faults run parallel to the major faults orientation. The semblance slices below this interval illustrated the complexity of the deeper section faults pattern (Figure 3.11).

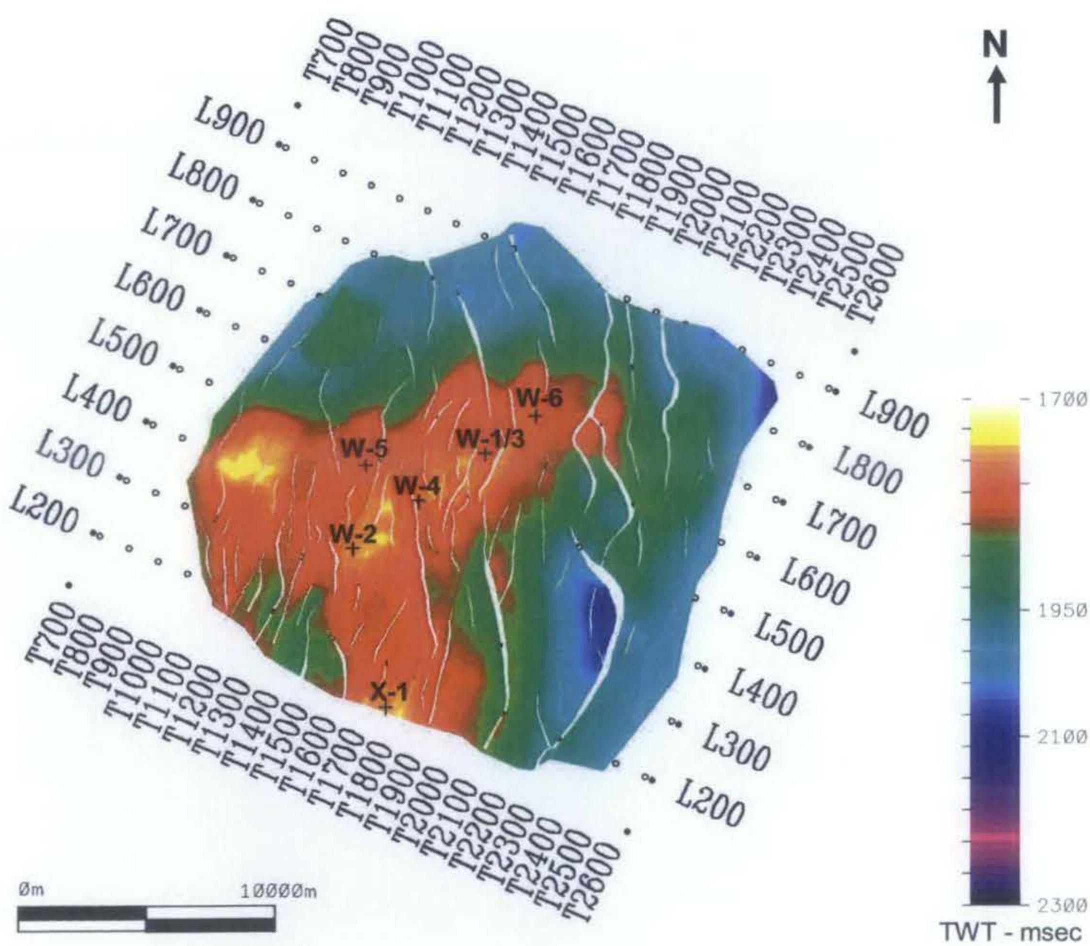


Figure 3.10. Base Carbonate time structure map.

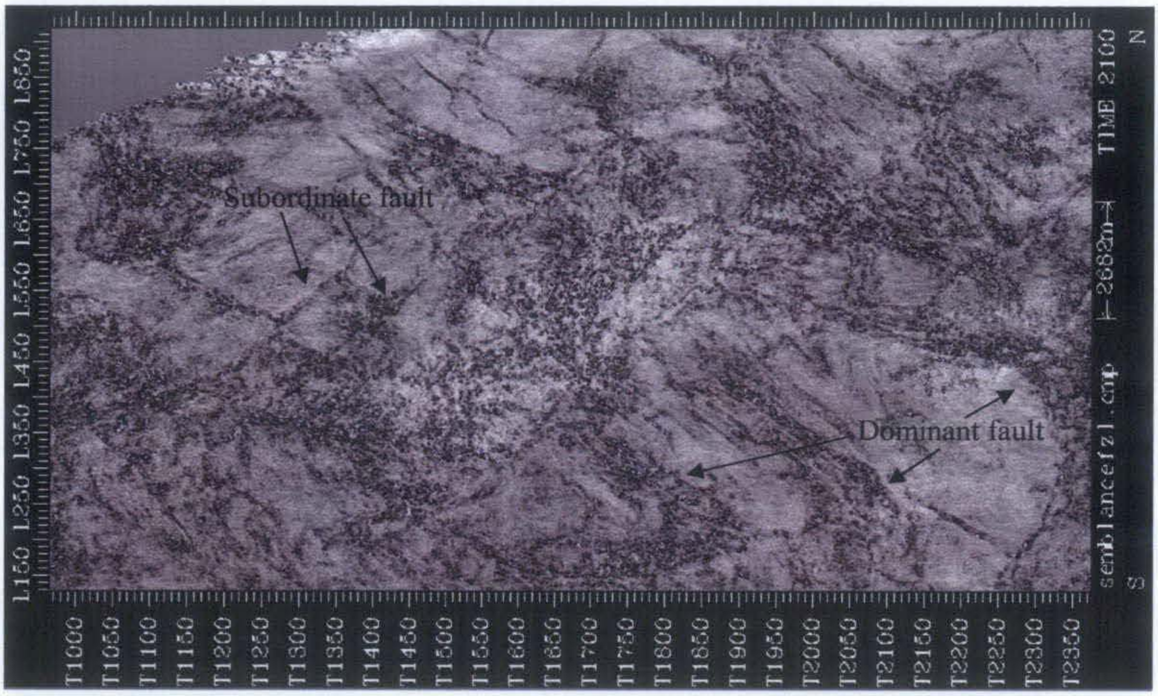


Figure 3.11. Semblance slice at 2100 msec (below Base Carbonate) shows the highly faulted area in the deeper zone. Faulting affected the entire area covered by the 3D survey. The dominant fault system strikes almost North-South and subordinate system strikes in West-East. Note: The time slice orientation is rotated, see map for actual position.

4.0 CHAPTER FOUR: ATTRIBUTES ANALYSIS

4.1 Attribute Analysis

The attribute analysis is part of the seismic stratigraphy (geomorphology) framework studies of the project. Recent publication from Davies *et al.* (2007) provides the best example for the geomorphological illustration as interpreted from the seismic attributes. The attribute analysis was carried out to assist the qualitative interpretation.

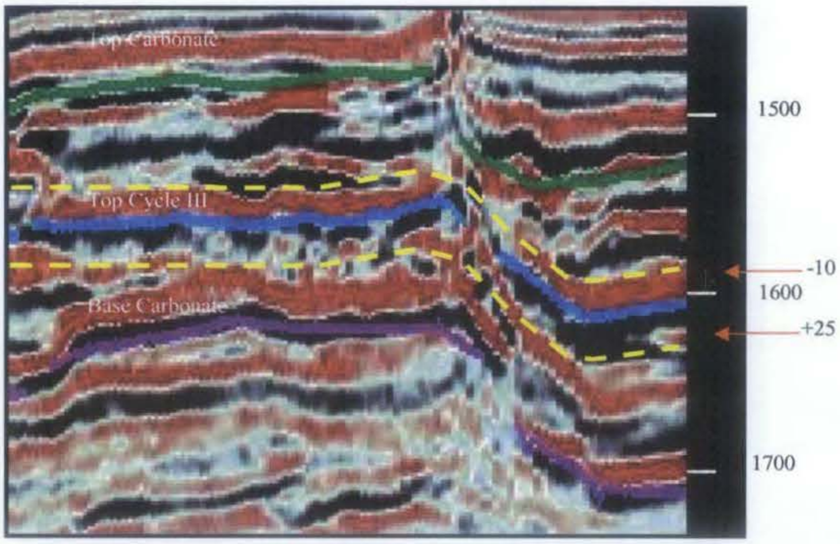


Figure 4.1. Attributes extraction was carried out using specific window. For example, from Top Cycle III horizon with -10 msec (above) and +25 msec (below).

The attributes extraction was carried out using horizon based extraction with specified window (Figure 4.1). The uncertainties of the extraction depend on the accuracy of the horizon picking and also on the seismic data quality. Several types of attributes generation were carried such as RMS (Root Mean Square), maximum peak, maximum trough, instantaneous phase and instantaneous frequency (Figure 4.2). The RMS amplitude provides the best illustration of the carbonate interval, and therefore is selected for detail attributes analysis in this study. Using specific colour manipulation, RMS attributes display the best image of buildups geomorphology. The colour conventions used for this study use the two extreme colours instead of conventional multicolour typical for RMS attribute.

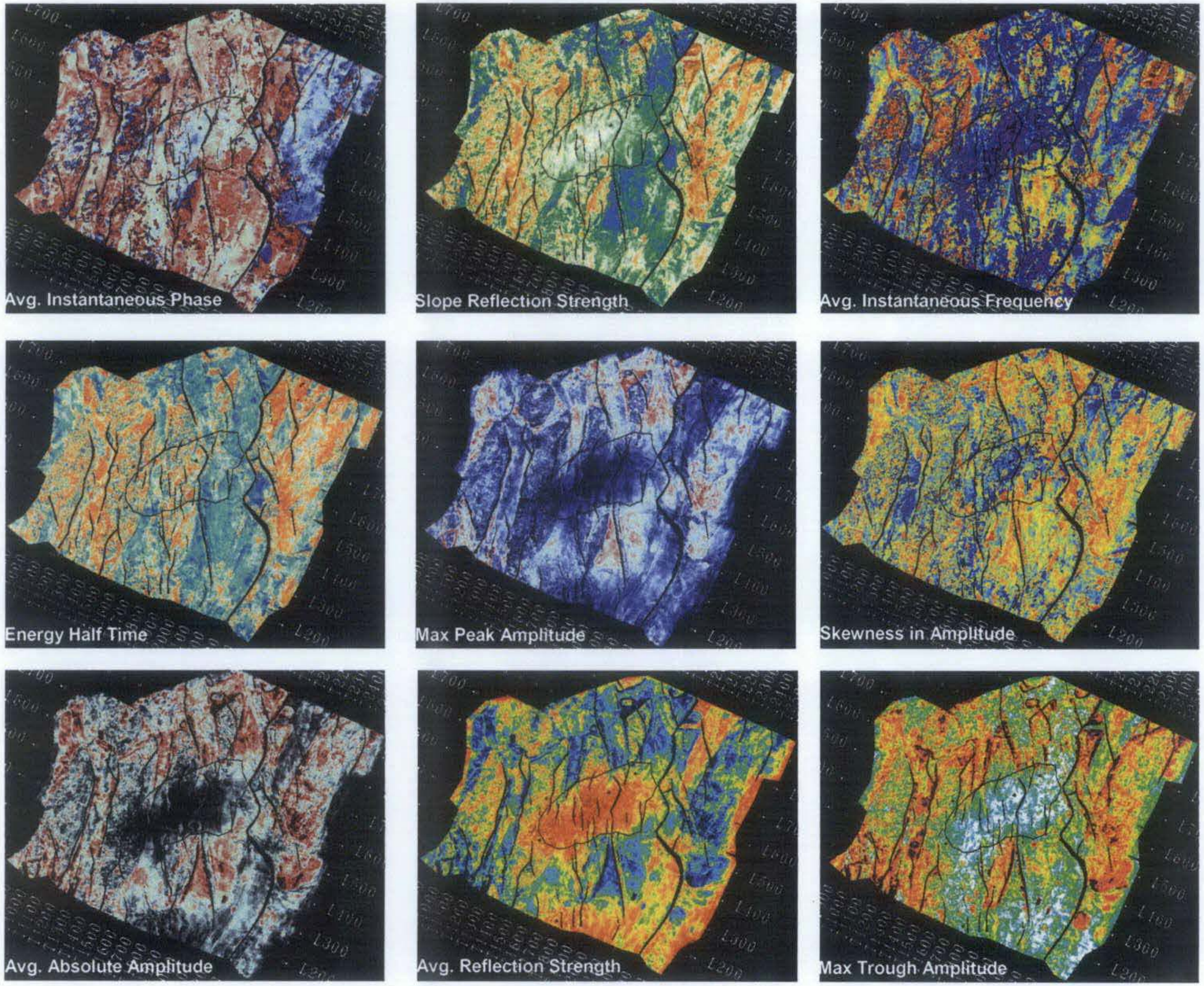


Figure 4.2. Top Cycle III attributes (+10 to +30msec). Among these attributes, average reflection strength and average absolute amplitudes also give better buildups outline definition.

The images from attributes display clearly illustrate a distinctive zone of buildup and interbuildup area. The boundaries depicted from RMS attributes commonly related to transition of reef to fore reef zone near the slope position. However, there is also indication of the strong amplitude anomaly (black) that generated by onlapping of trangressive sediments onto the older strata.

The buildup area is defined by series of reef, fore reef and back reef facies alternations. This shallow water buildup is separated by relatively deep interbuildup area, of which was filled with muddy carbonates facies characterized by fine grain carbonate materials and sometimes intercalated with clastic sediments.

4.2 Top Carbonate RMS Amplitude

The RMS attribute extracted from the Top Carbonate horizon shows a typical elongate geometry of the buildups with size ranges from 1 km^2 to more than 21 km^2 (Figure 4.3). The distributions of small isolated rounded shape (patch) buildups are very limited. The buildups generally show a N-S trend (slightly to the west). General trend of the buildups oriented in a similar trend with the faults. These fault blocks provide a template and allowed the carbonate to grow on the elevated horst blocks.

The geomorphology interpretation from RMS attribute seems to match very well with the image from the seismic sections. Three seismic sections were selected as illustration of the geometry of the build-ups (Figure 4.4). The interbuildup area from this sections show a typical sediment-infilled area that display continues and parallel reflectors with onlapping pattern. The buildups geometry is wider in the central area and narrower in the marginal area. This central area is probably the place of nucleation for the carbonate to grow.

The results from W-4 well (Figure 4.5), which was drilled in the saddle area (within the inter-buildup) confirmed the presence of deeper marine facies, with mostly chalk and fine grain limestone. The well was drill to confirm the existence of permeability barrier between these two difference compartments. The west compartment (W-2, W-5, X-1) shows 12-13% CO_2 content, compared to

TOP CARBONATE RMS AMPLITUDE

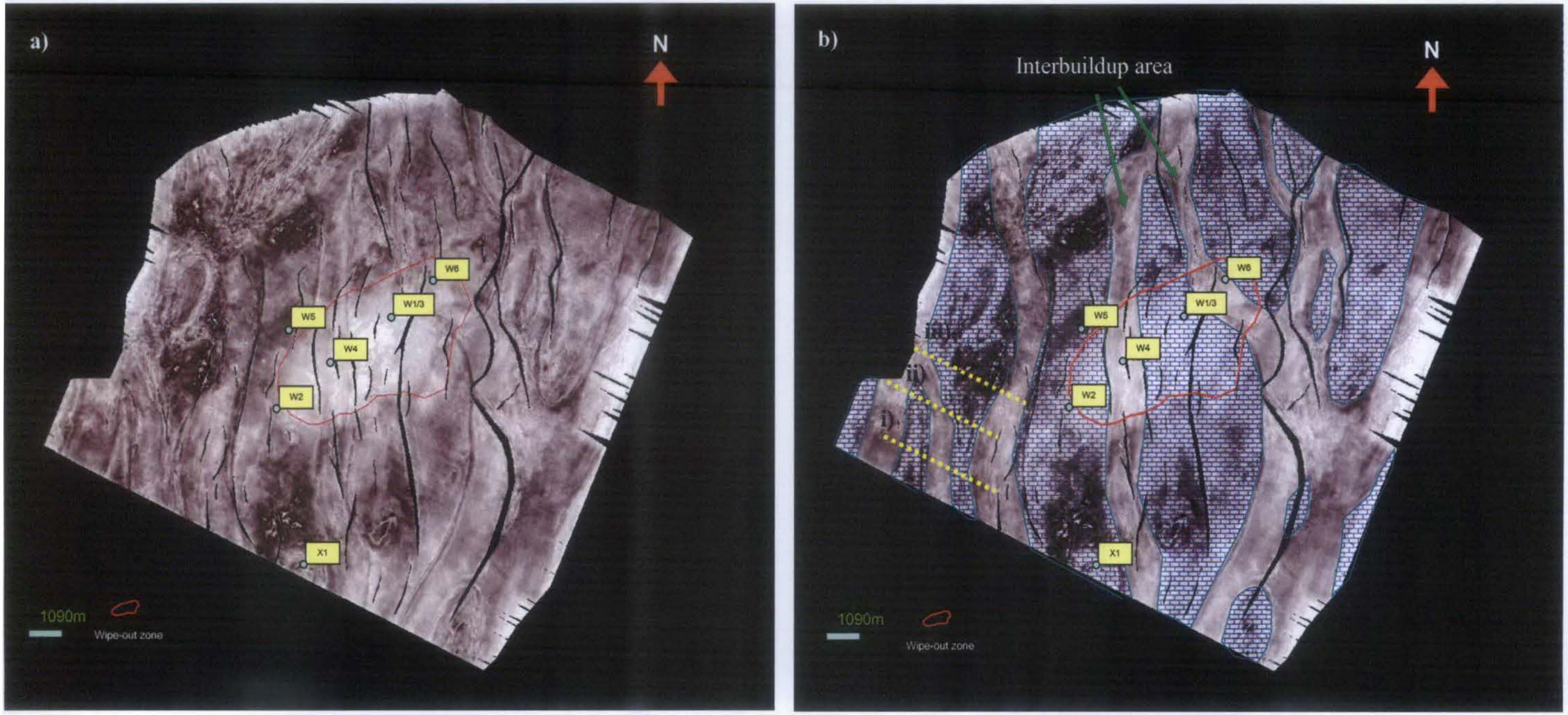


Figure 4.3 a) RMS attribute for Top Carbonate (-2 to +35 msec window). b) RMS attribute (a) with buildup geomorphology interpretation.

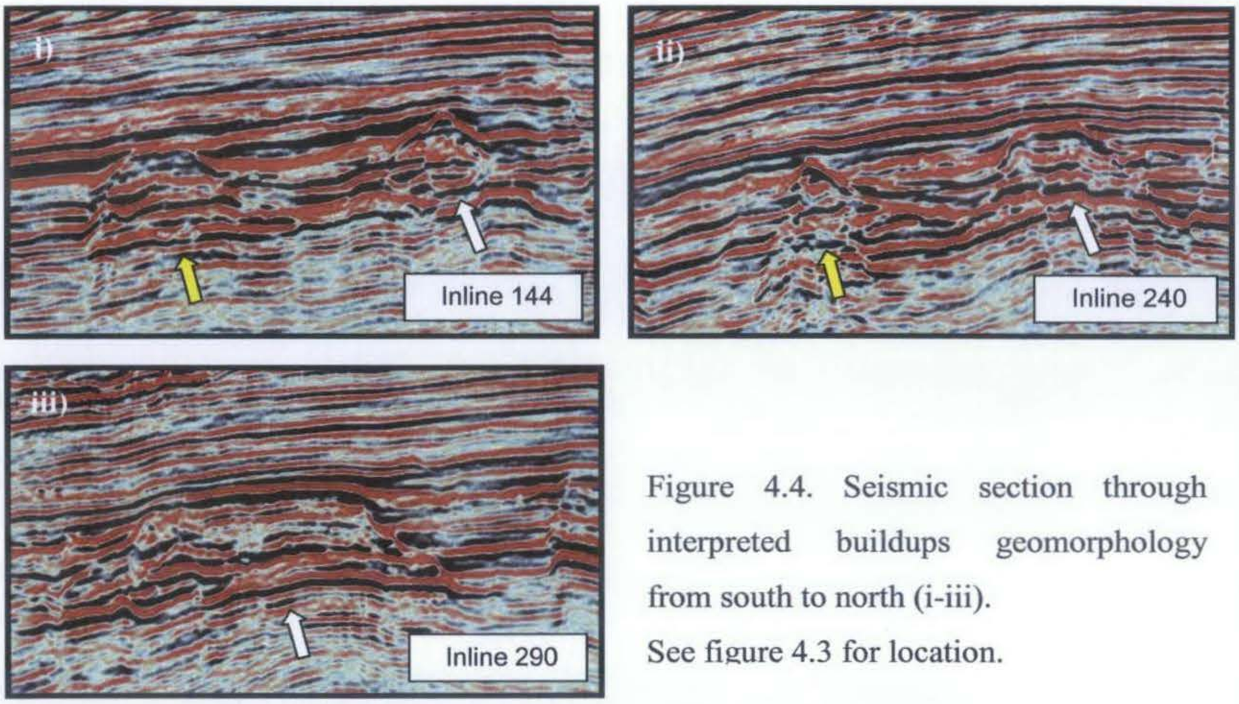


Figure 4.4. Seismic section through interpreted buildups geomorphology from south to north (i-iii). See figure 4.3 for location.

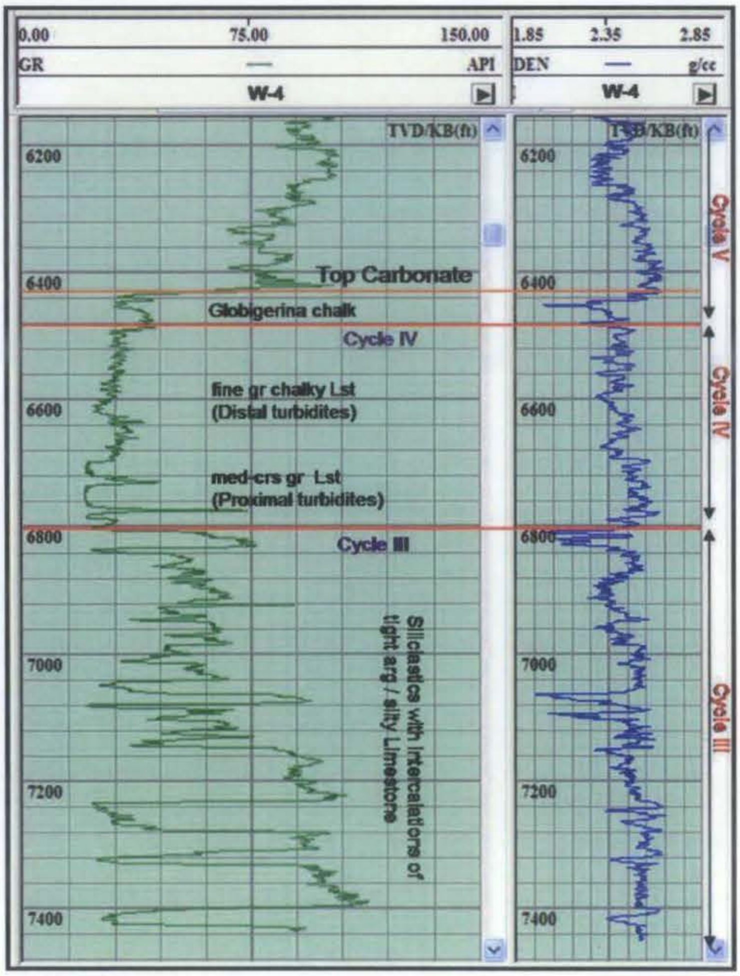


Figure 4.5. W-4 well was drilled in the interbuildup zone; in the depositional low (basinal area), characterized by deeper marine carbonate facies.

east compartment (W-1, W-3, W-6) with higher CO2 at 17-21%. This deeper carbonate facies in the interbuildup area has a potential to act as permeability barrier, which could provides a stratigraphic trap for hydrocarbon accumulation. The difference of gas-water contact between these two compartments is 100ft. The position of the Top Carbonate marker (W-2: 6060 tvdss, W-4: 6350 tvdss) in both wells recorded at difference depth, with difference of 290 ft (88m); these variation of depth definitely allow the deposition of deeper marine facies in the interbuildup area (W-4).

4.3 Top Cycle III RMS Amplitude

The RMS attribute imaged captured from the Top Cycle III illustrates the initial stage of the buildups extension and coalescence. The arrangement of the buildups seems to be controlled by the topography of the fault blocks and orientated in N-S (slightly to the east) direction. The sizes of the build-ups range from 0.25 km^2 to more than 12 km^2. The small and rounded carbonates located close to the elongated buildups. There is also evidence of backstepping growth pattern (dotted arrow – Figure 4.6) indicative of trangressive nature of the accumulation. However, this morphology is only preserved at the eastern buildup area (see Chapter 6).

An arbitrary seismic line through the identified four buildups (G-H) shows a typical carbonate buildups character; with less internal reflector, chaotic and mounded features (Figure 4.7). The section also shows the buildups grew on the high elevated horsts block. The semblance attribute and time slice at 1710msec were used to illustrate the faults pattern and buildups characterization (Figure 4.8). The image from time slice show the possibility of karstified surface near the Top Cycle III horizon, associated with a sequence boundary. This is corroborated with sequence stratigraphic analysis which confirmed the presence of a major sequence boundary at this interval.

TOP CYCLE III RMS AMPLITUDE

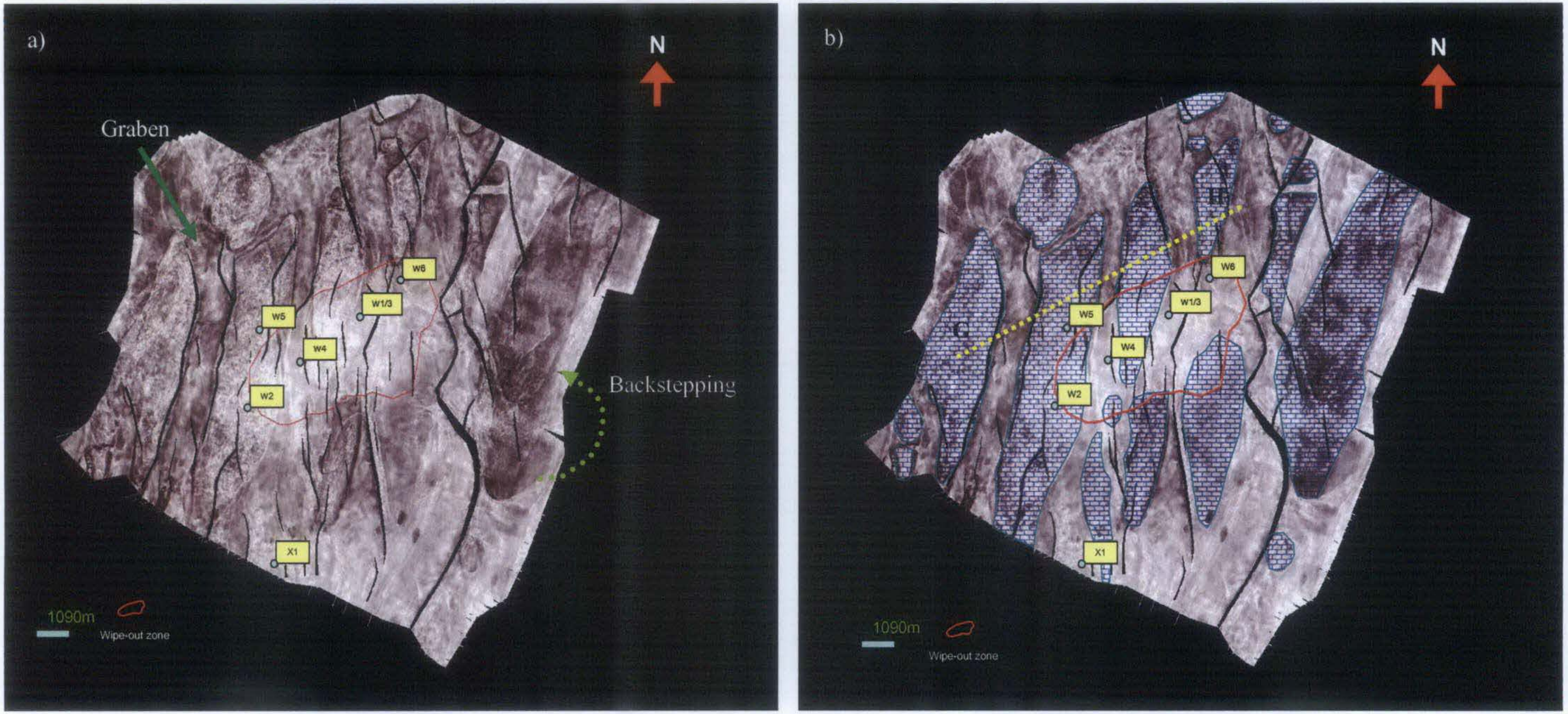


Figure 4.6. a) RMS attribute for Top Cycle III (+10 to +30 msec window). b) RMS attribute (a) with buildup geomorphology interpretation.

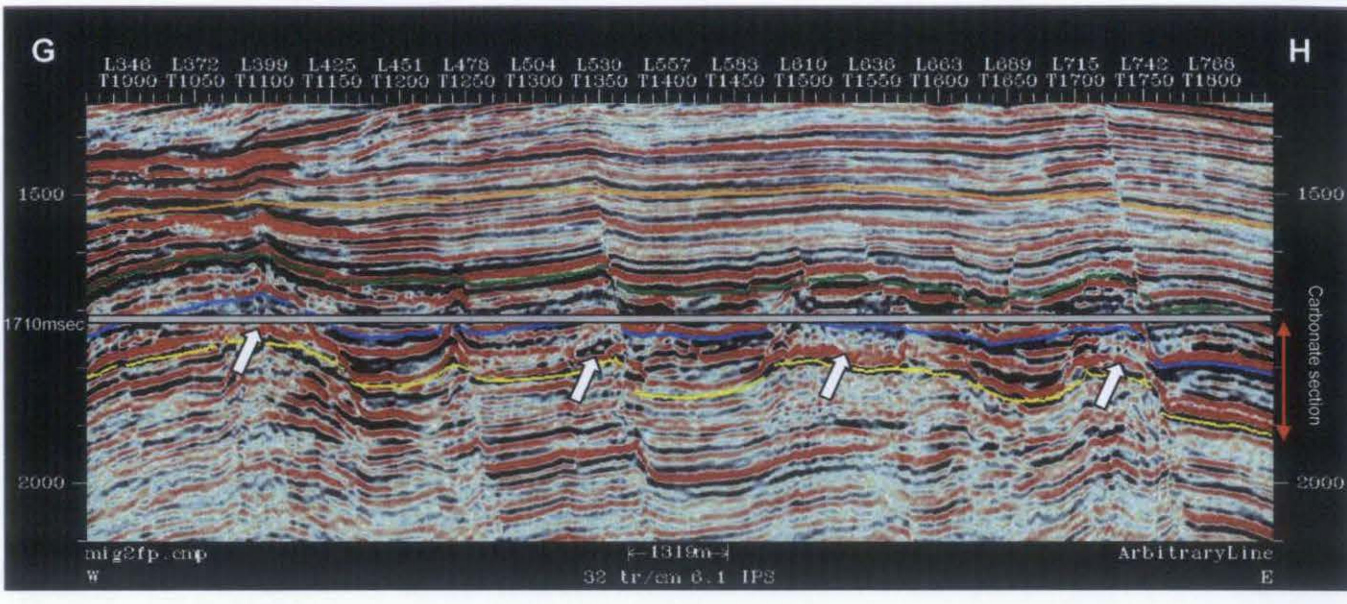


Figure 4.7. SW (G) – NE (H) arbitrary seismic line, slice at 1710msec. White arrows indicate the mounded and chaotic feature which interpreted as buildups in Figure 4.6.

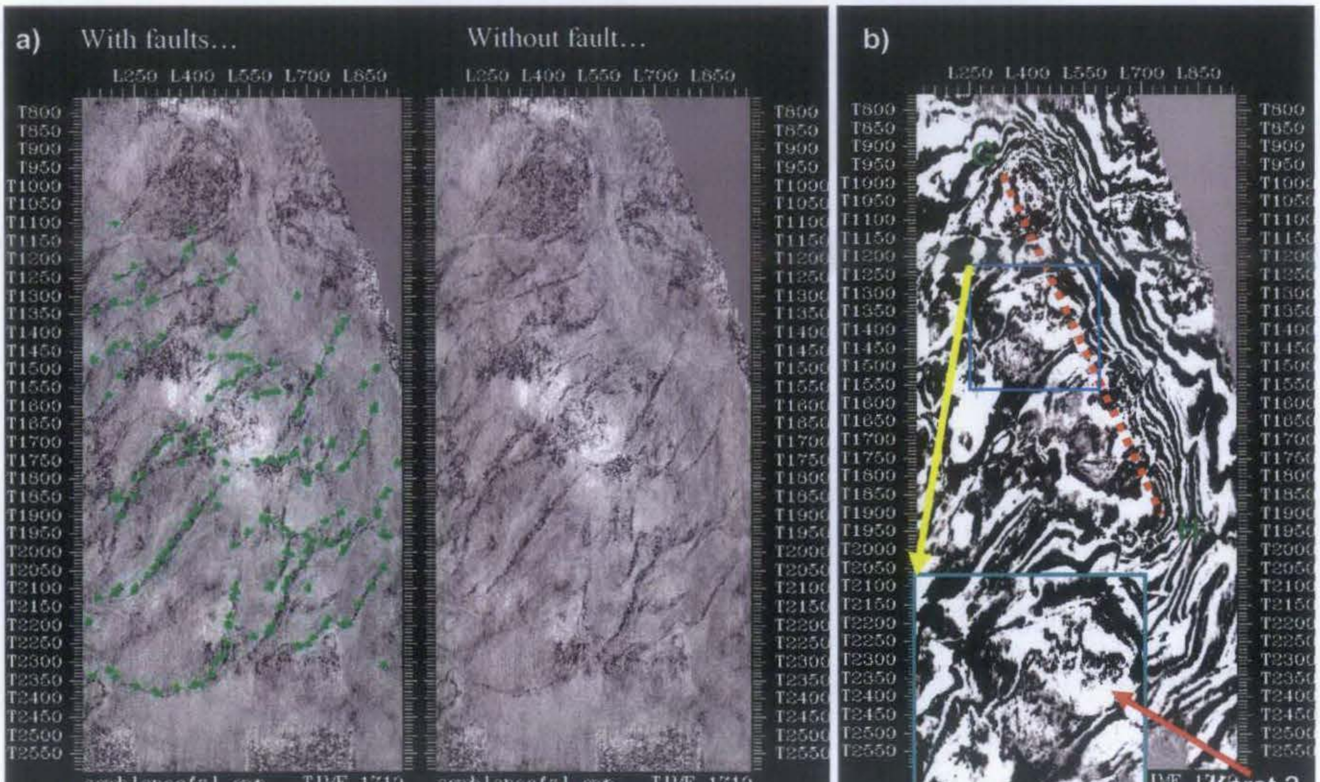


Figure 4.8. a) Semblance slice at 1710msec with fault interpretation. b) Time slice at 1710msec shows possibility of karstic surface near Top Cycle III.

4.4 Base Carbonate RMS Amplitude

Two attribute extractions were made from this horizon (0 to +10msec and +10 to +50msec; Figure 4.9 & Figure 4.10) to capture the image of the buildups at two different stratigraphic intervals. The deepest selected window (Figure 4.10) illustrates older buildups with smaller size and rounded geometry. The orientation of these buildups is in N-S, with size ranging from 0.25 km^2 to more than 6 km^2. These build-ups distribute well in the western area.

BASE CARBONATE RMS AMPLITUDE (I)

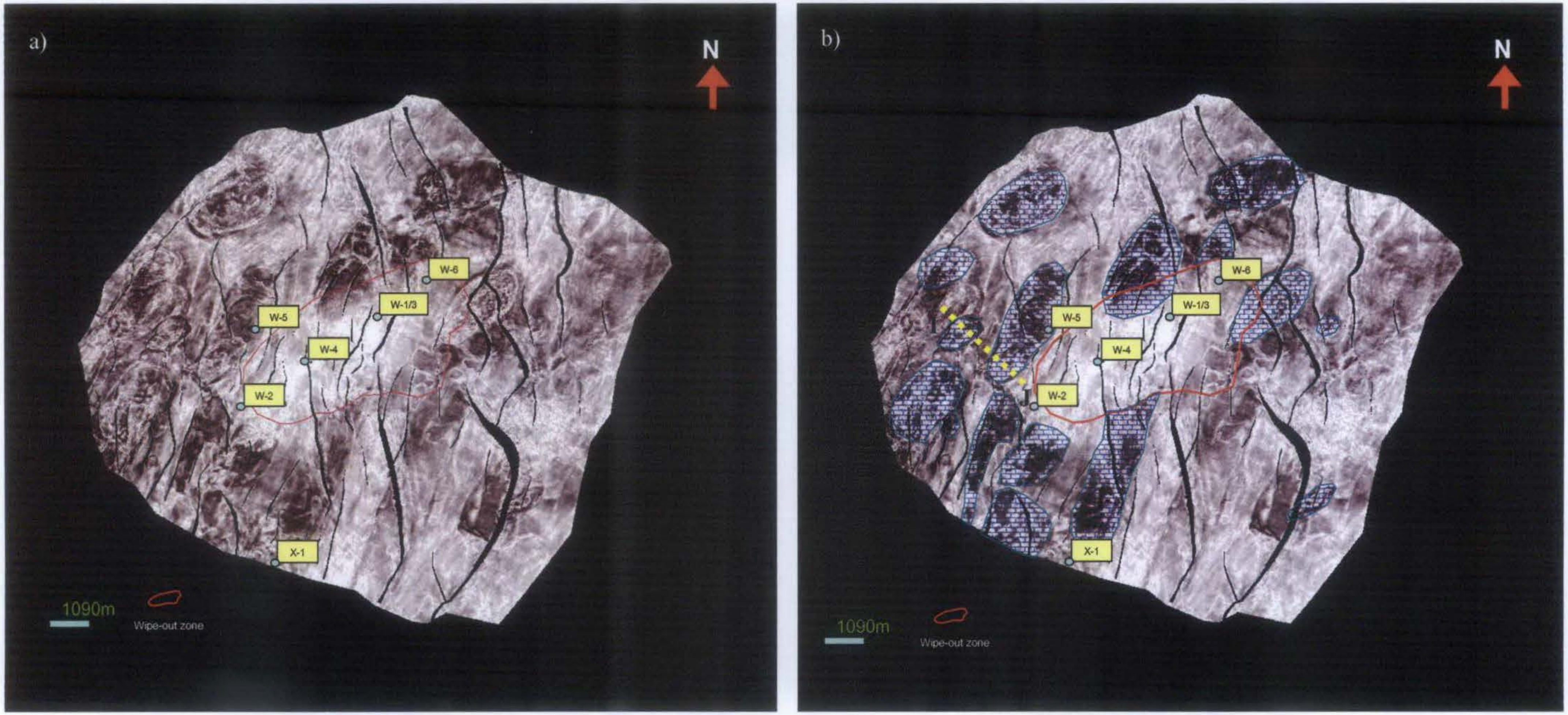


Figure 4.9 a) RMS attribute for Base Carbonate (0 to +10 msec window). b) RMS attribute (a) with buildup geomorphology interpretation.

BASE CARBONATE RMS AMPLITUDE (II)

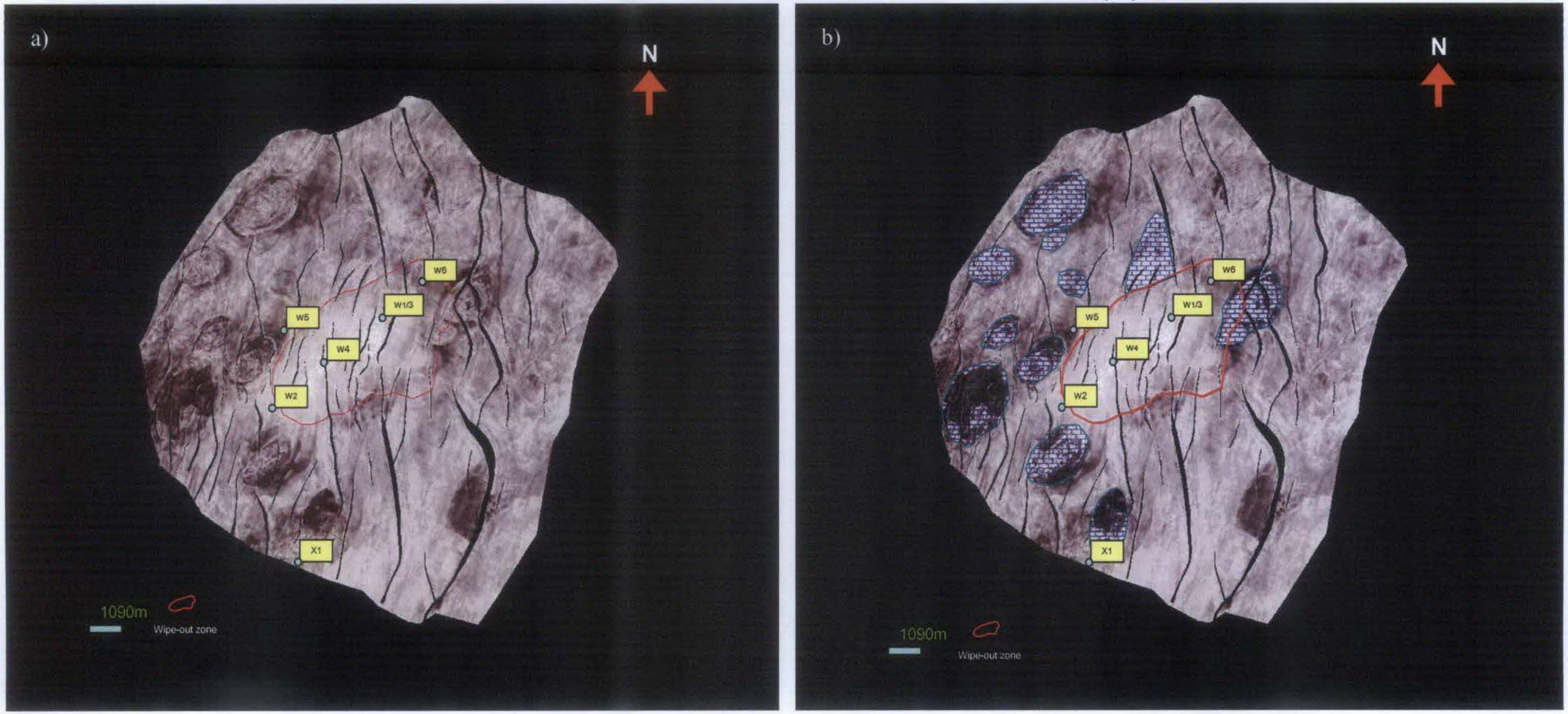


Figure 4.10. a) RMS attribute for Base Carbonate (+10 to +50 msec window). b) RMS attribute (a) with buildup geomorphology interpretation.

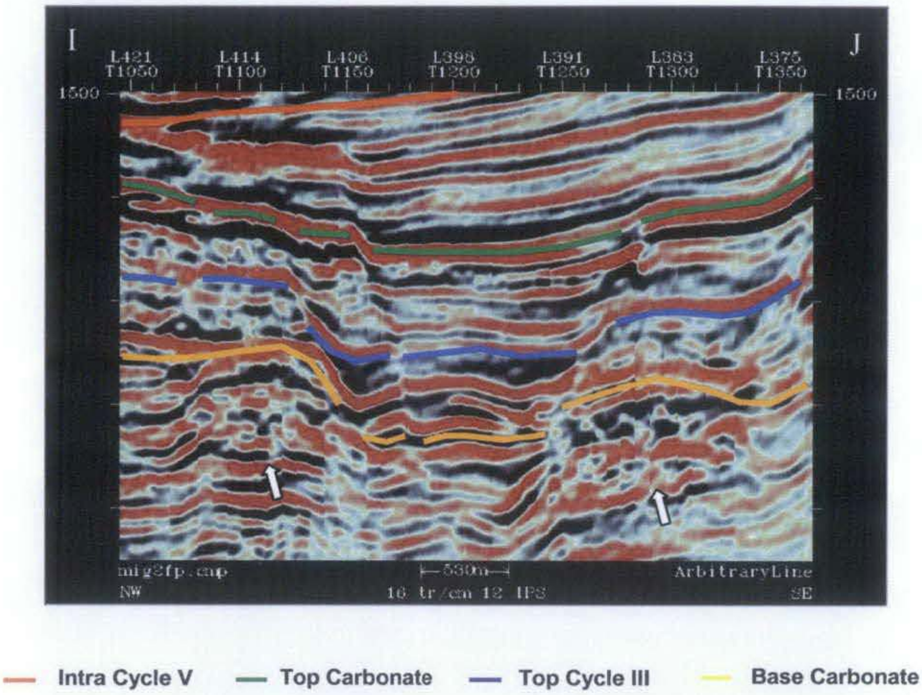


Figure 4.11. Seismic section below Base Carbonate horizon shows a typical patch buildup seismic character with mounded and chaotic reflectivity (arrow). See Figure 4.9 for location.

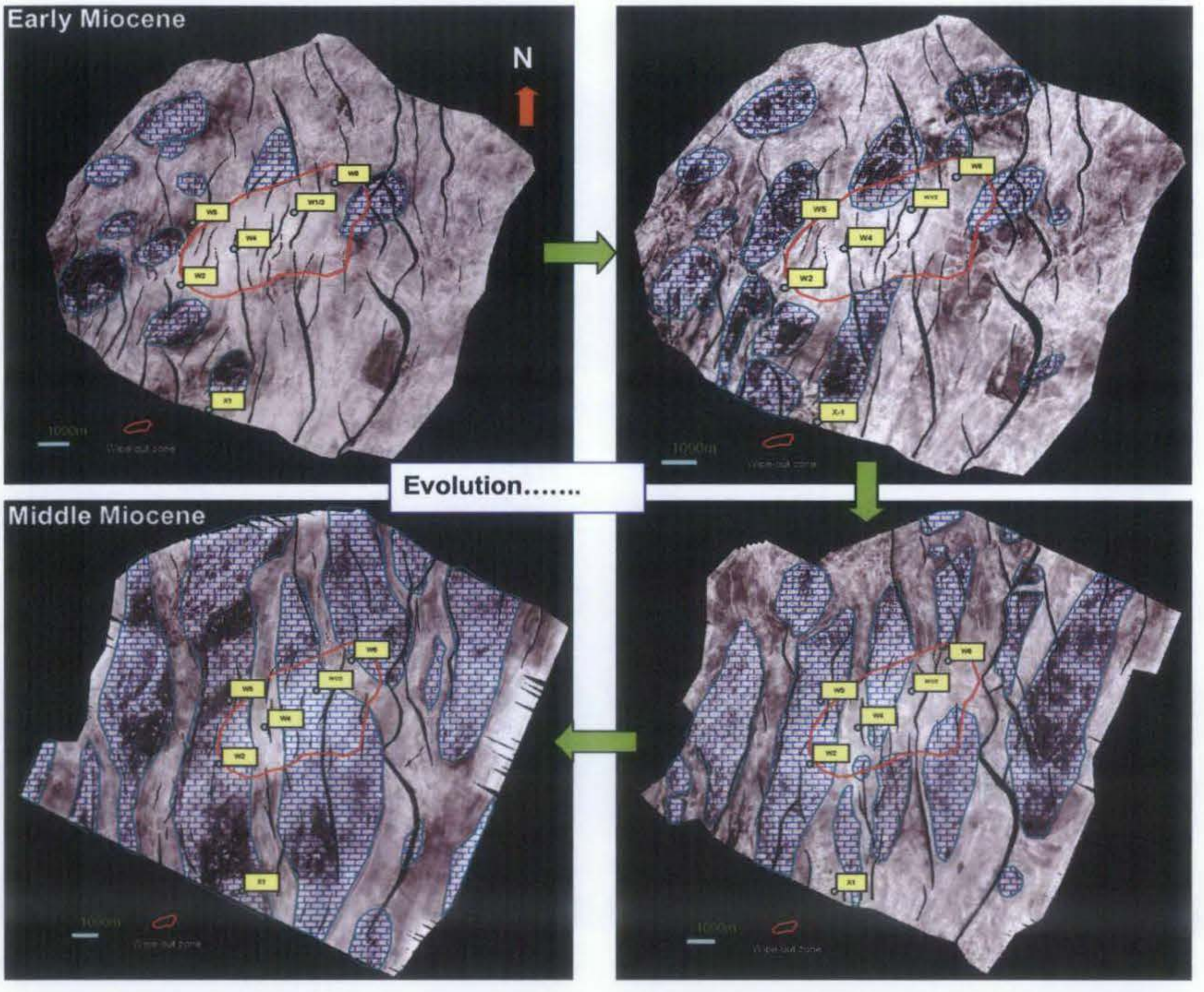


Figure 4.12. Buildup evolution from Early Miocene (Base Carbonate) – Middle Miocene (Top Carbonate). The growth took place in north-south direction which also probably corresponds to north-south paleowind orientation.

It can be conclude that the RMS attribute is the best to illustrate the growth of carbonate buildups in this area. The buildups evolved since Early Miocene to Middle Miocene. The lateral expansion of the buildups was in the north-south (NS) orientation, and was controlled by the north-south paleowind direction. The evolution and detail architecture of the buildups will be discussed further details in Chapter 5.

5.0 CHAPTER FIVE: SEISMIC FACIES AND SEQUENCE STRATIGRAPHY

5.1 Seismic Facies

Seismic facies is the characterization of the sediments using seismic parameters, and is defined by a group of distinctive reflection continuity, configuration, amplitude, frequency, external geometry and possibly interval velocity of seismic reflectors (Badley, 1985). Adapted from Vail *et al* (1977), Badley (1985) had summarized the seismic facies characterized by mounded and draped reflection configuration related to the carbonate facies.

Properties of seismic facies	**Reefs and banks: Shelf/platform margin, back shelf patch reefs and pinnacle/barrier reefs.**
1. Reflection configuration	Mounded, chaotic or reflector free; pull-up or pull down common.
2. Geometry & structure	Elongate lens-shaped (shelf/platform edge and barrier reefs); elongate to sub circular lens-shaped (patch and pinnacle reefs/bank); form on stable structural elements.
3. Amplitude	High along boundaries; may be moderate to low internally; commonly reflector free.
4. Continuity	High along boundaries; internally discontinuous to reflector free.

Table 5.1. Summary of the seismic facies, modified after Badley (1985).

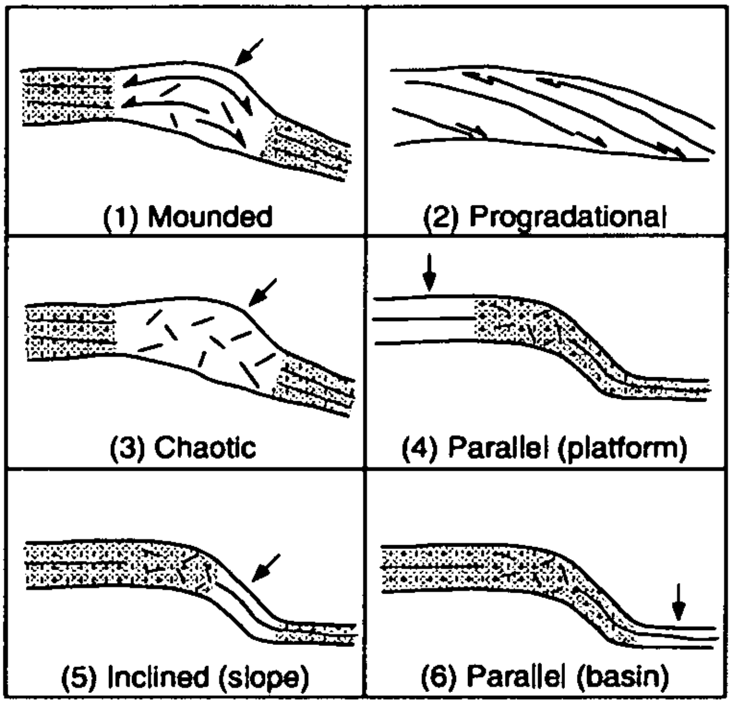


Figure 5.1. Six seismic carbonate facies in relation with reservoir quality (Bachtel et al, 2004).

A detailed seismic facies characterization of carbonate is given by Bachtel *et al* (2004). He identified six seismic facies, and is listed in descending order below. This scheme provides some prediction about the sedimentary facies and reservoir quality.

1. Mounded
   - Bidirectional downlap of internal reflector, internal geometry convex up, thickening occur locally where mounded facies occur.
   - Shelf margin or shelf interior reefs and associated grainstone shoals.
2. Progradational
   - Toplap against upper sequence boundary (SB) and downlap into maximum flooding surface (MFS).
   - Low relief sigmoidal or steeper oblique geometry, facies are typically inclined into sediment transport direction.
   - Grain dominated lithofacies (including boundstone) associated with the platform margin, reef flat and platform interior facies that prograde away from the shelf margin.

3. Chaotic
   - Internally disrupted with chaotic character, these facies are transitional with mounded facies. Can be related to data disruption.
   - Shelf margin or shelf interior patch reefs, analogues to the mounded seismic facies, predicted to be variable reservoir properties.
4. Parallel (platform)
   - Concordant and parallel reflector between SB, straight to slightly wavy, continues – semi continues.
   - Platform interior, represent wide range of rock types from grain to mud dominated.
   - Good reservoir quality because erosion during sea level fall, poor reservoir quality especially muddier lagoonal facies.
5. Inclined (slope)
   - Reflector typically gently inclined decrease in gradient toward the toe of slope, with parallel geometry. Slope position and captured as progradational facies locally.
   - Slope, gradational from relatively good reservoir quality near platform margin to poor toward the toe of slope.
   - Decrease in grainsize, abundance of skeletal debris and increase in muddy sediment fabric.
6. Parallel (basin)
   - Basinward of the toe of the slope and generally comprise of high amplitude parallel facies.
   - Poor porosity and permeability, muddy fabric and fine grain skeletal debris.

Three main carbonate facies identified in this study; - reef, fore reef and back reef (Figure 5.2). The reef facies normally display a mounded feature and characterized by internal free reflectors. Fore reef located in the frontal zone of reef, along the slope and is characterized by parallel reflectors. Back reef facies shows more parallel reflectors, located behind the reef and associated with lagoonal facies (Figure 5.3).

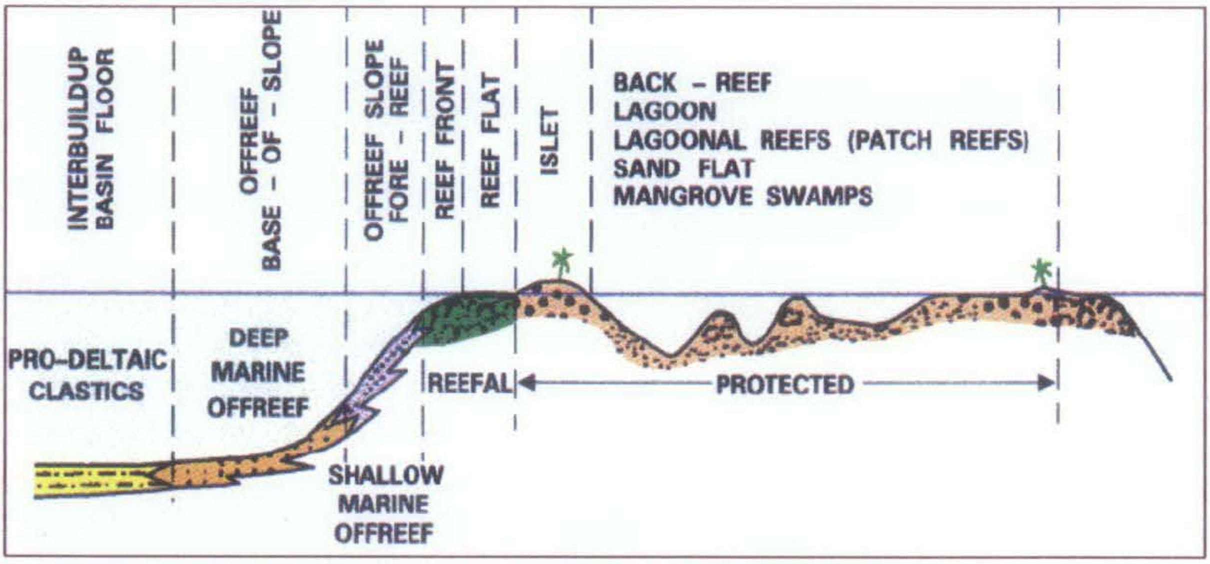


Figure 5.2. Physiographic zones and depositional environments within the carbonate buildup (modified after M. Yamin and Abolins 1999).

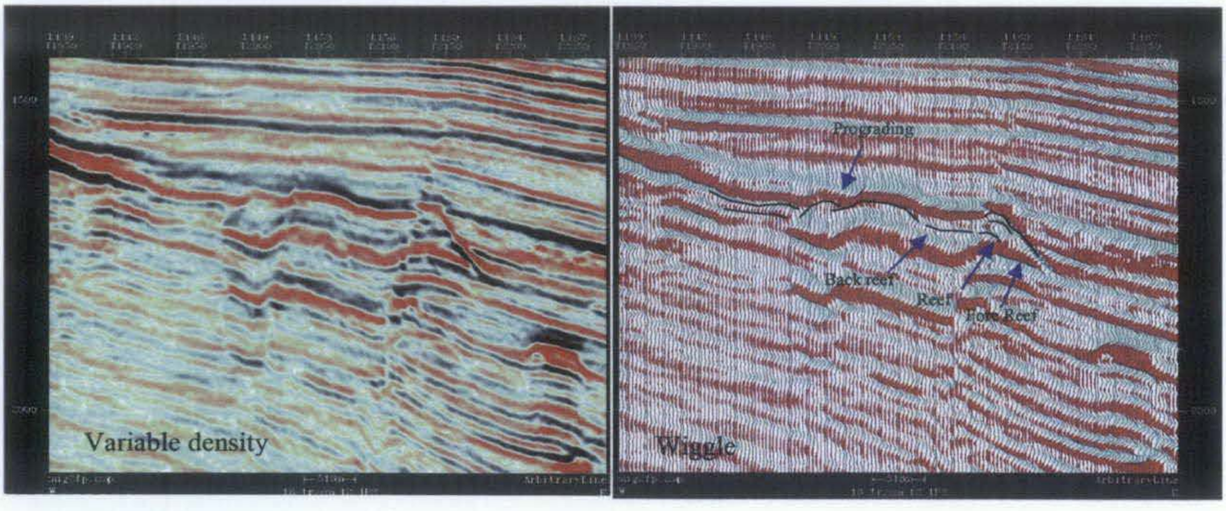


Figure 5.3. Variable density and wiggle display of reef, fore reef and back reef carbonate facies. Note: Prograding carbonate sequence is common in the study area.

According to Vahrenkamp (1998), the internal buildup architectures are related to paleowind direction. Windward margins are steep, remained more or less stationary through time and were probably reef lined. Leeward margins have bulging outlines and more gently sloping with an internal architecture that shows downwind progradation during highstand sea levels and upwind backstepping during periods of flooding.

For the seismic facies analysis, several seismic lines were selected and interpreted on both hard-copies and digital format. The observations from the seismic attributes analysis were also used to assist the facies recognitions. For example, the instantaneous phase attribute of buildups from the Top Carbonate illustrates a distinctive character between reefal and back reef facies (Figure 5.4 and 5.5), of which really show a significant difference between the parallel and mounded reflectors that corresponded to back reef and reefal / fore reef facies.

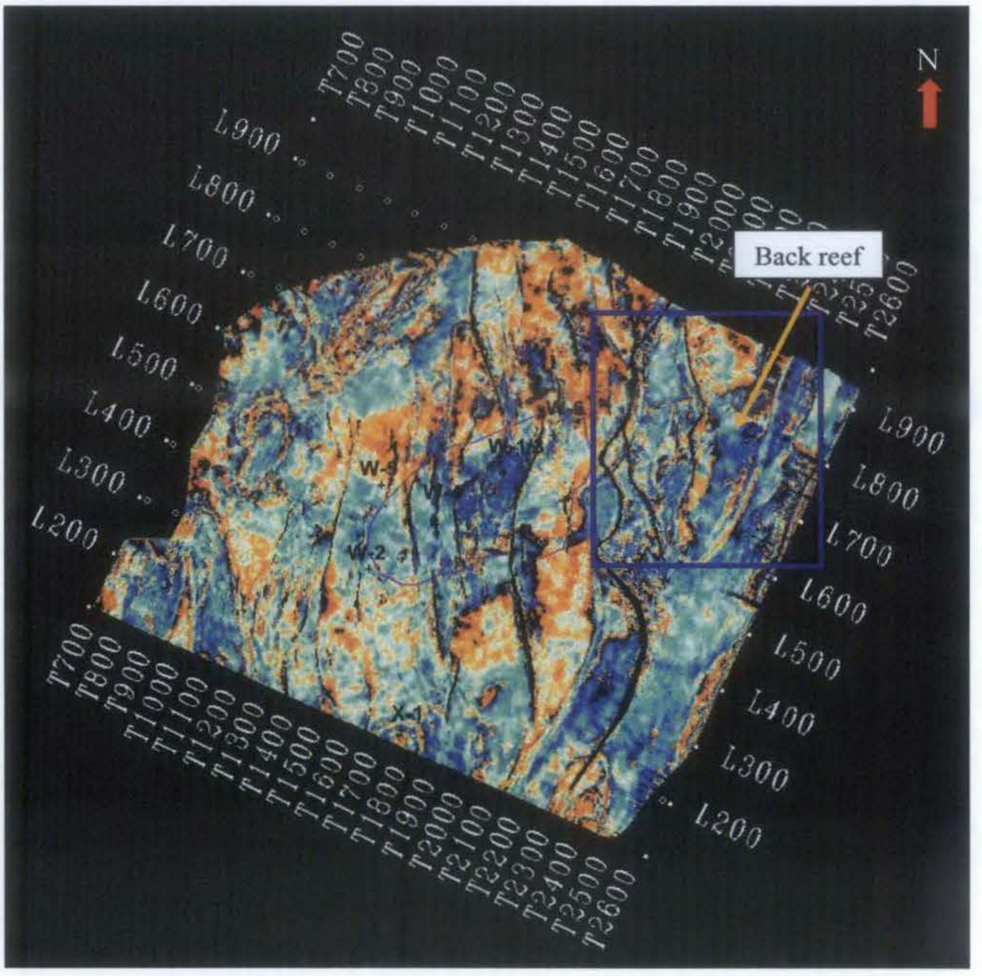


Figure 5.4. Average instantaneous phase of Top Carbonate (+20 to +30msec).

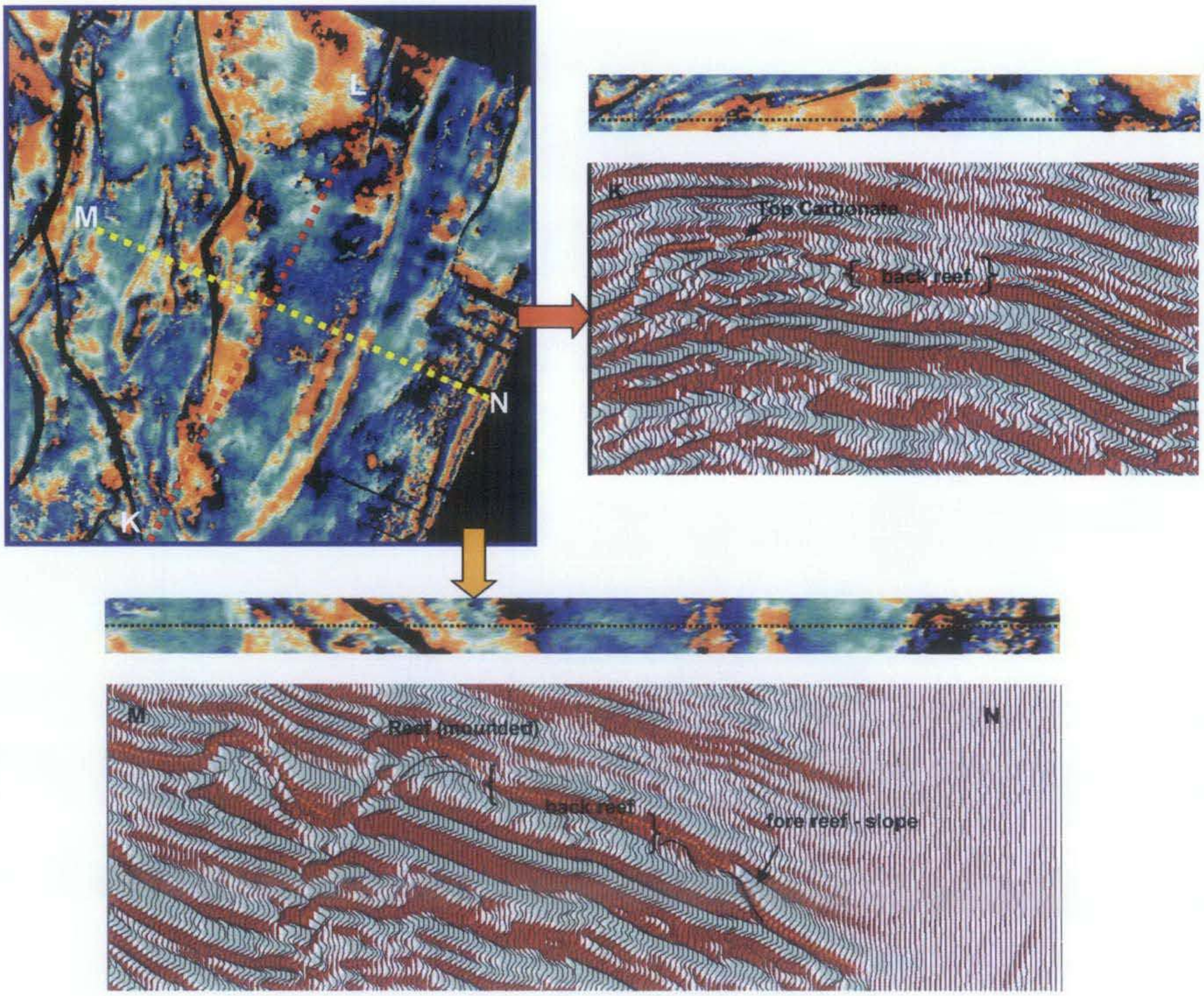


Figure 5.5. Close up view of the selected buildup from average instantaneous phase attribute (Figure 5.4). This attribute illustrating the back reef facies (lagoonal) displayed by continues parallel reflector which is prolific in the central area of the buildup. Reef / barrier mounded facies exist at the peripheral area of buildup.

5.2 Sequence Stratigraphy

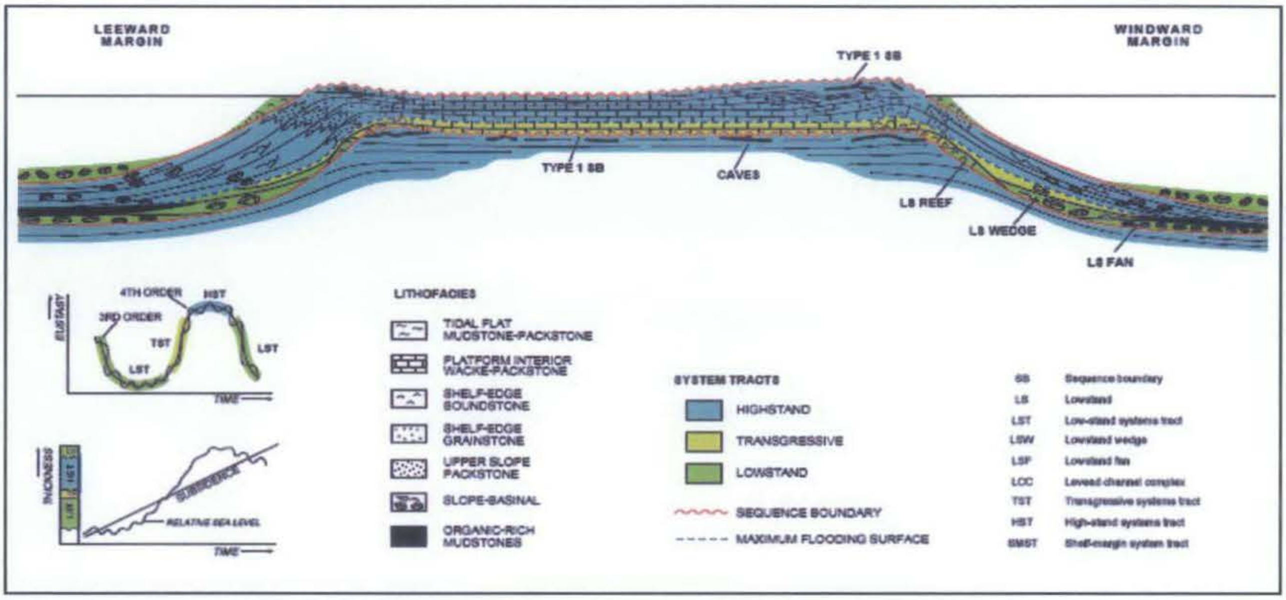


Figure 5.6. Depositional sequence model for isolated buildups (Handford and Loucks, 1993).

For the sequence stratigraphic study, most of the published models and schemes are referred to, including the "Exxon model" of Vail *et al* (1977), the genetic sequence stratigraphy of Galloway (1989) and other related publications. The carbonate sequence stratigraphic model of Handford and Loucks (1993) and Sarg (1988) are referred to and applied in the descriptions and documentation of sequence stratigraphy in the carbonate bearing intervals. The discussion of the stratigraphy and chronology make references to the global sequences of Haq et al., (1988).

Figure 5.6, conceptually illustrates the sequence stratigraphy of an isolated carbonate platform together with their contemporaneous depositional systems or systems tracts. The systems tracts are lowstand systems tract (LST), trangressive systems tract (TST) and highstand systems tract.

The lowstand systems tract forms during a fall of relative sea level. Irregular surface as a result of erosion and dissolution during subaerial exposure is identified as karst surfaces or sequence boundary (SB). The carbonates of the LST normally grow at the upper slope area as fringing reefs.

The trangressive systems tract is accumulated during the rise of relative sea level. The maximum point of sea level rise is known as the maximum flooding surface (MFS). The MFS can be recognized by the occurrence of downlap surfaces on seismic sections. The growth of carbonate during this period is not only seen as retrogradational pattern, but also aggradation or progradation patterns of the stack strata. This shows the relationship between the rate of carbonate production and the sea level fluctuations.

The highstand period is important for carbonate production. Due to high growth rate relative to slower sea level rise, progradation and sheddings are common due to limited accommodation spaces. The aggradational pattern is also observed that indicates the balance between the growth rate and the change of relative sea levels. For the isolated carbonate buildups, progradation occurred at the leeward margin.

5.3 Seismic Facies and Sequence Stratigraphic Interpretation

The sequence stratigraphic analysis was conducted only for the carbonate bearing interval covering the Top Carbonate and the Base Carbonate horizons. Three seismic lines were selected (A-B, C-D and E-F) with adjacent to W-2 and W-5 wells (Figure 5.7 and Appendix 5-8). A seismic stratigraphic unit used here, is defined as a recognizable continues package that can be traced laterally. These units were separated and grouped accordingly using sequence stratigraphic framework and further into appropriate systems tracts; - trangressive system tract (TST), lowstand system tract (LST) and highstand system tract (HST).

Two major sequences were identified (Sequence 1 and Sequence 2), bounded by three major sequence boundaries (Figure 5.10 & 5.11). Seven stratigraphic units (1-7) were recognized within the studied carbonate intervals (Figure 5.12). Sequence 1 (units 1-4) is characterized by predominantly TST and HST packages. This sequence is bounded at the top by a sequence boundary (Top TB 2.3) which is equivalent to the Top Cycle III marker (Figure 5.13). The TST units (1-2) shows a typical trangressive onlapping stratal pattern infilled the interbuildup area. However, the TST reefal systems are only developed in the southern area (near B) probably due to higher position of the southern compartment compared to the surrounding area. The highest growth of the carbonate facies in this sequence was during HST (units 3a-4), forming the amalgamated prograding packages. These thick prograding packages controlled the expansion of the buildups. In addition to that, the boundary between 3a and 3b units is only a minor sequence boundary (Appendix 8 and very localized, whereas the characteristic of unit 3b shows a typical TST with backstepping stratal packages.

Sequence 2 is characterized by thick HST units, indicates a major expansion period of the buildups. The prograding package (unit 6) extends laterally into interbuildup area. The duration for sequence 2 deposition is almost 5 m.a (Top Carbonate – Top Cycle III). In term of thickness, Sequence 1 and 2 are almost the same. The high carbonate production and stable relative sea level could be the factor for carbonate progradation to occurred. This sequence is overlain by the TST unit 7 which marked by Top Carbonate horizon.

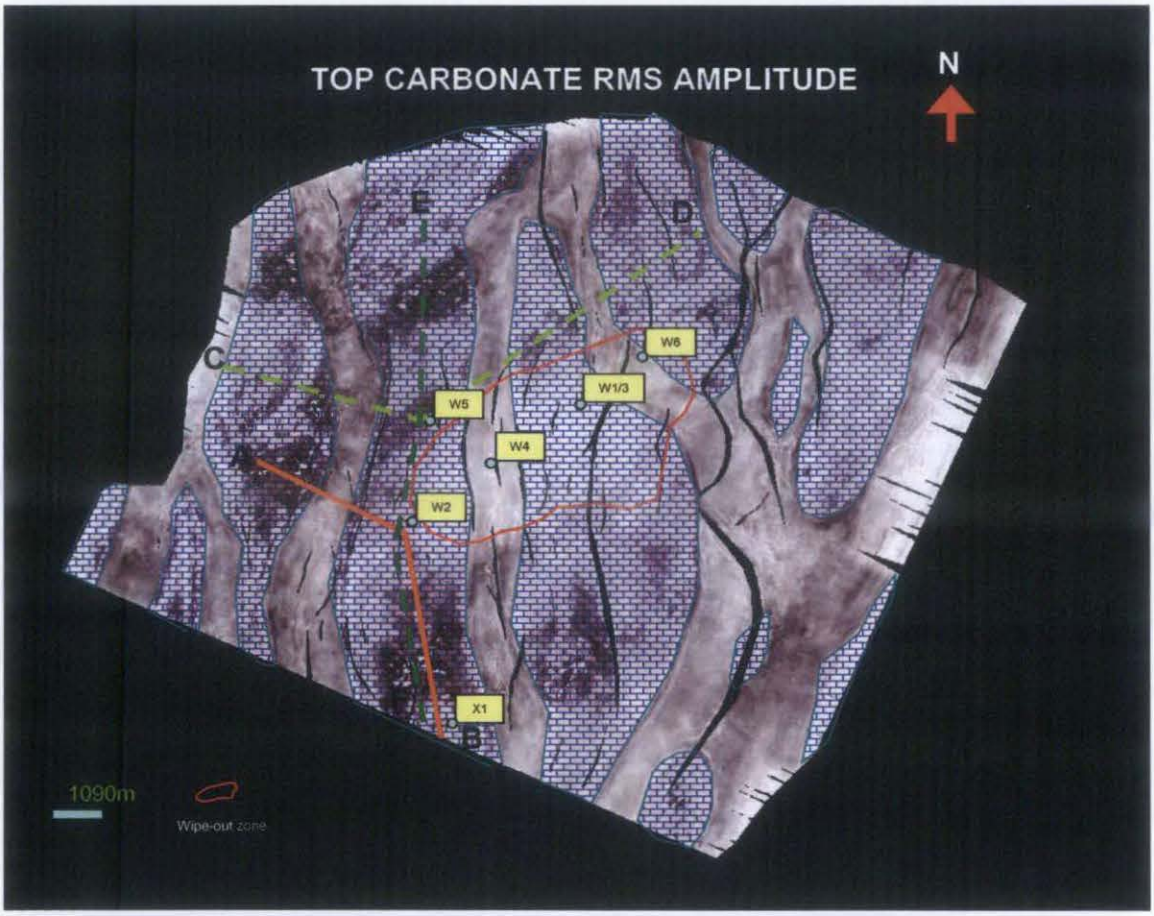


Figure 5.7. Three seismic lines were selected for the seismic sequence stratigraphy analysis. The lines were drawn across the W-2 and W-5 wells for better control from well data. A-B and C-D lines were tied using E-F line.

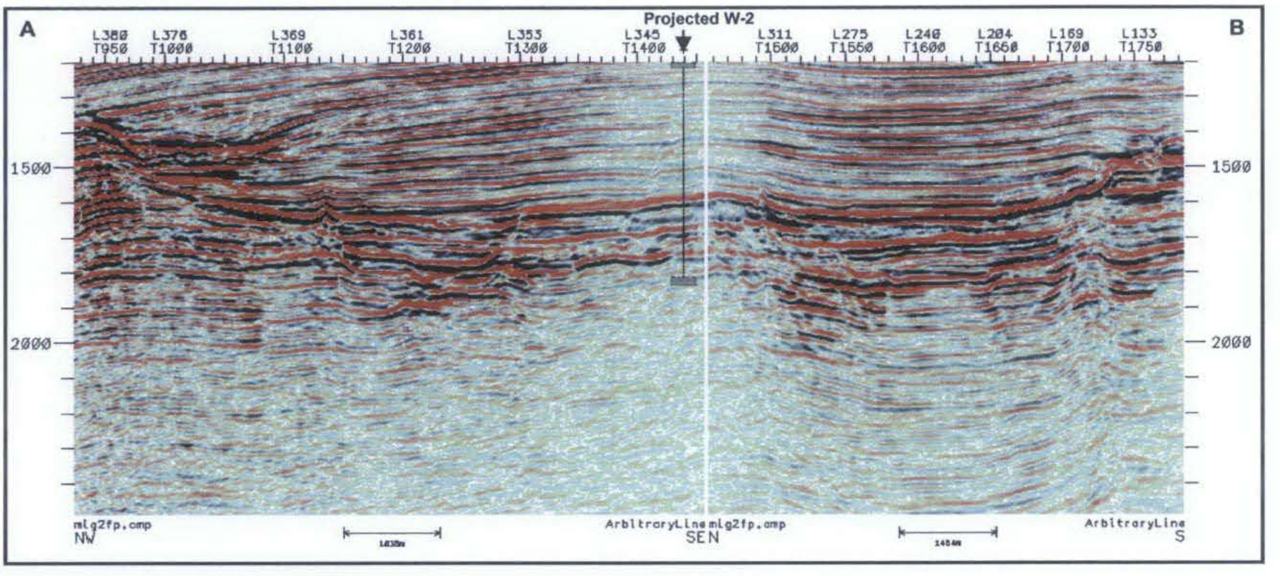


Figure 5.8. Arbitrary seismic line (A-B).

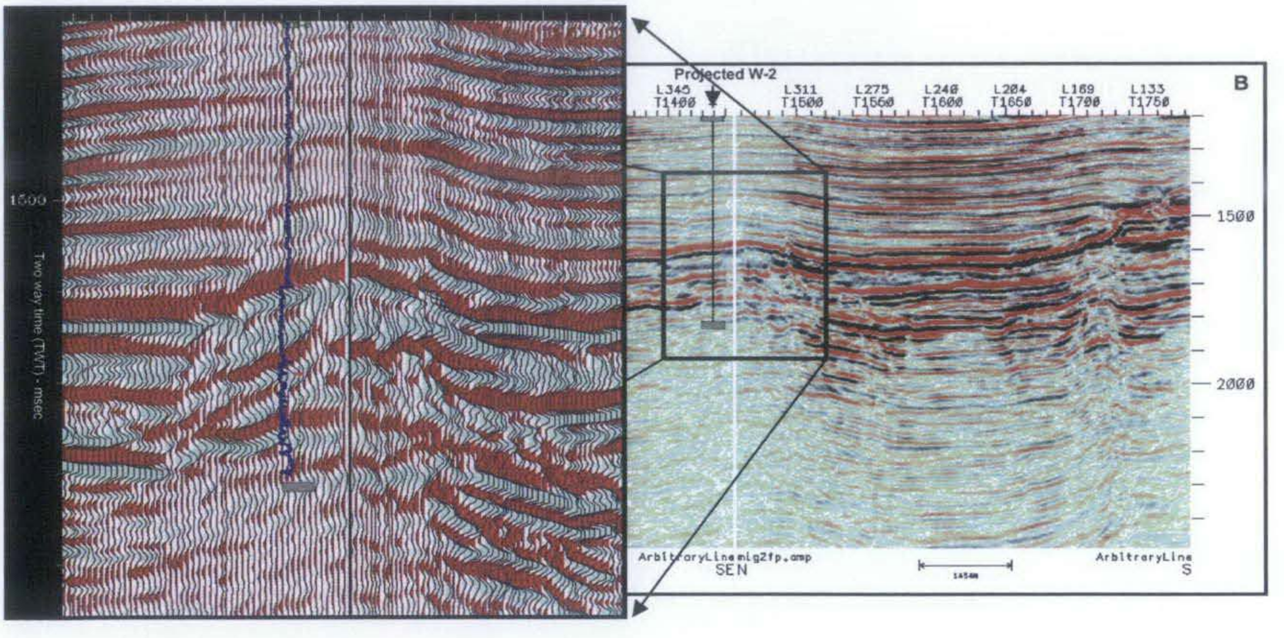


Figure 5.9. Arbitrary seismic line (A-B) with Gamma Ray log and wiggle display.

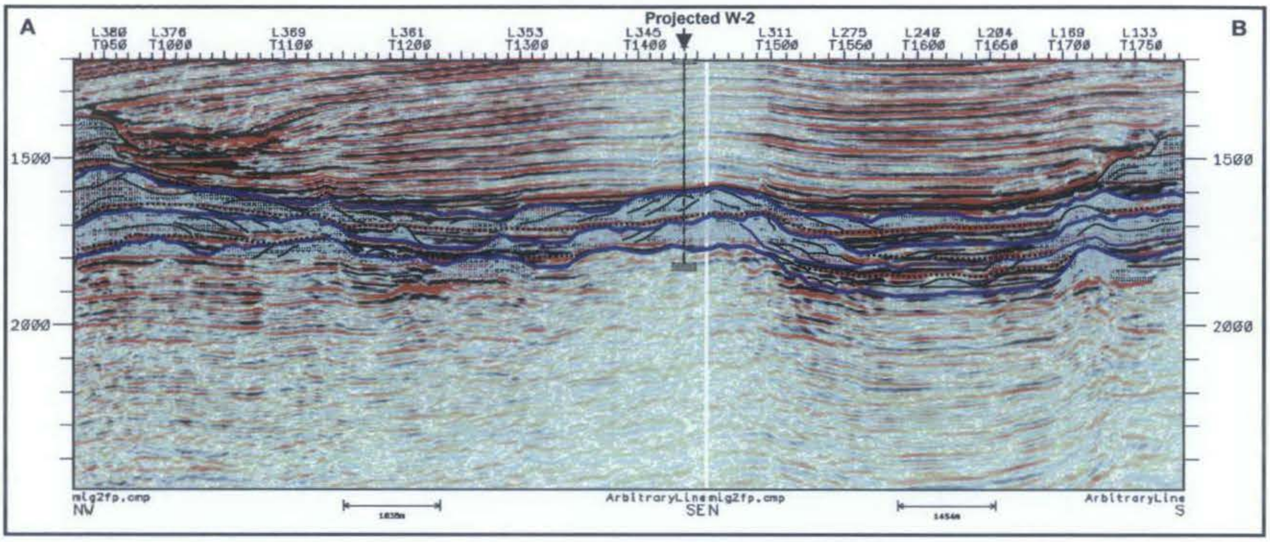


Figure 5.10. Geoseismic section (A-B), facies and sequence stratigraphic interpretation.

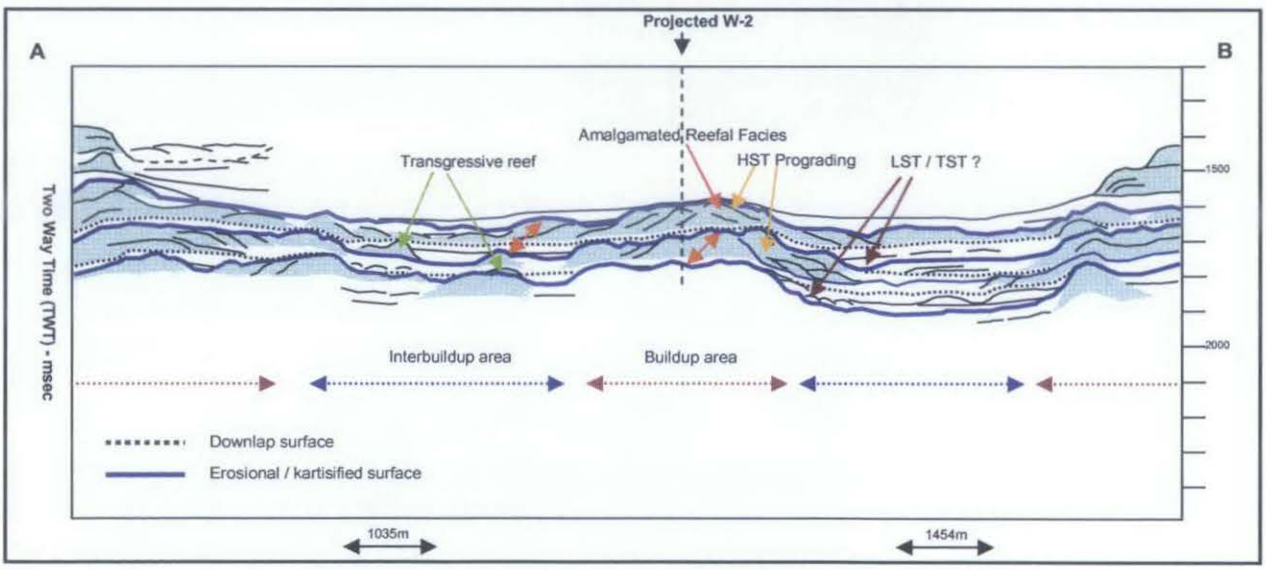


Figure 5.11. Seismic facies and sequence stratigraphy interpretation. Two major sequences are identified ( ), bounded by major erosional/karst surfaces.

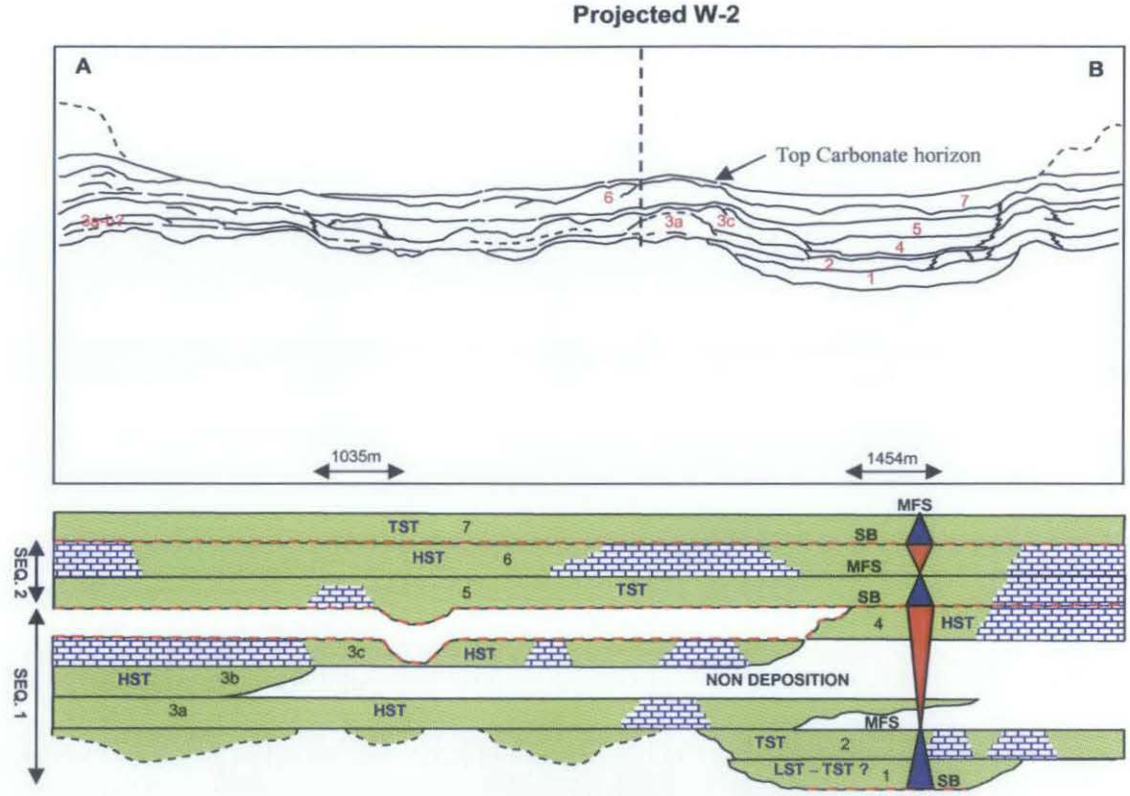


Figure 5.12. Sequence stratigraphic interpretation with unit subdivision. Thick prograding packages were developed during sea level highstand.

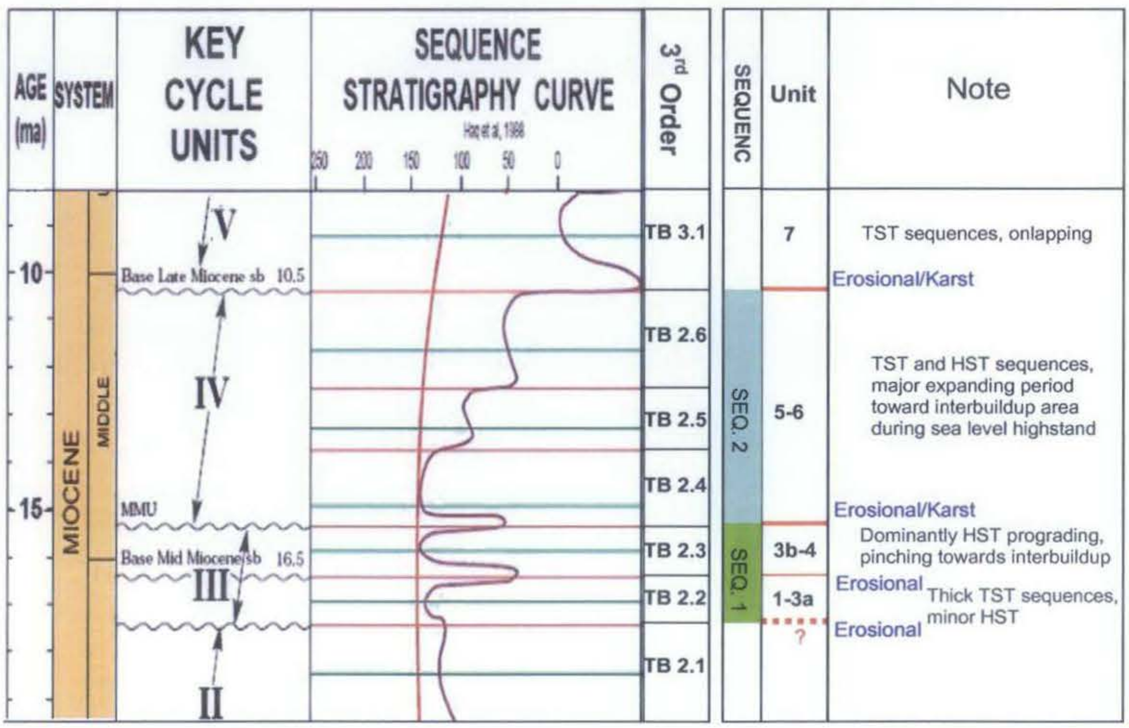


Figure 5.13. Global eustatic sea level curve (Haq. et al, 1988), units and sequence stratigraphic description for study area.

This analysis shows that the large and elongate geomorphology captured by RMS attribute (Top Carbonate) actually consists of several prograding packages that expand into the interbuildup area, developed during highstand sea level. Parts of these packages have been eroded or dissolved during subsequent sea level fall, which most of the strata were exposed subaerially. As a result, the exposed strata formed the karstified surfaces, which contained an enhanced porosity/permeability. On the seismic sections, the surface is characterized by irregular surfaces.

There is also and indication of slumping facies (see Appendix 6), in the form of broken fragments that had been dumped into low area of the down-throwned fault block. This process could be due to fault reactivation processess which has sheared-up the accumulated carbonate bodies. As suggested by Vahrekamp *et al.* (2004), the slumping occurred through the dissolution and bank margin collapsed. This is due to the alignment of the carbonate with the deep seated regional faults system, which periodically reactivated during carbonate growth.

Due to limitation of the seismic data resolution, most of the LST and TST are not readily differentiated. This could be related to the seismic frequency. For the dominant frequency of 30Hz, only beds with thickness greater than 30m will be resolved by the seismic. However, most of the captured images are TST and less of LST. The presence of TST buildups were not so extensive and it growth locally with smaller 'patch' geometry and shows a backstepps stratal pattern.

5.4. Evolution

Figure 5.14 shows the evolution of the carbonate buildups as described by Bachtel *et al,* (2004) in East Natuna, Indonesia. This model provides good analogues for the studied carbonate buildups. The four phases of buildups evolution are platform initiation and isolation, coalescence and expansion, backstepping and shrinkage, and finally drowning and burial.

The larger buildups evolved from smaller buildups on structural high. The horst blocks provide a suitable structural template for carbonate to grow. Initial growth form the 'patch' style geometry during Early Miocene, these low relief buildups then expand during Middle Miocene where progradational facies occupied the interbuildup area. Due to rapid sea level rises during the transgressive sea level, the buildup backstepped and their sizes shrunk. The growth of this low relief buildups were terminated at the end of Middle Miocene probably due to drowning. Contrary, the growth of 'pinnacle' type (high relief) took place after the termination of these low relief buildups during Late Miocene. However, the growth of this buildup is confined only in the western part of study area (Figure 3.8). This pinnacle type buildup was terminated in the middle Late Miocene. They formed on top of structural highs overlying the low relief buildups. Their morphological characteristic depicted as high area on the map of the Top Carbonate horizon.

As suggest by Epting (1980 & 1989) and Zampetti et al (2004), the growth of the Luconia's carbonate was terminated by gradual submerged (drowning) indicated by smooth, concentric seismic reflector forming a convex up mounded facies; with a rapid sea level rise accompanied by clastic input from the hinterland of Borneo. Vahrenkamp *et al* (2004) proposed two explanations for the ultimate demise of the buildups; first is due to drowning resulting from a combination of subsidence and eustatic sea level rise, and second by a much later drowning, which was preceded by a long period of exposure resulting from second order sea level fall.

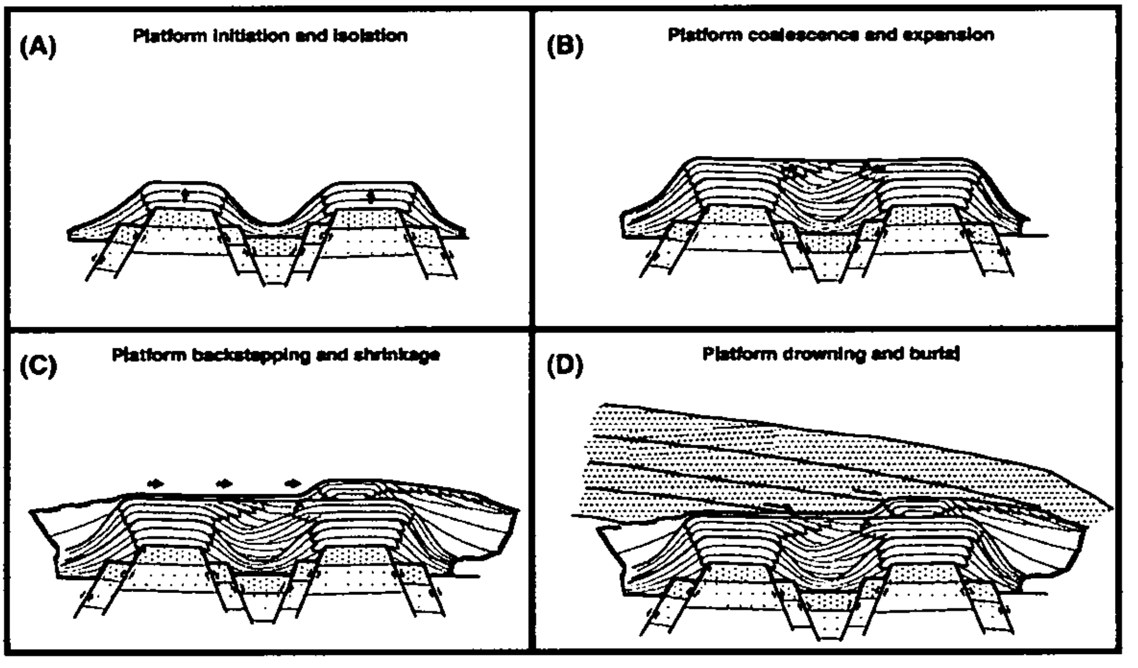


Figure 5.14. Analogy from Segitiga Platform (East Natuna, Indonesia) is used to explain buildup growth evolution in Central Luconia. (modified after Bachtel et al, 2004).

CONCLUSION

Through the application of seismic attributes analysis and sequence stratigraphy, the studied carbonate buildup has been analyzed, described and characterized in order to understand its evolution, facies type and facies distribution. The findings from this study will serve as reference for facies distribution, especially the reservoir facies, which would be significant in supporting the exploration and development of the associated hydrocarbon fields. This will contributes in lowering the exploration risks and also maximizing the returns.

The evolution of the studied buildup can be summarized into three development stages;

1. Early Miocene – Patch style, rounded and isolated buildup.
2. Middle Miocene – Elongated low relief buildup, expansion (progradational) occur in N-S orientation.
3. Late Miocene – Backstepping, and termination of low relief buildup. Growth continues with pinnacle geometry. Carbonates deposition end in the middle Late Miocene time.

There are three main factors that controlled the evolution and the architecture of the buildup in Central Luconia; tectonic (faulting and subsidence), rate of sea level change and paleowind direction. Horst and graben topography induced by extensional tectonics creates a major controlled on carbonate development in this area. The high topography of horst blocks provides the structural templates for the shallow water carbonate to be accumulated. Whilst, on the graben, the deep water carbonate facies thrived and forming the facies of the interbuildup area. The relative sea level controlled the architecture of the buildups. The thick and extensive carbonate buildup developed during highstand phase of relative sea levels. The major expansion occurred during the deposition of sequence 2 (Middle Miocene) where the carbonate production exceeds the rate of sea level rise and prograded into the interbuildup area. The paleowind direction controlled the direction of the carbonate expansion. The mounded facies occurred in the windward direction, whereas the progradational facies occurred on leeward side.

The carbonate facies within the studied buildup accumulated in two major sequences. In the lower interval, Sequence 1 is identified. It is characterized by thick trangressive and highstand packages. The upper boundary of this sequence is marked by a kartification surface, which is equivalent to TB 2.3. This surface is corresponded to a third order sea level fall in the Middle Miocene. The Sequence 2 in the upper interval is predominantly characterized by progradational facies, which marked the maximum expansion and coalescence of the buildups.

A good reservoir quality is likely to be found in the mounded (reefal), progradational facies and also in the facies associated with kartification processes that occurred during fallings of relative sea levels.

REFERENCES

Bachtel, S.L., R.D. Kissling, D. Martono, S.P. Rahardjanto, P.A Dunn, and B.A. MacDonald, (2004). Seismic stratigraphic evolution of the Miocene-Pliocene Segitiga Platform, East Natuna Sea, Indonesia: the origin, growth, and demise of an isolated carbonate platform, in Seismic imaging of carbonate reservoirs and systems: AAPG Memoir 81.

Badley, M.E. (1985). Chapter: Geology and Seismic Sections. Practical Seismic Interpretation. International Human Resources Development Corporation (IHRDC).

Davies, R.J., Posamentier, H.W., Wood, L.J. and Cartwright, J.A. (2007). (eds) Seismic Geomorphology: Applications to HC exploration and production. Geological Society of London, Special Publication, 277, 171-185.

Epting, M. (1980). Sedimentology of Miocene Carbonate Buildups, Central Luconia, Offshore Sarawak. Geol. Soc. Malaysia. Bulletin 12, August 1980, pp 17-30.

Epting, M. (1989). Miocene carbonate buildups of Central Luconia, offshore Sarawak, in A.W. Bally, ed., Atlas on seismic stratigraphy, V.3: AAPG Studies in Geology No. 27, p. 168-173.

Galloway, W.E (1989). Genetic Stratigraphic sequences in basin analysis II: Application to northwest Gulf of Mexico Cenozoic basin: AAPG Bulletin. V. 73, p. 143-155.

Handford, C.R., and Loucks, R.G. (1993). Carbonate depositional sequences and systems tracts; responses of carbonate platforms to relative sea changes, in Handford, C.R., and Loucks, R.G., eds., Carbonate Sequence Stratigraphy, recent developments and applications: AAPG Memooir 57, p. 3-41.

Haq, B.U., Hardenbol, J. and Vail, P.R. (1988). Mesozoic and Cenozoic chronostratigraphy and cycles of sea level change: In: Wilgus, C., Hasting, B., Posamentier, H., Van Wagoner, J., Ross, C. and Kendall, C. (Eds.), Sea Level Changes-an integrated approach. Society of Economic Paleontologists and Mineralogists, Special Publication 42, 71-108.

Mazlan Madon (1999a). Geological Setting of Sarawak. The Petroleum Geology and Resources of Malaysia. Petronas.

Mazlan Madon (1999b). Basin Types, Tectono-Stratigraphic Provinces, Structural Styles. The Petroleum Geology and Resources of Malaysia. Petronas.

M Yamin Ali and Abolins, P. (1999). Central Luconia Province. The Petroleum Geology and Resources of Malaysia. Petronas.

Sarg, J.F., (1988). Carbonate sequence stratigraphy. In: Wilgus, C.K, Hastings, B.S, Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C., Editors, 1988. Sea-Level Changes: an Integrated ApproachSoc. Econ. Paleontol. Mineral. Spec. Publ. **42**, pp. 155–181.

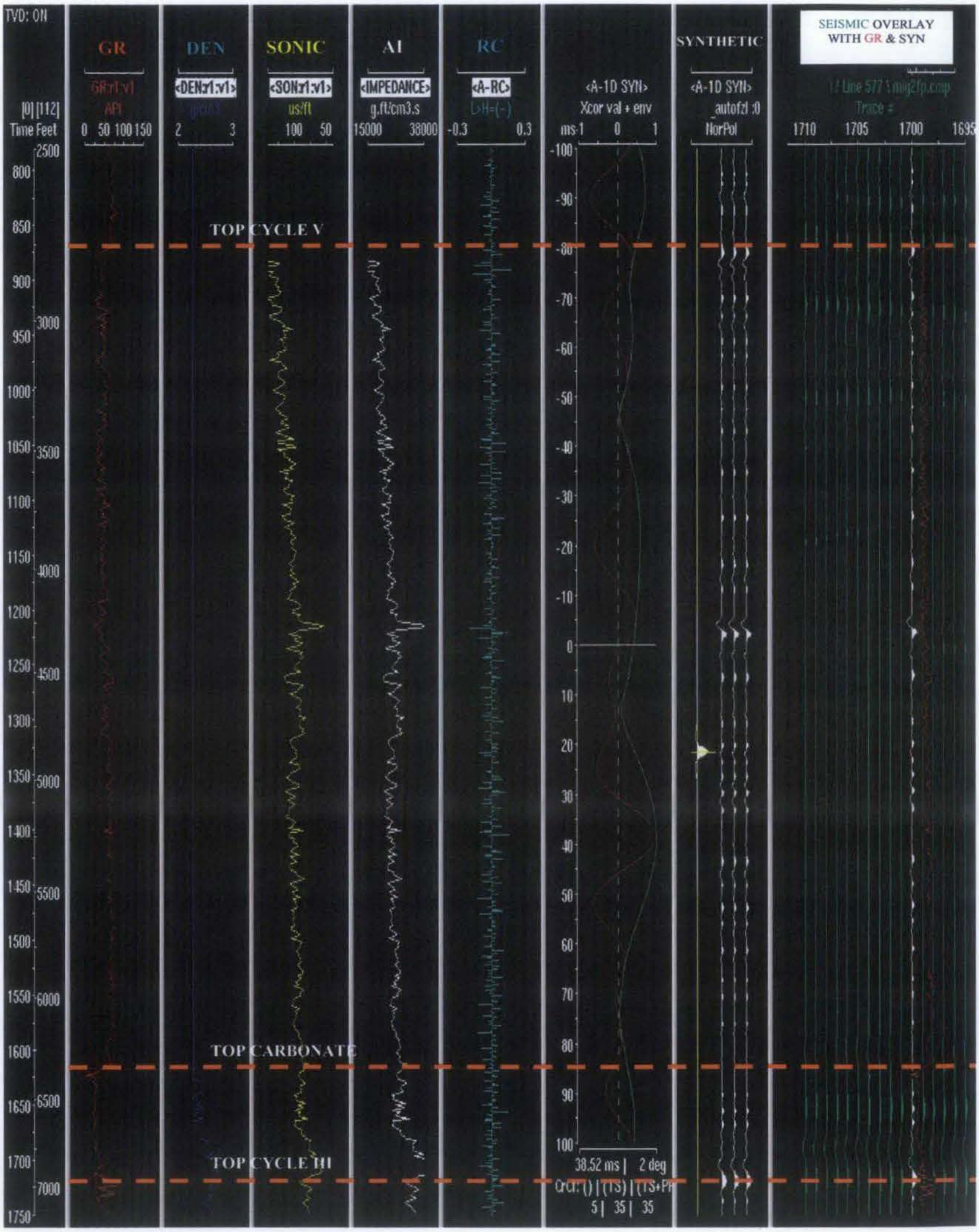
Vahrenkamp, V.C. (1998). Miocene carbonates of the Luconia province, offshore Sarawak: implications for regional geology and reservoir properties from Strontium-isotope stratigraphy. Geol. Soc. Malaysia, Bulletin 42, pp. 1-13.

Vahrenkamp, V.C., F. David , P. Duijndam, M. Newall, and P. Crevello. (2004). Growth architecture, faulting and karstification of a middle Miocene carbonate platform, Luconia Province, offshore Sarawak. Malaysia, in Seismic imaging of carbonate reservoirs and systems: AAPG Memoir 81, pp 329-350

Vail, P.R., Todd, R.G., and Sangree, J.B. (1977). Chronostratigraphic significance of seismic reflections, in C.E. Payton, Seismic Stratigraphy-Application to Hydrocarbon Exploration. AAPG Memoir 26, 160-168.

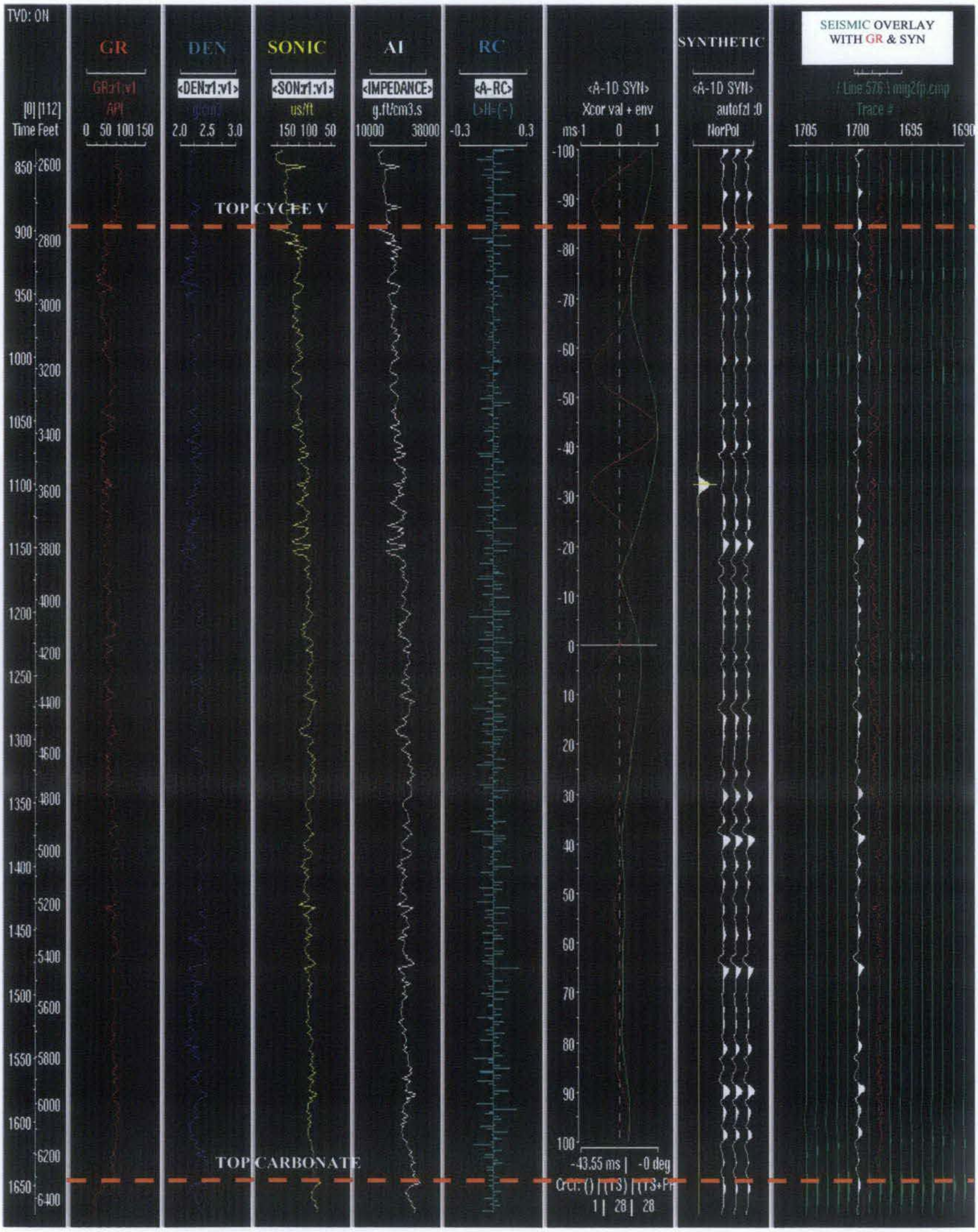
Zampetti, V., Schlager, W., Konijnenburg, J., and Everts, A.J. (2004) Architecture and Growth History of Miocene carbonate platform from 3D reflection data; Luconia Province, Offshore Sarawak, Malaysia. Marine and Petroleum Geology 21 pp 517-534.

APPENDIX 1



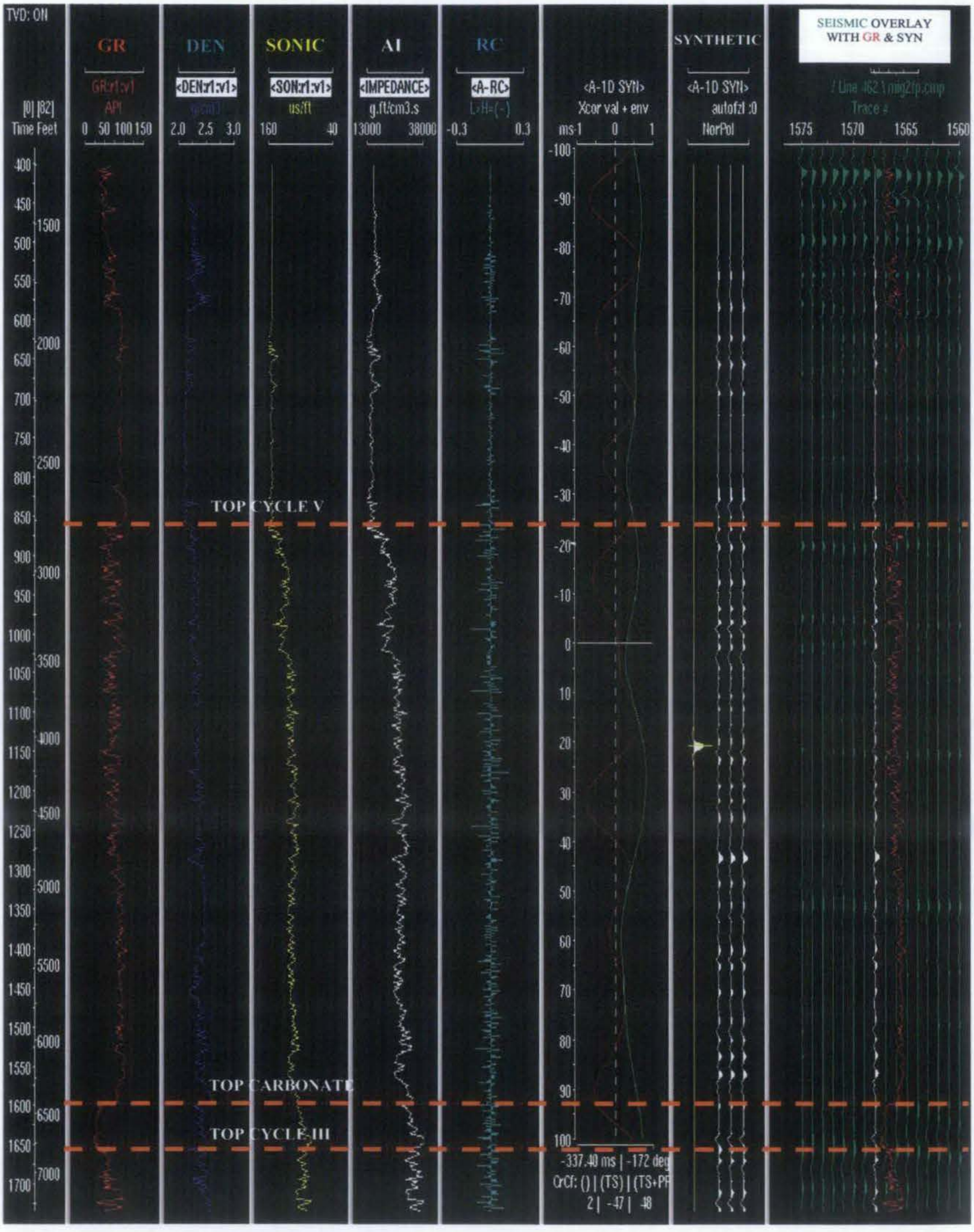
Synthetic seismogram for W-1 well. (Note: Density data only available in carbonate section)

APPENDIX 2



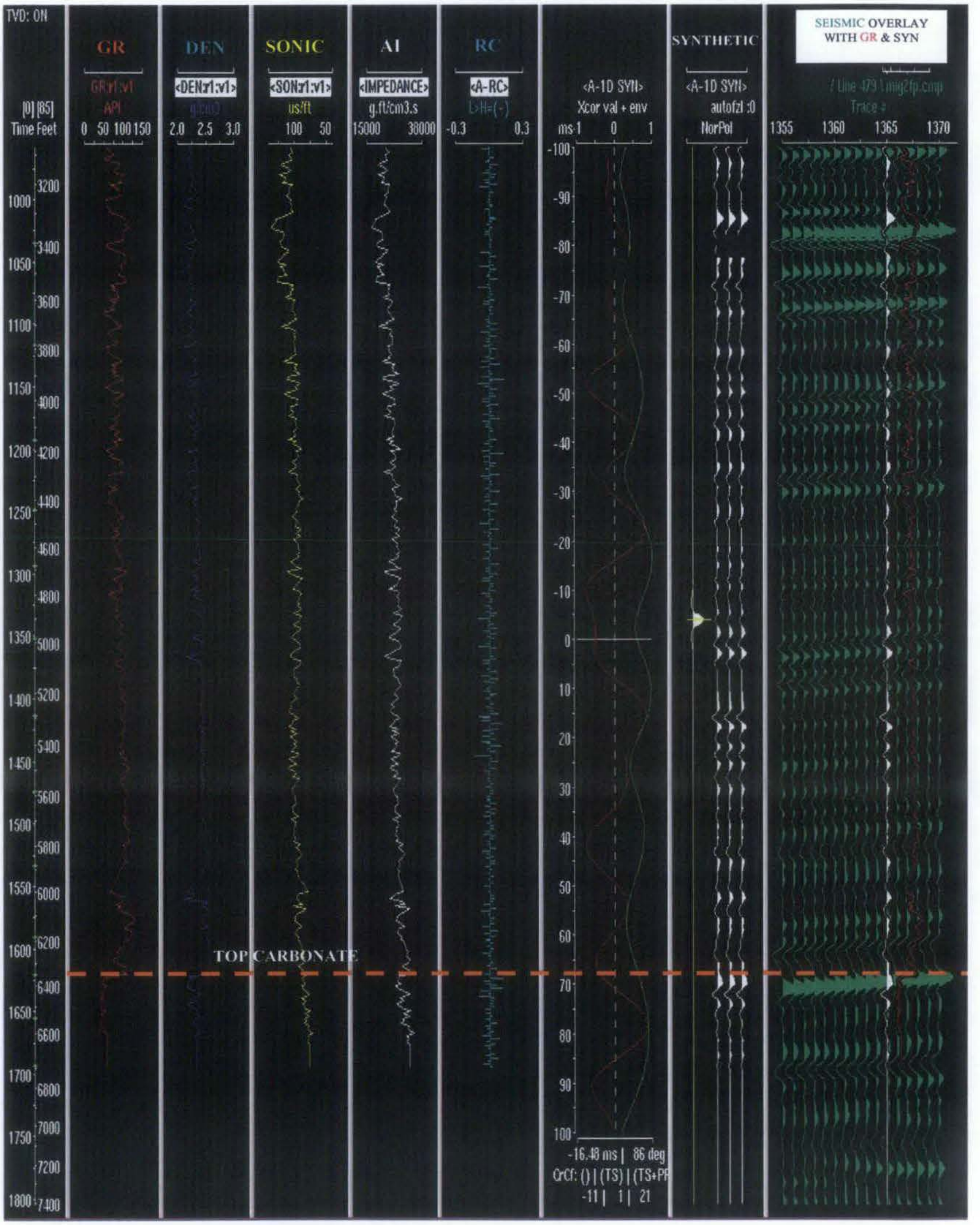
Synthetic seismogram for W-3 well.

APPENDIX 3



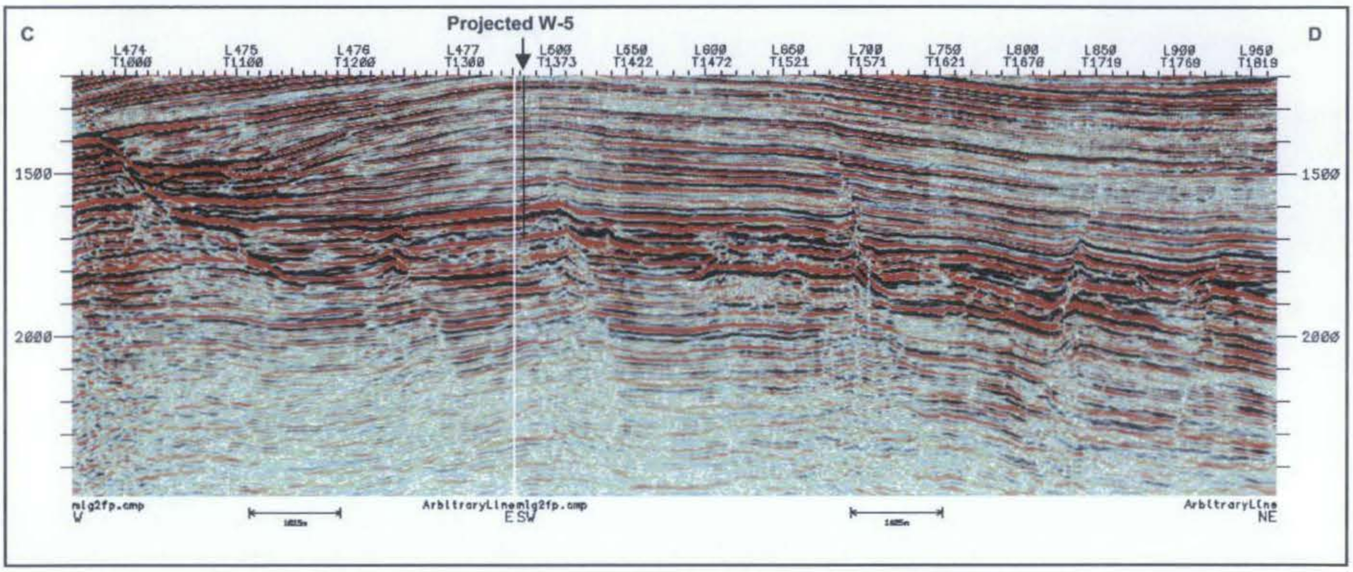
Synthetic seismogram for W-4 well.

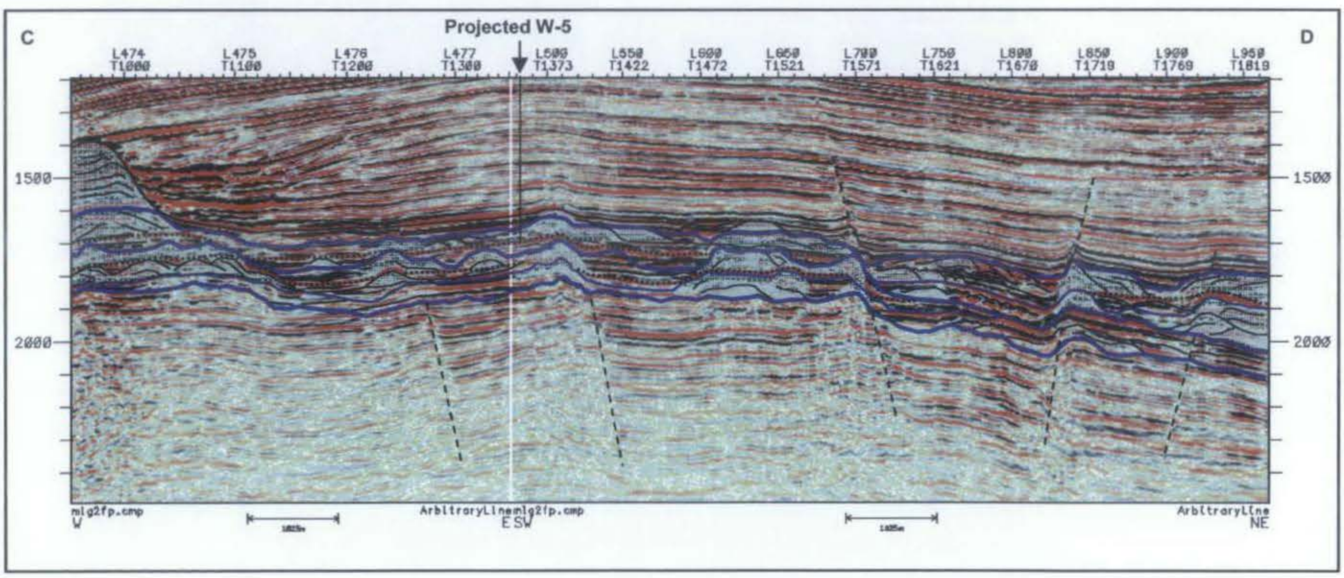
APPENDIX 4



Synthetic seismogram for W-5 well.

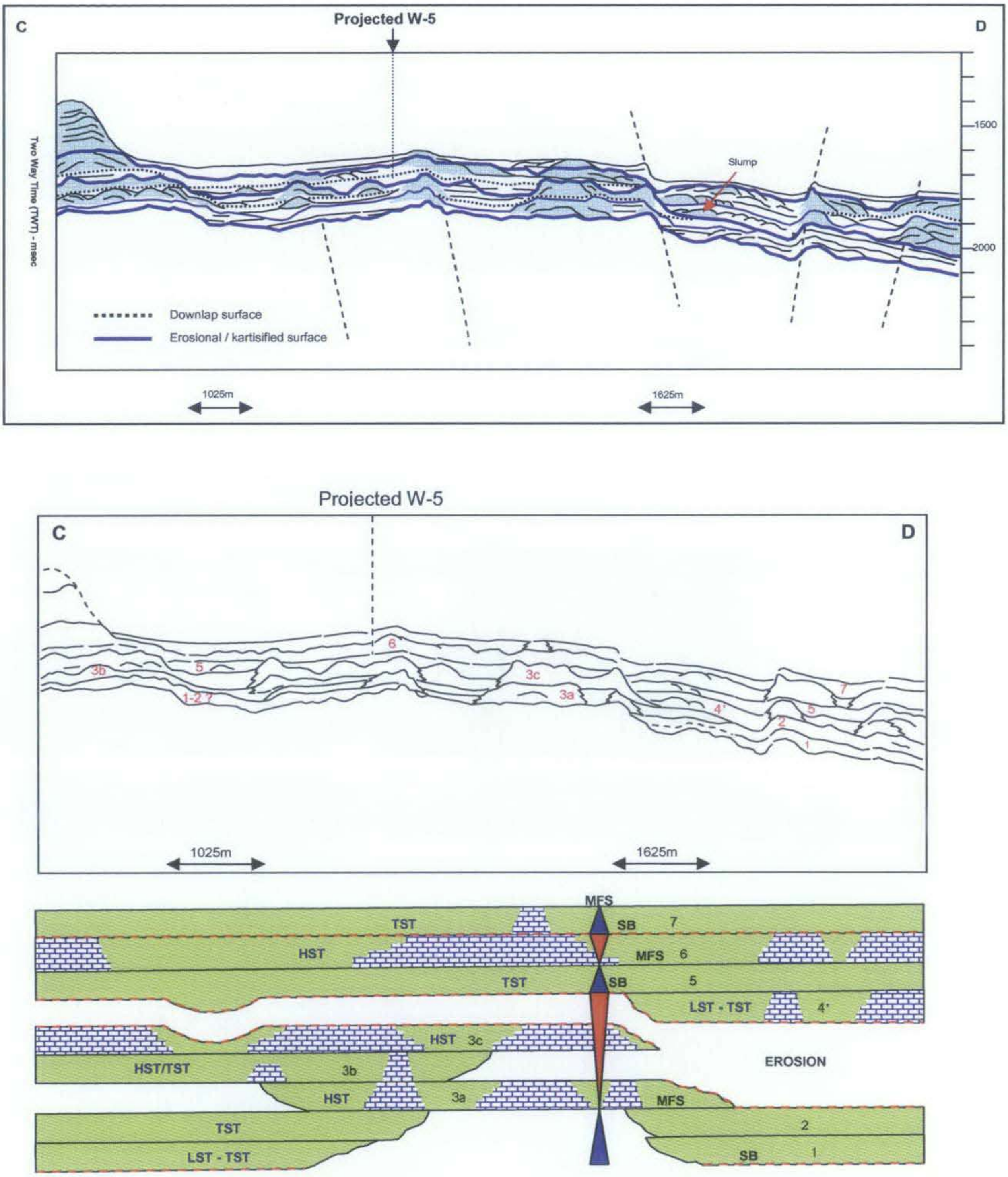
APPENDIX 5





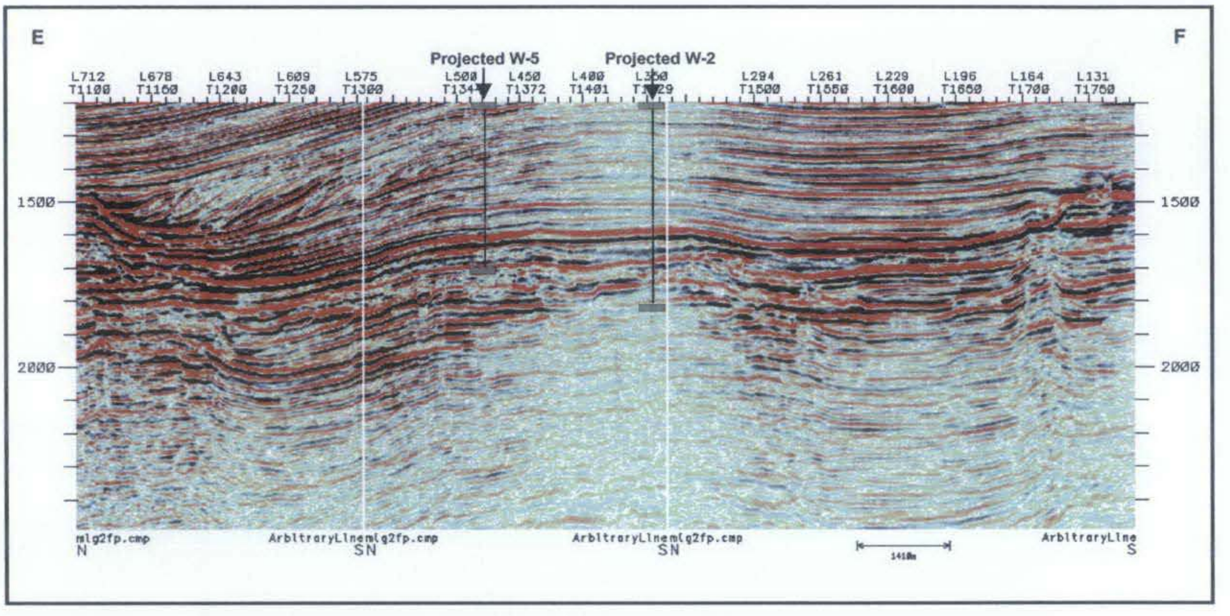
Arbitrary seismic line (C-D), with facies/stratigraphic interpretation.

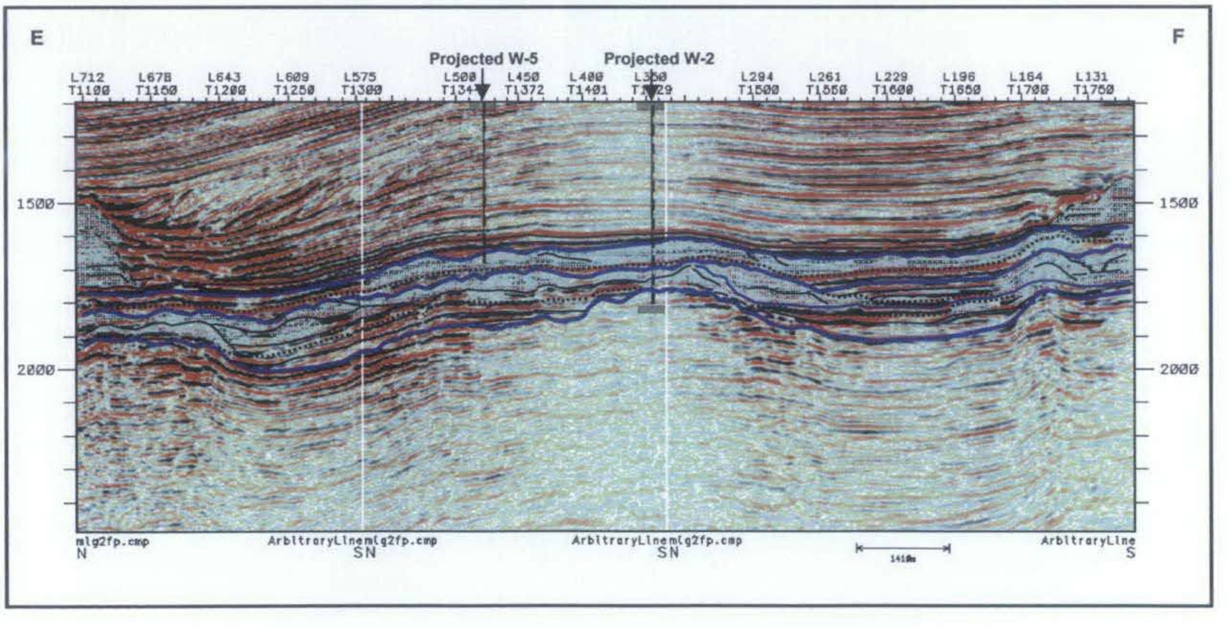
APPENDIX 6



Seismic facies and sequence stratigraphic interpretation (C-D).

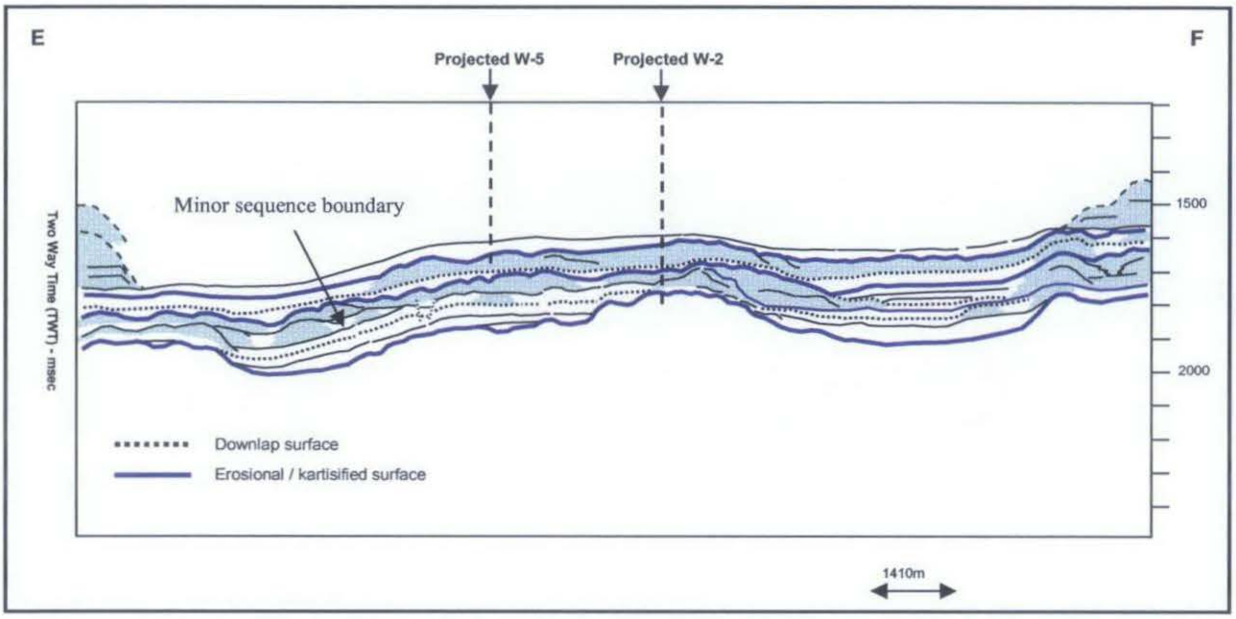
APPENDIX 7

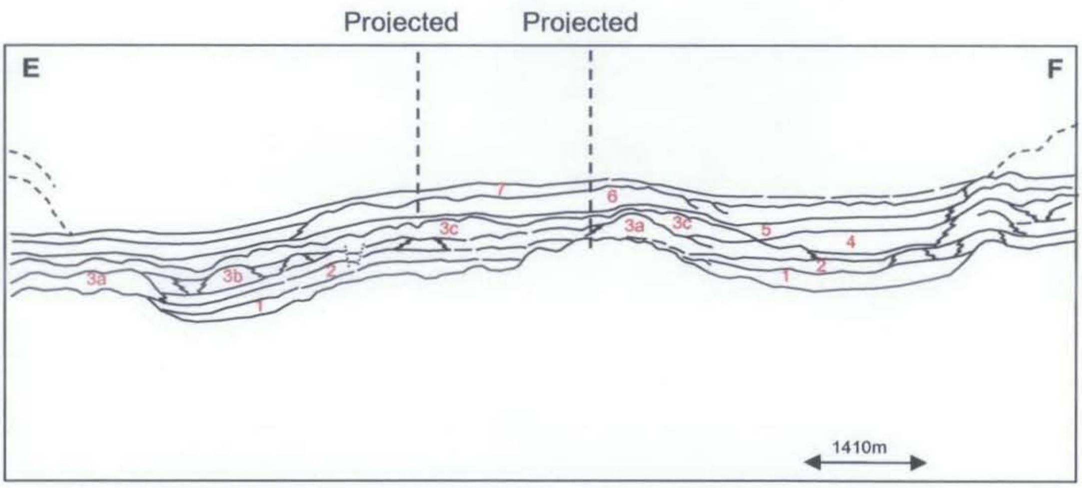


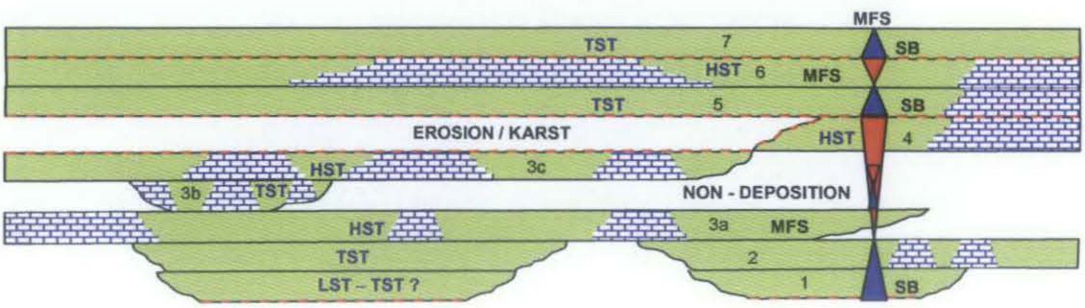


Arbitrary seismic line (E-F), with facies/stratigraphic interpretation.

APPENDIX 8







Seismic facies and sequence stratigraphic interpretation (E-F).