UNIVERSITY of the WESTERN CAPE

Electro Sequence analysis and sequence stratigraphy of wells E-M1, E-M3 and E-AB1 within the central Bredasdorp Basin, South Africa

By

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Abstract

The study area for this thesis focuses on the central northern part of the Bredasdorp Basin of southern offshore South Africa, where the depositional environments of wells E-M1, E-M3 and E-AB1 were inferred through electro sequence analysis and sequence stratigraphy analysis of the corresponding seismic line (E82-005). For that, the Petroleum Agency of South Africa (PASA) allowed access to the digital data which were loaded onto softwares such as PETREL and Kingdom SMT for interpretational purposes. The lithologies and sedimentary environments were inferred based on the shape of the gamma ray logs and reported core descriptions.

The sequence stratigraphy of the basin comprises three main tectonic phases: Syn-rift phase, Transitional phase and Drift phase. Syn-rift phase, which began in the Middle Jurassic during a period of regional tectonism, consists of interbedded red claystones and discrete pebbly sandstone beds deposited in a non-marine setting. The syn-rift 1 succession is truncated by the regional Horizon 'C' (1At1 unconformity). The transitional phase was influenced by tectonic events, eustatic sea-level changes and thermal subsidence and characterized by repeated episodes of progradation and aggradation between 121Ma to 103Ma, from the top of the Horizon 'C' (1At1 unconformity) to the base of the 14At1 unconformity. Finally the drift phase was driven by thermal subsidence and marked by the Middle Albian14At1 unconformity which is associated with deep water submarine fan sandstones. During the Turonian (15At1 unconformity), highstand led to the deposition of thin organic-rich shales. In the thesis, it is concluded that the depositional environment is shallow marine, ranging from prograding marine shelf, a transgressive marine shelf and a prograding shelf edge delta environment.

Declaration

I, Tegan Corinne Levendal declare that the **Electro sequence analysis and sequence stratigraphy of wells E-M1, E-M3 and E-AB1 within the central Bredasdorp Basin, South Africa** has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

X

Tegan Levendal

January 2015

Acknowledgment

Firstly, I would like to thank my Heavenly Father, without whom none of this work would be possible.

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Chapter 1

1.1) Introduction

The study area is located within the Bredasdorp Basin, situated offshore South Africa in a south easterly direction. The Bredasdorp Basin is southeast of Cape Town and west- southwest of Port Elizabeth (Figure 1.1). The basin covers about 18,000 sq. km in generally less than 200 meters water depth (Wood, 1995).

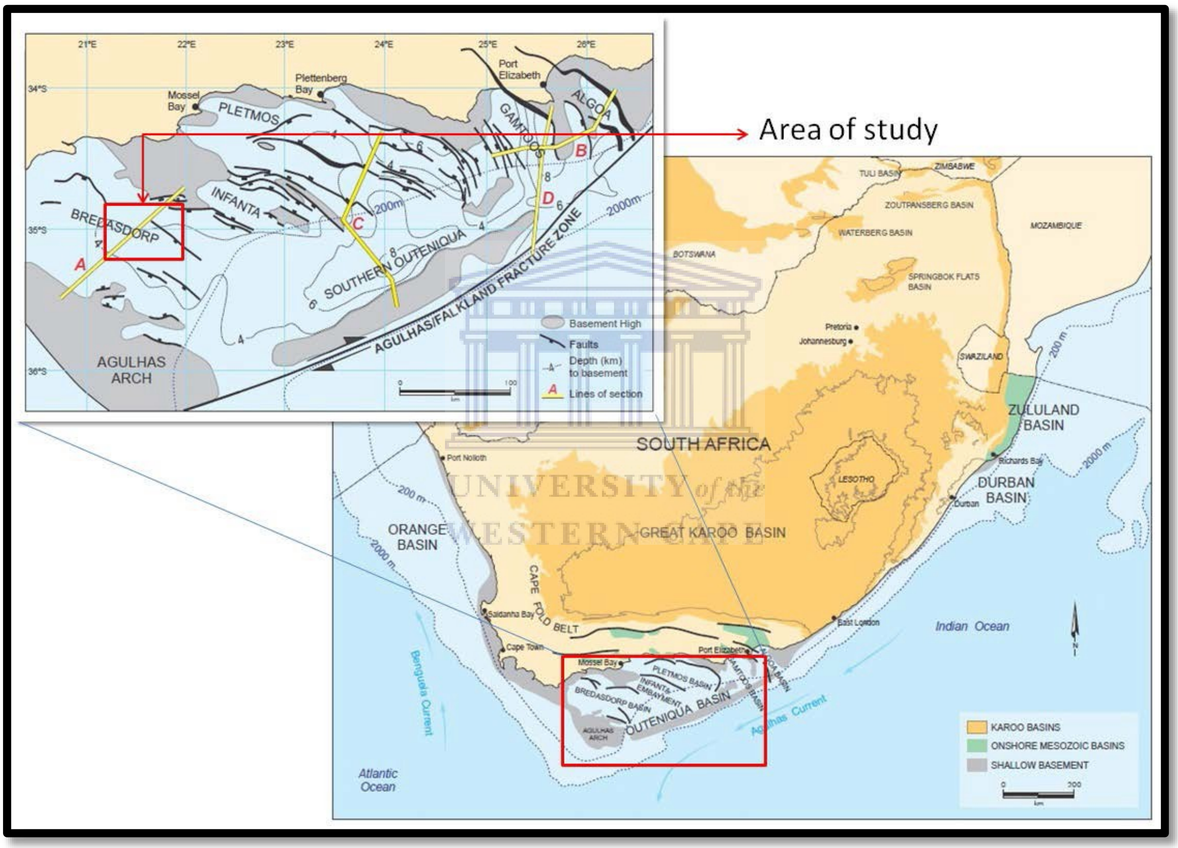

Figure 1.1: Western, eastern and southern offshore zones of South Africa (modified after Broad, 2004)

Electro sequence is defined as follows. Serra (1986) related the facies as seen by well log to the rock facies. He defined the term electrofacies as “the set of log response which characterizes the bed/litho unit and permits it to be distinguished from other. Electrofacies are observed to have certain well log shapes, a ramp shaped log response is termed as an electro sequence. An electro sequence is indicative of geological changes”. Serra noted that a ramp shaped log response may reflect:

a. A progressive change in mineralogical composition with depth.

b. The evolution of textural parameters

c. A simultaneous variation in mineralogical composition and in texture

d. A saturation transition between water and hydrocarbons.

In order to determine such geological processes, the identification and interpretation of electro sequences is needed. The trend of geological information in the electro sequence is shown by the logs itself. Therefore, methods that extract the electro sequences from wireline log information in the frequency domain will be studied.

Sequence stratigraphy is the study of genetically related strata within a chronostratigraphical framework (Van Wagner et al., 1990). Basically, sequence stratigraphy describes the vertical and lateral deposition of sediments in terms of relative sea level changes, where the key elements of sequence stratigraphy include the combination of lithostratigraphy, biostratigraphy and seismic data.

1.2) Aims and Objectives

Electro sequence analysis will be used to establish geological trends, by using the well log shapes, on the target horizons of wells E-AB1, E-M3 and E-M1 (Figure 4.1), in order to develop the depositional environment and relate it to the sequence stratigraphy of the Bredasdorp Basin. The objective is to extract enough information through electro sequence analysis by identifying vertically continuous depositional, stratigraphic and sequence stratigraphic units. From this information a particular stratigraphic model will be built for the three wells mentioned above.

For the sequence stratigraphical analysis, the interpretation will be based on the biotratigraphic data for fossil age related aspects, well log data, lithology of strata and seismic data. The work done for this thesis involved three steps. Step1, considering the tectonic setting (type of sedimentary basin) which is to be discussed in the regional setting of the Bredasdorp Basin. Step 2, discusses the palaeodepositional environment which is linked to the electro sequence analysis and finally Step 3, is concerned with analyzing and interpreting the sequence stratigraphic framework, which accounts for the surfaces and the strata that fill the basin. The use of wireline logs, seismic interpretation and geological reports of wells E- AB1, E-M1 and E-M3 contributed in achieving the aims and objectives of this thesis.

Chapter 2

2.1) Regional Geology

South Africa has a long coastline of about 3,000kms (PetroSA, 2004, 2005).Beyond the coastline, the different areas of the offshore environment are controlled by the continental margin, shallower continental shelf, a slope and the abyssal plain. Offshore southern South Africa, the continental shelf varies between 50-200km wide (Figure 2.1.1).

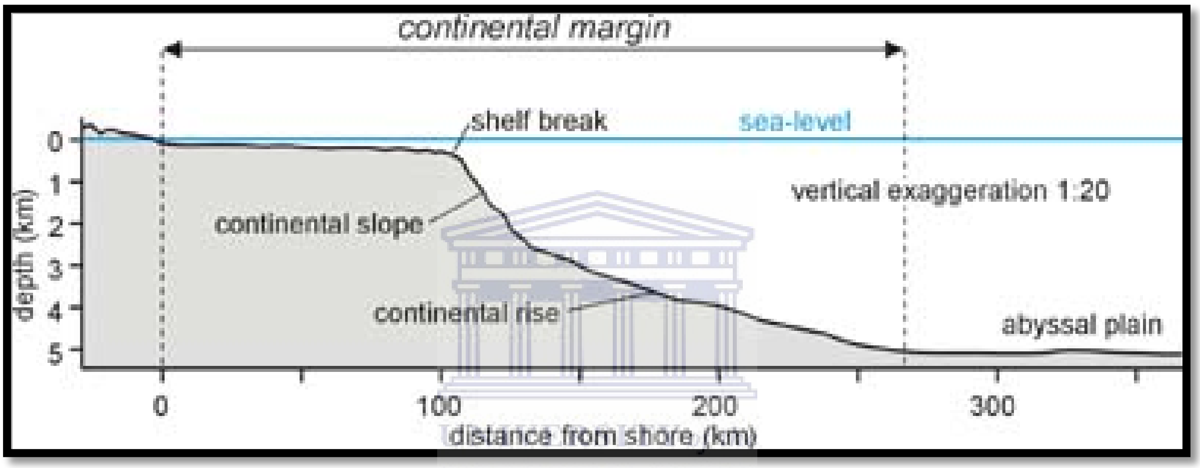

Figure 2.1.1: South Africa continental margin and oceanic crust (taken from http://www.classroomatsea.net/general_science/ocean_basins.html)

South Africa's offshore basins are passive margin basins, created during Gondwana break-up and the opening of the South Atlantic Ocean in the Early Cretaceous period (Brown et al., 1995). In the course of rifting, westward extensional stress resulted in swarms of parallel normal listric faults and half-grabens (Fig. 2.1.2, Brown et al., 1995; McMillan et al., 1997) with the thickness of the infill depending on the relative block offsets.

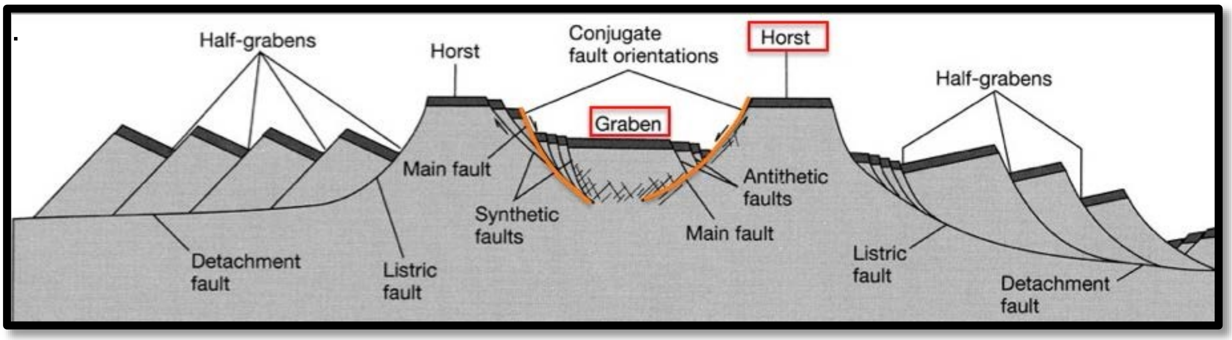

Figure 2.1.2: Formation of a half-graben from a set of parallel listric normal faults (taken from http://www.webpages.uidaho.edu/~simkat/geol345_files/conjugate_faults.jpg)

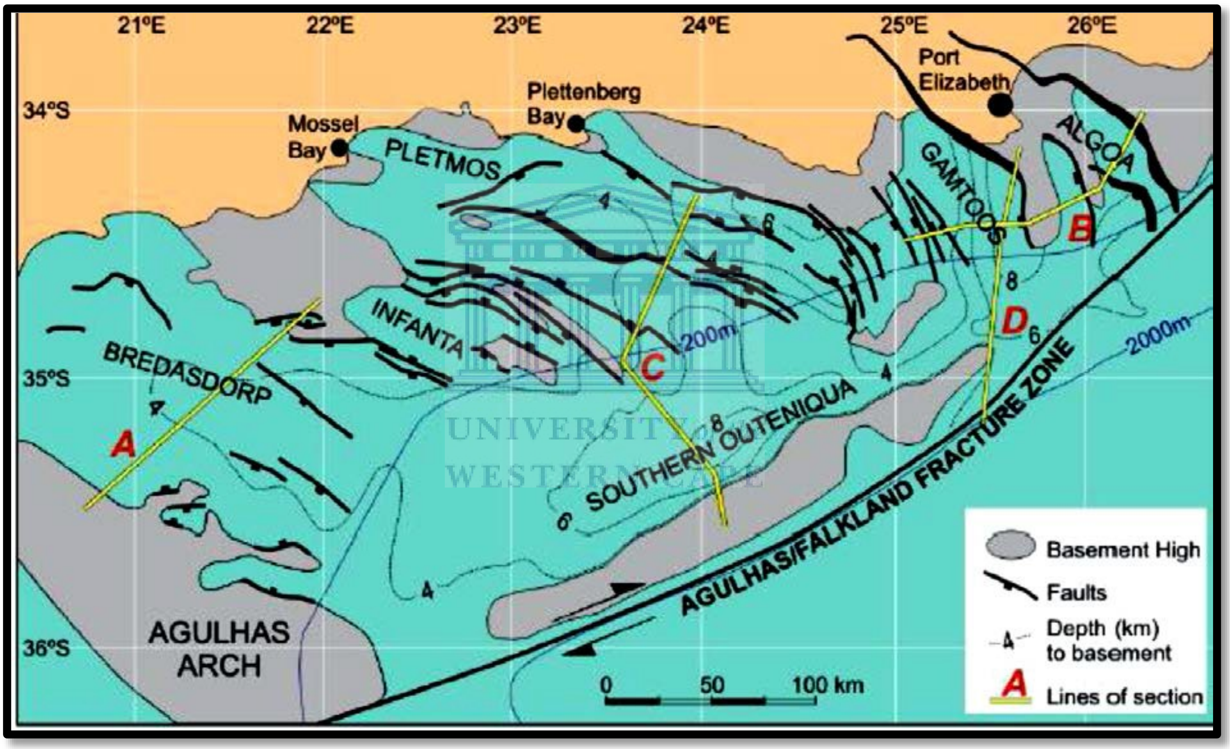

Figure 2.1.3: Locality map of southern offshore basins explored for oil and gas (courtesy of Petroleum Agency SA, 2003).

During the Early Cretaceous rifting, the same system of westward extensional stress controlled the movement along the Agulhas/Falkland Fracture Zone (Figure 2.1.3) giving way to a series of “en échelon” pull-apart sub-basins (McMillan et al., 1997) which comprises the main Outeniqua Basin (Figures. 1.1, 2.1.3).

These sub- basins are the Bredasdorp, Pletmos, Gamtoos and Algoa basins which are made up internally of half-grabens (Figure. 2.1.3); and filled with variable thicknesses of syn-rift and drift sediments.

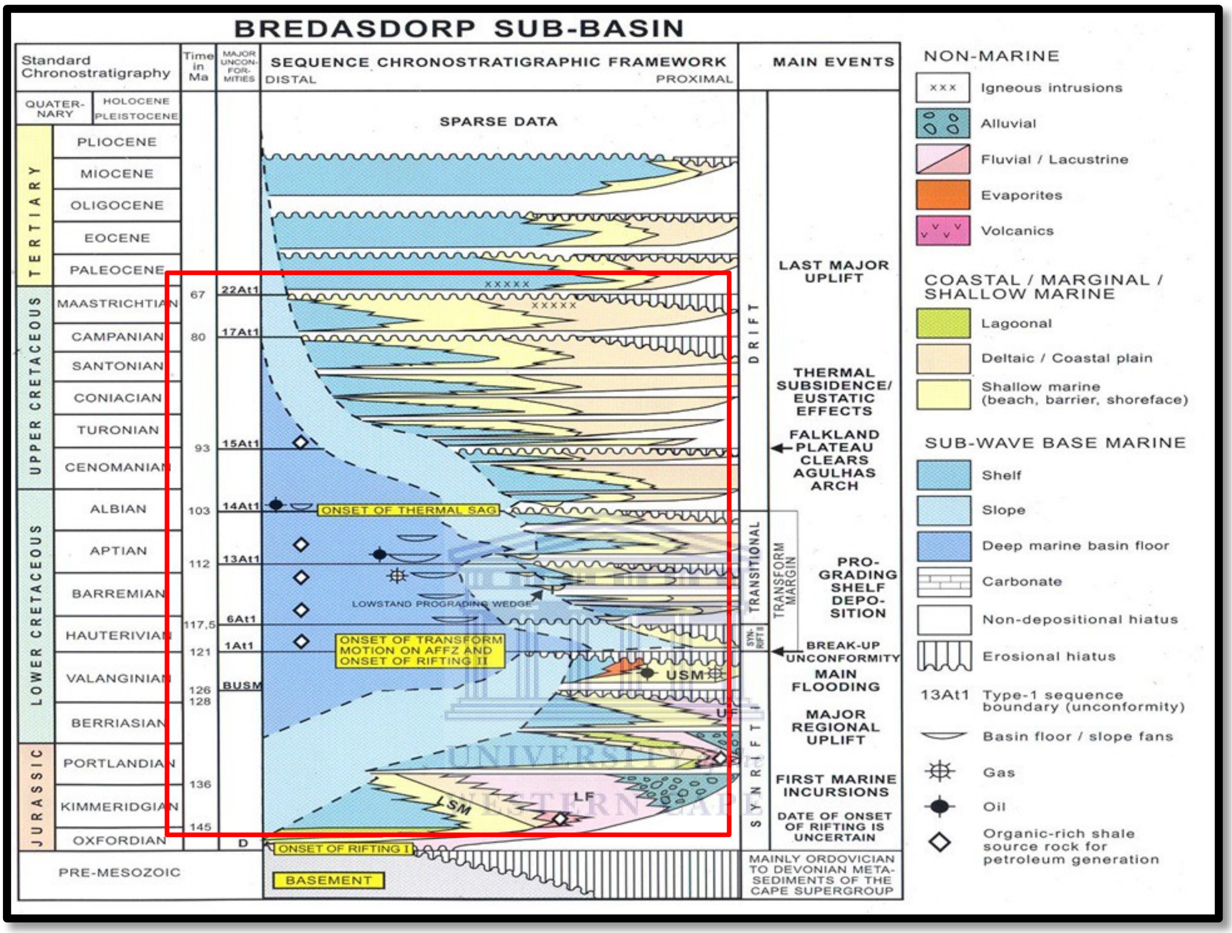

Figure 2.1.4: Chronostratigraphy of the Bredasdorp Basin. The red rectangle illustrates the tectonic events that played a role in the formation of the basin (modified after PetroSA, 2003).

Tectonic Setting and Stratigraphy

Breakup of Gondwana to the east caused dextral transtensional stresses (McMillan et al., 1997) which gave rise to normal faulting in the northern Agulhas-Falkland Fracture Zone. Syn-rift faulting between the Agulhas Arch and the Infanta Arch was northwest to southeast oriented and resulted in graben and half-graben basins

(Brown et al., 1995; McMillan et al., 1997). Sedimentation in terrestrial and marine environments continued from horizon D to horizon C (1At1) (Figure 2.1.4) until about ~103Ma, when most of the syn-rift faulting ceased and post-rift activity (tectonics, erosion, and deposition) commenced (Brown et al., 1995).

Paleotopographical control on sedimentation is apparent from horizon D to 14At1 (Figure 2.1.4; McMillan et al. 1997) as horsts and grabens both contain condensed units. During the rift phase, the sediment supply into the Bredasdorp Basin was sourced from the north and northeast, comprising of sediments derived from orthoquartzites and slates from the Cape Supergroup as well as sandstones and shales from the Karoo Supergroup (McMillan et al. 1997).

The 1At1 (Horizon C) unconformity was triggered by the uplift of the arches and horsts (Brown et al., 1995) and the end of the most active rift sedimentation (McMillan et al., 1997). Sequences 1At1 to 13At1 were formed by a combination of reactivated normal faulting and continued deposition of syn-rift onlap-fill sequences (McMillan et al., 1997). This cycle occurred predominantly in the central Bredasdorp Basin between 126-103 Ma (Brown et al., 1995), which coincided with late syn-rift activity in the subsiding basins. This subsidence was initially rapid (1At1), but started diminishing towards the end of the supercycle (Brown et. al., 1995; McMillan et al., 1997).

Erosion occurred during this time and carved submarine valleys and canyons into pre-1At1 units, providing channels for sediment supply into the deeper basin from the northwest, west and southwest (McMillan et al., 1997). The onset of unconformity 6At1 was also triggered by uplift (Brown et. al., 1995). Turbidity currents dominated the sediment influx into the central basin from 5At1 to 13At1, when that area lacked sufficient water circulation and oxygen (McMillan et al., 1997).

The second supercycle of the syn-rift stage gave way to third-order cycles 6-12 between 117.5-112Ma (Brown et al., 1995). Regional subsidence at high rates produced sequence 6A and as subsidence rates and faulting slowed down (115.5-112Ma) the deposition of system tracts 8-12 occurred, with sequence 7 removed by 8At1 erosion (116-115Ma) (Brown et al., 1995).

Since Early Aptian (112Ma) to Mid-Albian (103Ma) the sea level dropped causing the erosion of highstand shelf sandstones and the deposition of turbidities (coming from west to southwest) in the centre of the basin (Turner et al., 2000). These sediments formed channels and lobe systems with coarsening-upwards fan lobes and amalgamated fining-upward channel deposits (Turner et al., 2000). These channels dominate the western to south-western area, while the fan lobes dominate the eastern part of the basin (Turner et al., 2000). Aptian source rocks can be found in the south of the basin due to a submarine channel (5km wide and 50km long) with updip tributaries that transferred sediments to the south (McMillan et al., 1997). Organic material is predominantly type II with a type-I component (Van Der Spuy, 2000). The channel of 13A forms the site of oil accumulations according to McMillan et al. (1997).Sequence 14A contains basin floor-fan sandstones in the centre of the basin with some oil bearing reservoirs (McMillan et al., 1997).

Late Cenomanian (Figure 2.1.4) shows erosion, marked by unconformity 15At1, with minor warping and some uplift (McMillan et al., 1997). Erosion was at a maximum in the most eastern part of the basin. Shale found immediately above 15At1 (Figure 2.1.4) contains a high amount of plankton and other organic materials with little source rock potential for the southern part of the basin (McMillan et al., 1997). Progradation occurred between Turonian and Mid-Coniacian times. A domal structure was formed in the south eastern Bredasdorp Basin around the Cretaceous period (Figure 2.1.4). Since the Tertiary (67Ma) until the present, sedimentation of a highstand shelf comprising of glauconitic clays and biogenic clays with minor sands occurred. These sediments were derived from the erosion of the Agulhas Arch flanks (uplifted during the Late Cretaceous-Early Miocene period). When this uplift stopped, it caused biogenic clay to settle over the southerly parts of the basin (McMillan et al., 1997). Overlying the Miocene deposits, Late Pleistocene and Holocene unconformities are found once the upliftment stopped. (McMillan et al., 1997).

The Bredasdorp Basin went through two syn-rift phases resulting in two sequences which are separated by a Type 1 sequence boundary (Figure 2.1.4). The first syn-rift phase occurred during the Late Middle Jurassic-Early Cretaceous (157.1Ma-121 Ma) and the second one during the Hauterivian (121.5Ma-117.5Ma). Afterwards, a transitional phase (117.5Ma to 103Ma) was recorded. This transitional phase controlled the deposition of a lowstand prograding wedge near the shelf edge and of the basin floor fans and slope fans towards the deepest part of the basin (Figure 2.1.4). At this point of the transitional phase the main organic-rich shale with a good potential as oil source rock was deposited. Finally, the onset of thermally induced sag, recorded by the unconformity 14At1, points to the beginning of the drift phase in the Bredasdorp Basin.

2.2) Source rock maturity

In order for oil and gas to accumulate, an organic rich source rock needs to be present, and porous and permeable reservoir rocks are needed to store the accumulated oil and gas. A system of traps and seals also has to be present to prevent the oil and gas from escaping. For a rock to be referred to as a petroleum source rock it must have the correct quality and sufficient quality of dispersed organic matter, and be thermally mature.

The Bredasdorp Basin is rich in gas and oil prone marine source rocks of Kimmeridgian to Berriasian age (Broad, 2004). The Bredasdorp Basin contains deep marine origin source rocks situated in the transitional rift-drift sequence.

2.3) Production history

Sandstone reservoirs are present in both the syn-rift and drift sections. Reservoirs are shallow marine to fluvial deposits. The drift sandstones are deep marine turbidite deposits. The trapping mechanisms within the syn-rift are structural, whereas the drift marine shale creates the main seals. (Broad, 2004)

The first exploratory well, F-1, was drilled during the 1970's. Gas was encountered within shallow marine sandstones. However, reservoir quality was relatively poor. During the late 1970's, Soekor drilled several syn-rift structural highs beneath the rift/drift unconformity (1At1) showing gas. During the 1980's, Soekor followed up with F-2 borehole (on the same structure as F-1), discovering porous and permeable shallow marine reservoir sandstones. This discovery gave rise to 26MMscfd of gas and a total of 1200 st- tk b/d natural gas liquids. (Burden, 1992)

The F-A gas fields form the Mossel Bay Gas Project, producing 25000 b/d of petrol and diesel for more than 25 years. Along the Southern Flank of the basin, various syn-rift structural highs have been drilled, producing substantial gas.

Exploration in the drift succession began with drilling of borehole E-AA1 in 1986, located in the central basin. The purpose of this borehole was to test domal closures at 1At1 and 13At1. The borehole discovered oil and gas in the Albian deep marine turbidites in the 14A sequence. The E-AA1 discovery comprised of submarine fan and channel sandstones that developed on type1 unconformity surfaces, which are Albian to Aptian in age. These deep marine fan complexes have aided the understanding of seismic- stratigraphic principles and their application to the basin (Burden, 1992).

Similar fields were discovered within the Bredasdorp Basin with regards to the initial discovery with oil flow rates of 8500 st- tk b/d (Sonibare et al., 2012). Since 1970, Soekor's offshore exploration in the Bredasdorp Basins acquired 46000km of multichannel seismic data. Three 3D seismic surveys have been acquired over the F- A gas field, E-M, E-AA and E-AR oil fields. A total of 135 boreholes has been drilled since August 1992.

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Chapter 3

3.1) Methodology

All data was collected from Petroleum Agency SA (PASA), and includes well reports, completion reports and wireline logs for wells E-M1, E-M3 and E- AB1, as well as seismic line E82-005. For the electro sequence analysis, wireline logs were evaluated and analyzed in order to establish the depositional environment. Biostratigraphy analyses, together with seismic line E82-005 were interpreted to analyze the sequence stratigraphy of the Bredasdorp Basin.

Seismic stratigraphy involves identifying the sequence boundaries and system tracts with the aid of geological reports and well log data provided by PASA. The Well tops were correlated wells E-M1, E-M3 and E-AB1 (Figure 4.4), after this, a synthetic seismogram was generated to link wells E-M1, E-M3 and E-AB1 to the seismic line E82-005 (Figure 4.5), where the well tops corresponded to high amplitudes displayed on the seismic line and can be seen as the red boundaries. The well tops were used to position the sequence boundaries.

3.2) Log curve shapes

A basic scheme to classify sand bodies in the Gulf Coast area of the USA, developed by Shell (Serra and Sulpice, 1975) was based on the shape of the SP log and mirror image of the resistivity log. Principal shapes observed were the bell, cylinder and funnel (Figure 3.1.1).The scheme was intended to give a classification of log shapes in order to make correlations easier. However, the gamma ray log interpretation will be used based on the criteria by Rider (1996) due to the fact that gamma ray curve gives a greater variety of shapes, shows greater definition and has more character. A Gamma ray log is an indicator of clay content, therefore its shape shows the variations in radio activity that originates from clay minerals. A funnel shape indicates decreasing log values upwards, showing a decrease in clay content (Figure 3.1.1). Bell shape shows gamma ray values increasing upwards from a minimum, reflecting an increase in clay content.

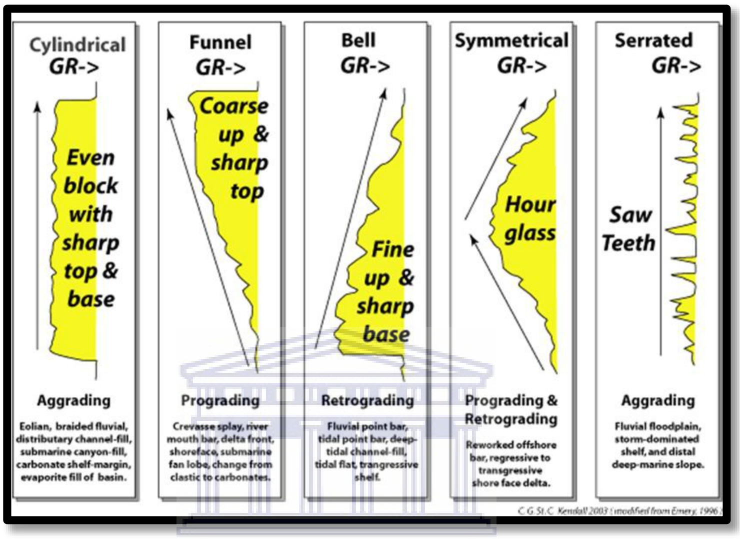


Figure 3.2.1: Log shape classification (from Kendall, 2003)

The increase in clay content is correlated to a decrease in grain size. The bell shape can be interpreted as indicative of a fining upward deposit. Conversely, the gamma ray funnel shape indicates coarsening upwards successions (Rider, 1996), like in the case of sections composed of basal bioturbated offshore muds, shallow marine sands and finally root beds and coal at the top. This could be interpreted as a prograding, estuarine shoreline succession (Figure 3.2.1).

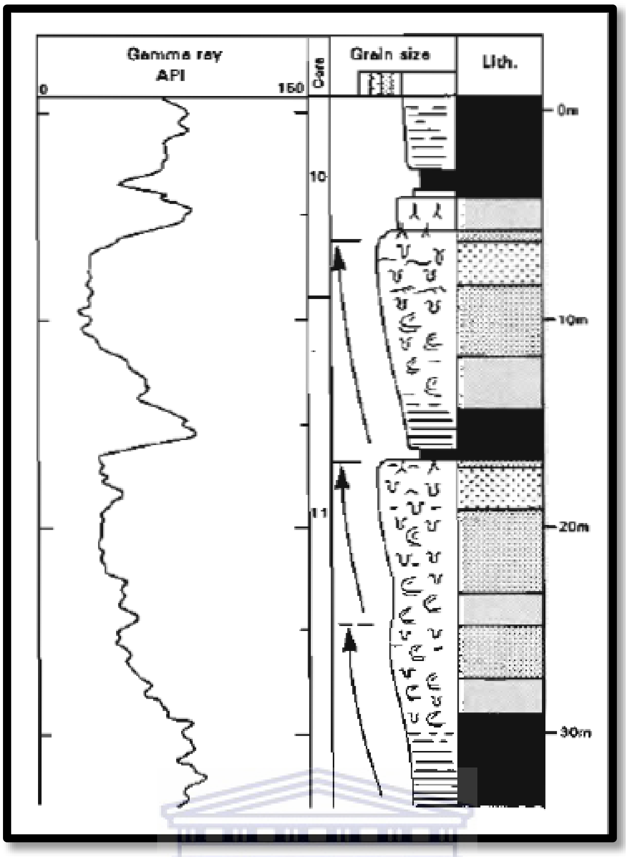


Figure 3.2.2: Funnel shapes of the gamma ray log corresponding to coarsening upwards sequences. (Modified after Rider, 1996)

A decrease in gamma ray values will generally indicate an increase in grain sizes. The bell shape may indicate a fining upward sequence which may be an alluvial/fluvial channel but also transgressive shelf sand. The funnel shape coarsening upwards succession may be the result of shallow marine progradation (Rider, 1996) or a deltaic progradation. Figure 3.2.3 is a clear representation of the above mentioned log curve shapes according to their grain sizes and their possible interpreted depositional environments.

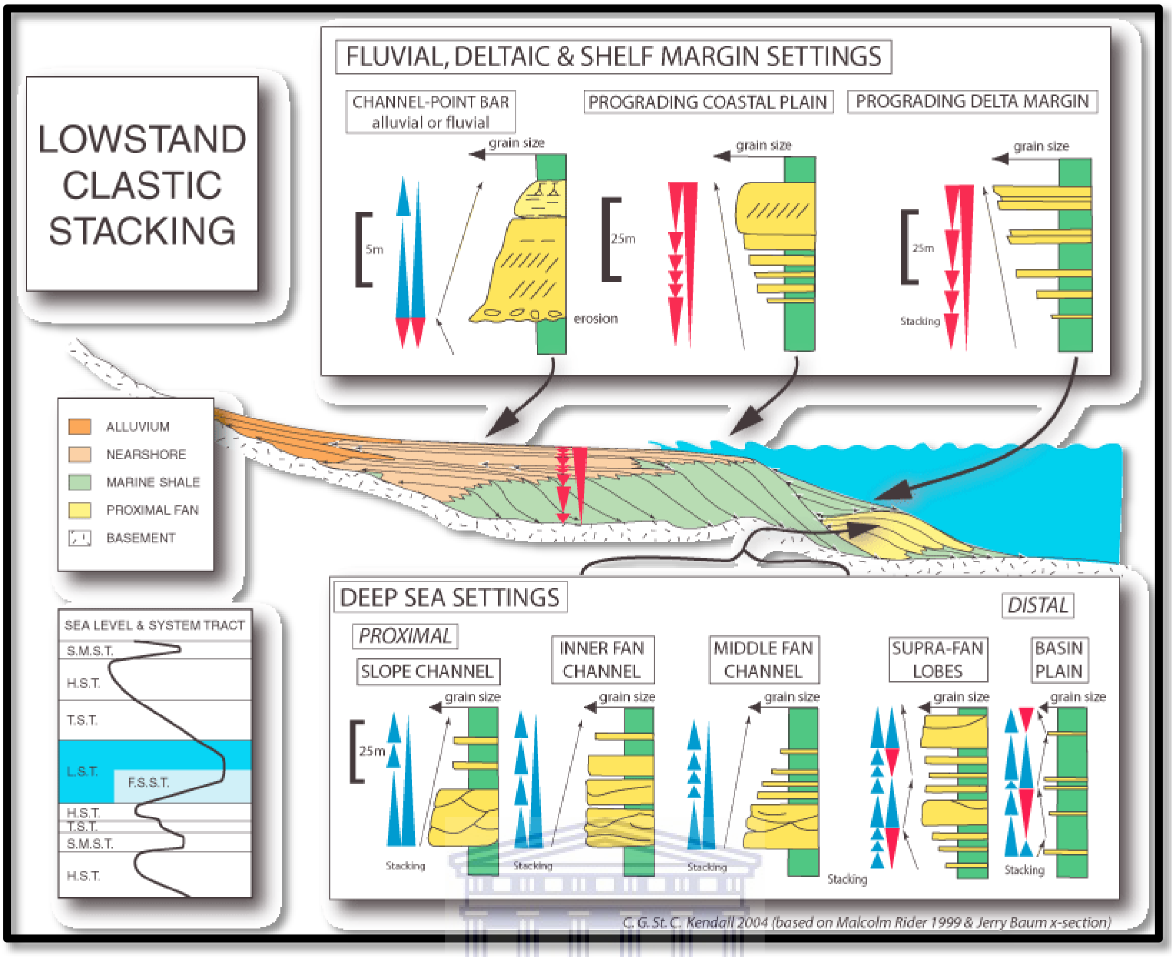


Figure 3.2.3: Illustrating the log curve shapes together with their grain size in a possible depositional environment (from Kendall, 2004).

3.3. Review of Core data analysis

PASA generously provided the core reports for wells E-AB1, E-M1 and E-M3.The cores were observed at PASA's facility for description purposes. The core reports contain facies descriptions and possible depositional environment interpretations that could be helpful in comparing laid out cores to the core report and correlating wireline logs as well. The study of cores in this project was critical because gamma ray log signatures alone could lead to erroneous interpretations of depositional environments. This is even more so as gamma ray log curve shapes are similar for both clastic and carbonate rocks from comparable depositional positions.

3.4) Interpretation of Lithology

The log data PetroSA provided was in a digital format. It was converted to a readable format using Petrel software licensed to the University of the Western Cape. Petrel software was chosen to model this reservoir because it is a Microsoft Windows-based software for 3D visualization with a shared subsurface modelling tool which allows relating different reservoir disciplines in a common model. A data base was created within Petrel, clearly delineating the different information and data needed to complete this project. As an essential first step, geophysical and geological data were imported into the Petrel main data base. These geophysical and geological data included: resistivity, deep induction, sonic, density and neutron logs, and lithological interpretation which was derived from the examination of both log- and drill-derived data.

Electro sequence analysis of the log signatures of wells E-AB1, E-M1 and E-M3 was performed to decipher geological log shape trends of the target horizons. These trends were then transferred to a seismic section, running through the three studied wells, in an attempt to establish if the geological trends in one well can be correlated to those of another well.

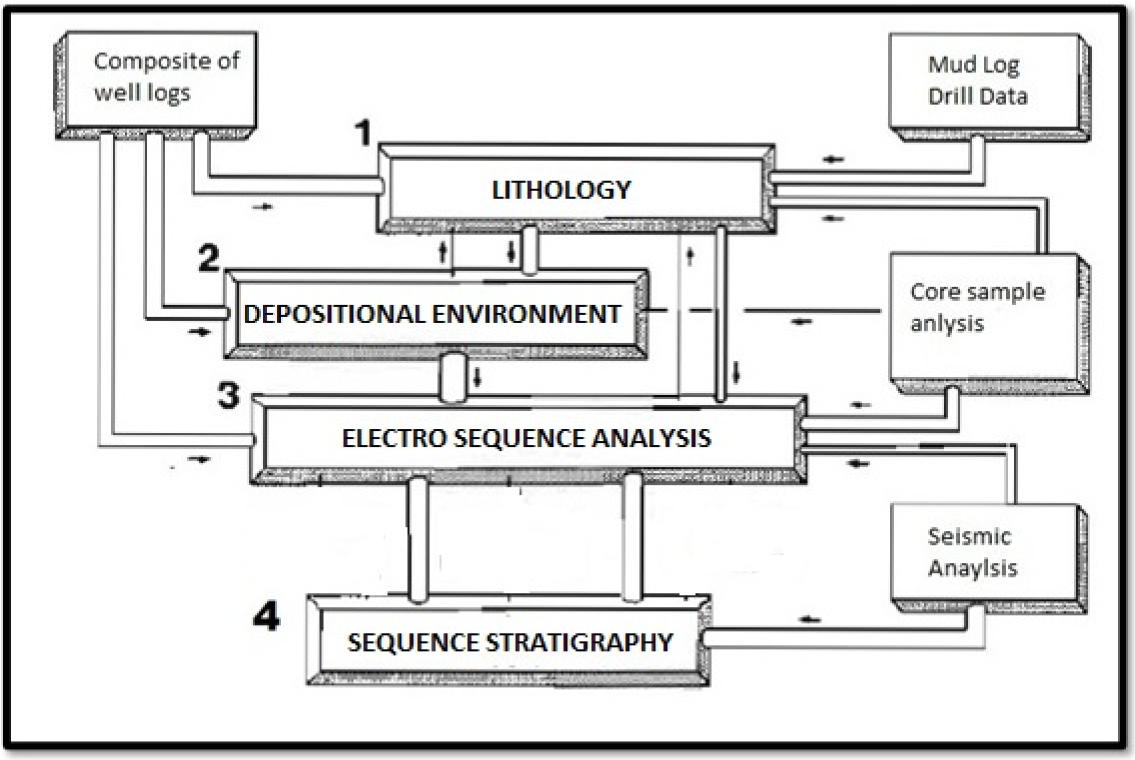


Figure 3.3: Sequence Stratigraphy analysis flowchart (modified from Rider, 1996).

3.5) Principles of sequence stratigraphy

The basic principle of sequence stratigraphy is that "Deposition of sediments and their spatial and temporal distribution in a basin are controlled by the interplay between sediment supply, basin-floor physiography and changes in the relative sea level" (Catuneanu, 2006). Catuneanu later states that "The latter refers to changes in the elevation of sea level resulting from a combination of eustatic fluctuations, basin-floor subsidence or upliftment and sedimentary supply". Sequence stratigraphy analysis aims to divide the stratigraphic record into depositional sequences (Mitchum et al., 1977) which are successions of relatively conformable and genetically related strata bounded (at base and top) by subaerial unconformities or their correlative conformities.

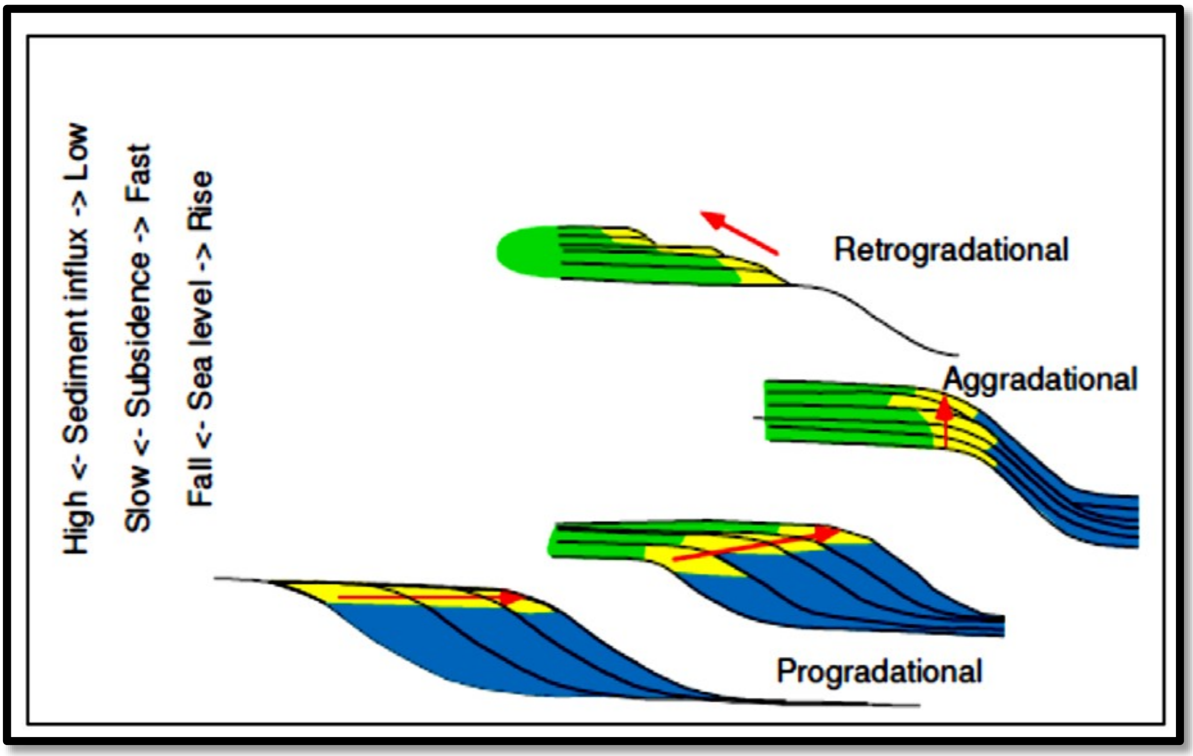


Figure 3.4: Illustrating the sequence geometric and facies shift (from Van Wagoner et al., 1988)

Each sequence can be internally divided into system tracts (Van Wagoner et al. 1988, Brown & Fisher 1977) or sets of contemporaneous depositional systems identified by strata terminations, depositional patterns and position inside the sequence. Features of the systems tracts are controlled by the available space for sedimentation (or accommodation) which depends on the interplay between subsidence, eustasy and sedimentary supply. Such control allows for the understanding of the relationship between the system tracts and certain portions of the eustatic curve (Posamentier et al. 1988).

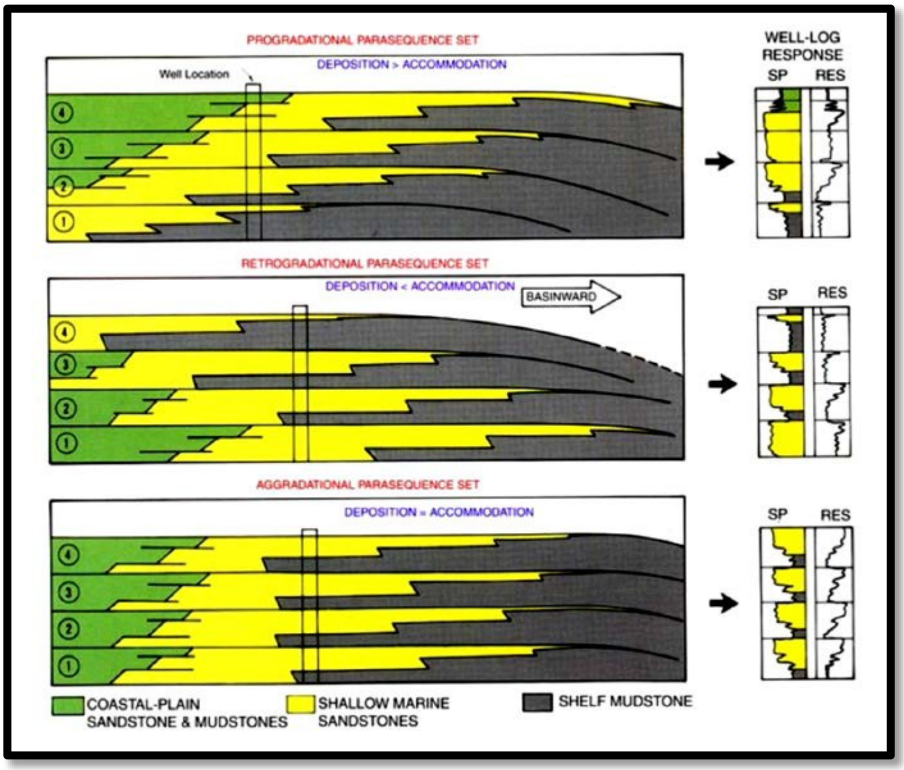


Figure 3.5. Illustrating the parasequence set, (from Van Wagoner et al., 1988)

The elemental unit used to analyze depositional sequences and systems tracts is the parasequence (Van Wagoner et al., 1988), which is a prograding- and shallowing- upward succession of relatively conformable beds bounded by marine flooding surfaces (or equivalents) at top.

Such parasequences can be stacked in parasequence sets (Van Wagoner et al., 1988) showing prograding, aggrading or retrograding patterns reflecting different rates of accommodation growth.

3.5.1System Tracts

Below (Figure 3.6) is a demonstration of a system tract model displaying the key signatures which include; highstand system tract, lowstand system tract.

(consisting of either basin-floor and slope fans or lowstand wedge) and transgressive system tract.

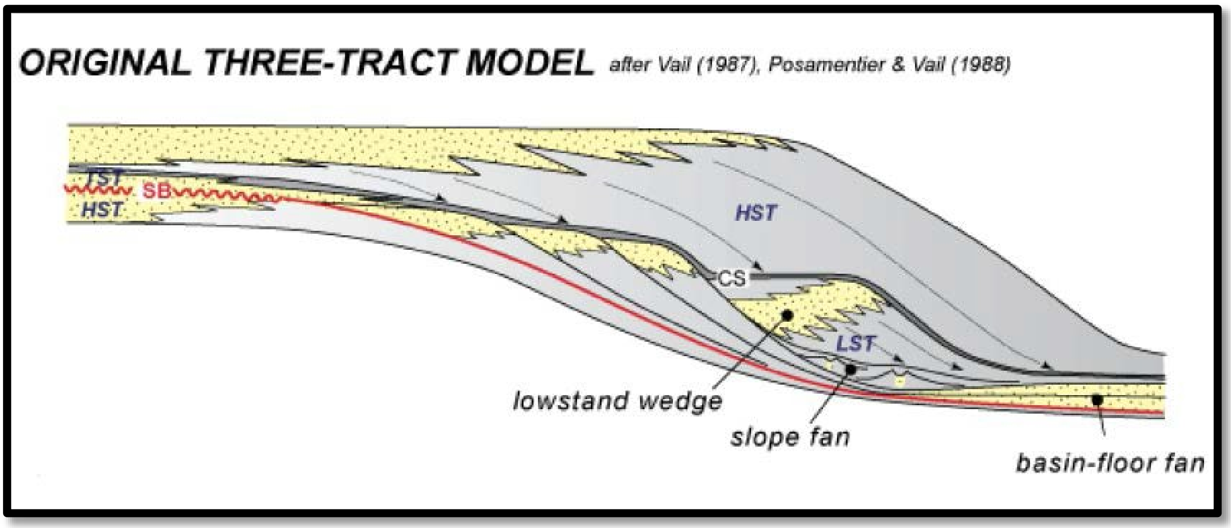


Figure 3.6: Displaying the original three-tract model (after Vail, 1987, Posamentier and Vail, 1988)

The lowstand system tract (LST), is deposited between the lower sequence boundary and the beginning of relative sea level rise, which is represented by the first transgression of the shelf, and the formation of a wave ravinement surface named the transgression surface, (Figure. 3.6). LST's are comprised of deep water turbidite systems which are both basin floor fans and slope fans, as well as lowstand wedge, which are shelf edge deltas and their feeding fluvial deposits with progradational and aggradational parasequence sets respectively.

The transgressive system tract (TST) is situated between the transgressive surface and the maximum flooding surface. The latter represents the point of maximum landward movement of coast and maximum sea level (beginning of transgression, and during the ravinement surface). The TST is comprised of a retrogradational parasequence set.

The highstand system tract (HST) occurs between the maximum flooding surface and the upper sequence boundary, and contains aggradational to progradational parasequence sets.

3.5.2) Sequence stratigraphic framework

The best approach for stratigraphic modelling is a mutual calibration of wireline logs and core data, which is illustrated through electro sequence analysis in the beginning of chapter 4.

“The sequence stratigraphy framework provides the genetic context in which surfaces and strata are placed into a coherent model that accounts for all temporal and spatial relationships of the facies that fill a sedimentary basin” (Catuneanu, 2006). The construction of this framework starts with the observation of strata terminations, followed by the identification of sequence stratigraphic surfaces, which in turn, allows for proper interpretation of strata such as system tracts and sequences.

Stratal terminations

Stratal terminations mentioned above refer to the geometric relationships between strata and the stratigraphic surfaces for example, onlap/downlap/toplaps. They reflect the direction and type of syn-depositional shoreline shifts.

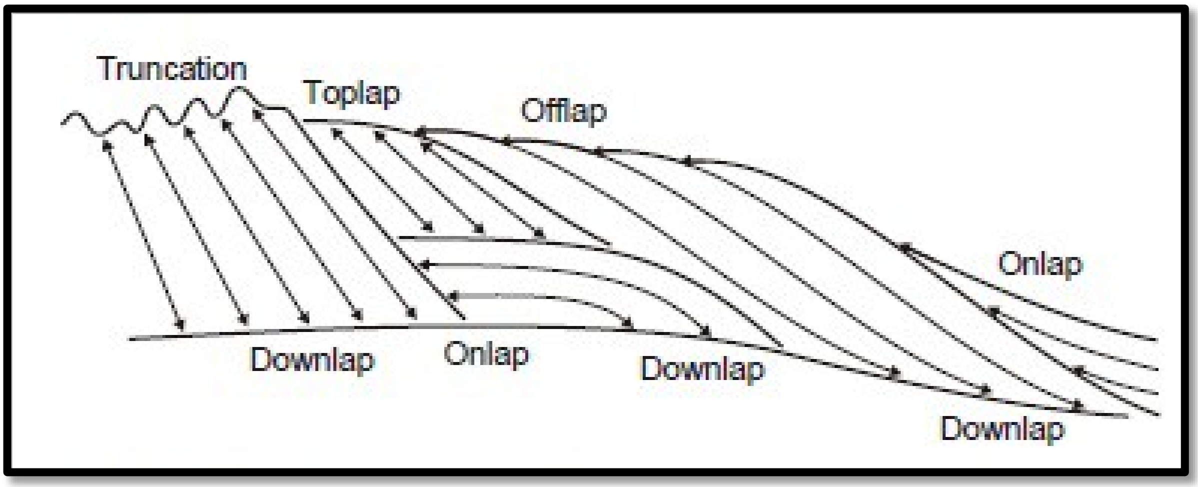


Figure 3.7: Showing types of strata terminations. (from Emery and Myers, 1996)

According to Catuneanu (2006), truncations, toplaps, onlaps, offlaps and downlap surfaces may be identified from local to regional scale based on geometric relationships of underlying and or overlying strata with the contact that separates them. These terms have been incorporated into sequence stratigraphy in order to describe the stacking patterns of strata units and provide criteria for identifying various surfaces and system tracts.

Stratigraphic surfaces

Sequence boundaries (surfaces) help to build the chronostratigraphic framework for the sedimentary succession under analysis. Such (surfaces) can be identified based on the (a) nature of depositional environment, (b) types of strata terminations associated with the surfaces and (c) depositional trends b e l o w and above that stratigraphic contact.

Stratigraphic surface	Nature of contact	Facies		Depositional trends[3]		Substrate-controlled ichnofacies	Stratal terminations	Temporal attributes[8]
		below	above	below	above			
Subaerial unconformity	Scoured or bypass	Variable (where marine, c-u)	Nonmarine	NR, FR	NR, T	N/A	Above: fluvial onlap Surface: offlap Below: truncation, toplap	Variable hiatus
Correlative conformity[1]	Conformable	Marine, c-u	Marine (c-u on shelf)	FR	NR	N/A	Above: downlap Surface: downlap Below: N/A	Low diachroneity
Basal surface of forced regression[2]	Conformable or scoured	Marine (c-u on shelf)	Marine, c-u	NR	FR	*Glossifungites*, where reworked by the RWR	Above: downlap Surface: downlap Below: N/A, truncation	Low diachroneity
Regressive wave ravinement	Scoured	Shelf, c-u	Shoreface, c-u	NR, FR	FR, NR	*Glossifungites*	Above: downlap Surface: N/A Below: truncation	High diachroneity
Maximum regressive surface	Conformable[7]	Variable[5]	Variable (where marine, f-u)	NR	T	N/A	Above: marine onlap Surface: onlap, downlap Below: N/A	Low diachroneity
Maximum flooding surface	Conformable or scoured	Variable (where marine, f-u)	Variable (where marine, c-u)	T	NR	*Glossifungites, Trypanites, Teredolites*	Above: downlap Surface: onlap, downlap[4] Below: N/A, truncation	Low diachroneity
Transgressive wave ravinement	Scoured	Variable (where marine, c-u)	Marine, f-u	NR, T	T	*Glossifungites, Trypanites, Teredolites*	Above: coastal onlap Surface: N/A Below: truncation	High diachroneity
Transgressive tidal ravinement	Scoured	Variable (where marine, c-u)	Estuary mouth complex	NR, T	T	*Glossifungites, Trypanites, Teredolites*	Above: coastal onlap Surface: N/A Below: truncation	High diachroneity
Within-trend NR surface	Conformable	Delta front or beach	Delta plain or fluvial	NR	NR	N/A	N/A	High diachroneity
Within-trend FR surface[6]	Conformable	Prodelta	Delta front	FR	FR	N/A	Above: downlap Surface: N/A Below: N/A	High diachroneity
Flooding surface	Conformable or scoured	Variable	Marine, f-u or c-u	T, NR	T, NR	*Glossifungites, Trypanites, Teredolites*	Above: onlap, downlap Surface: onlap, downlap[4] Below: truncation	Low to high diachroneity

Figure 3.8: Diagnostic features of the main stratigraphic surfaces (modified after Catuneanu, 2002, 2003, and Embry and Catuneanu, 2002).

System tracts and sequences

This is the last step in the sequence stratigraphic framework, when both surfaces and strata between them are interpreted in genetic terms. Each system tract is unequivocally characterized by specific strata stacking patterns and positions within the framework of sequence stratigraphy surfaces (Catuneanu, 2006)

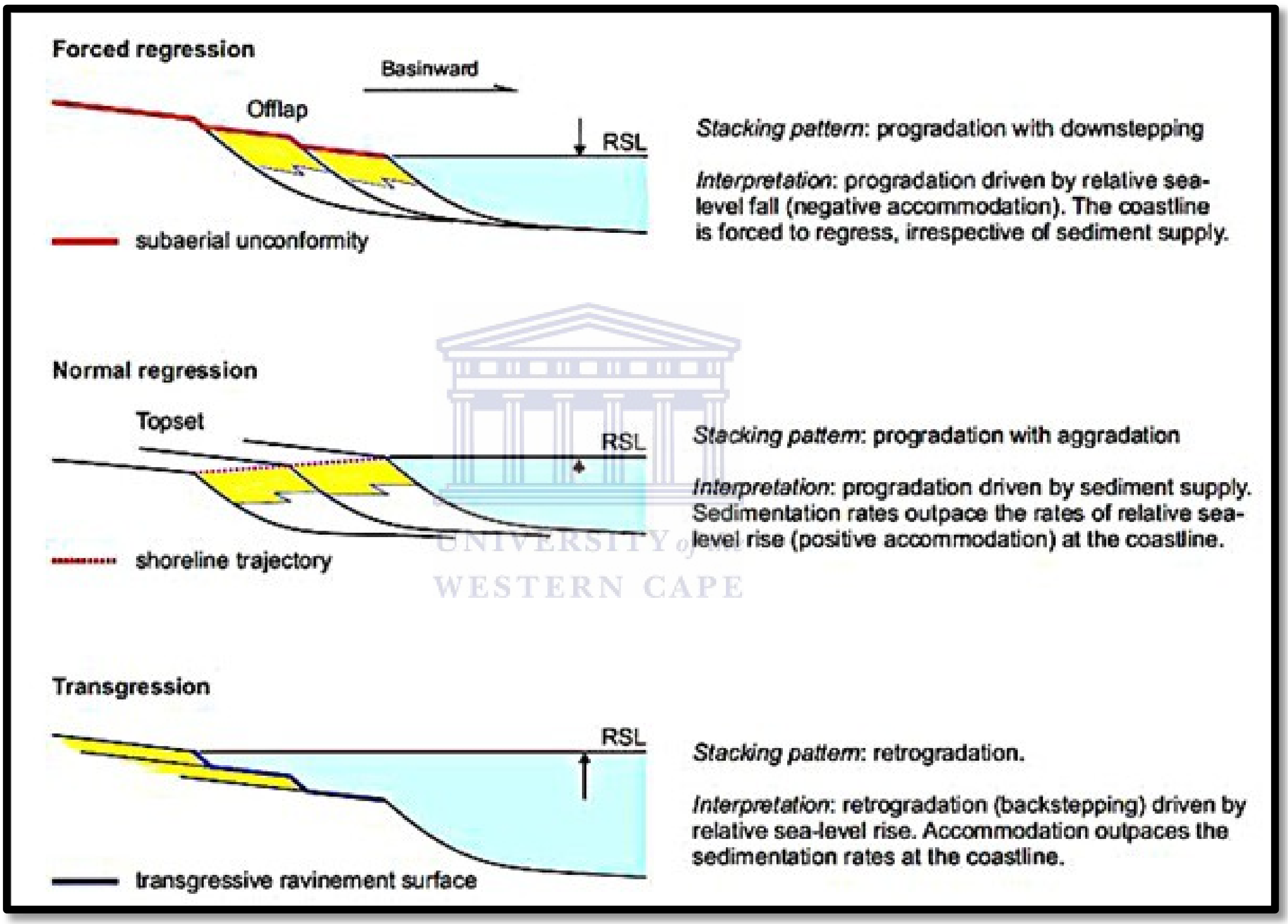


Figure 3.9: Stratal stacking patterns related to shoreline trajectories. After Catuneanu et al. (2011).

Chapter 4

4.1) Results

The first section of the results with regards to the interpretation of the gamma ray log signatures should be read in conjunction with the core data provided by the well logs. The sequence stratigraphic interpretation was done on seismic line E82-005 where all three wells E-M1, E-M3 and E-AB1 are visible.

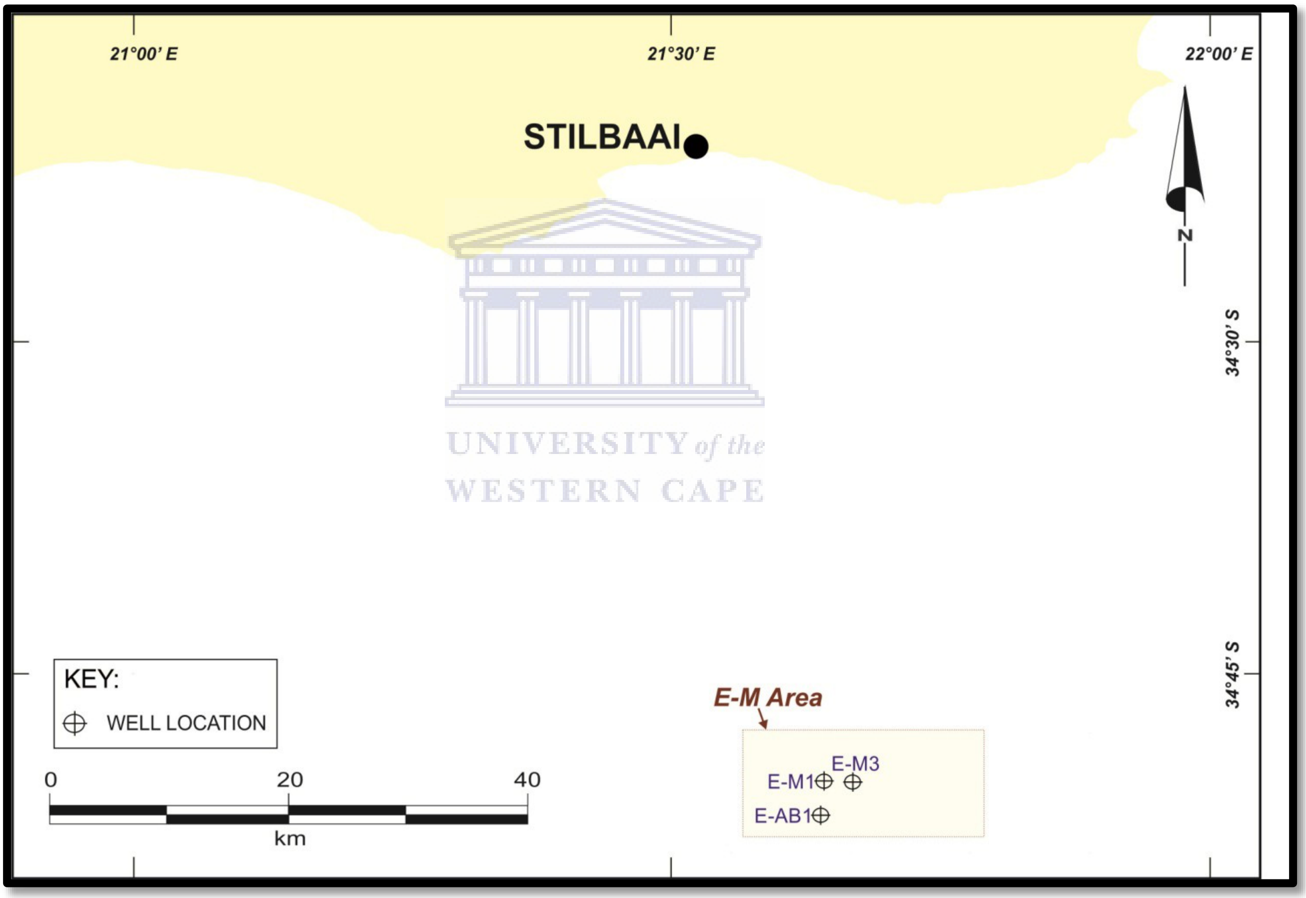


Figure 4.1: Displays the location of wells E-AB1, E-M1 and E-M3, offshore Stilbaai, South Africa.

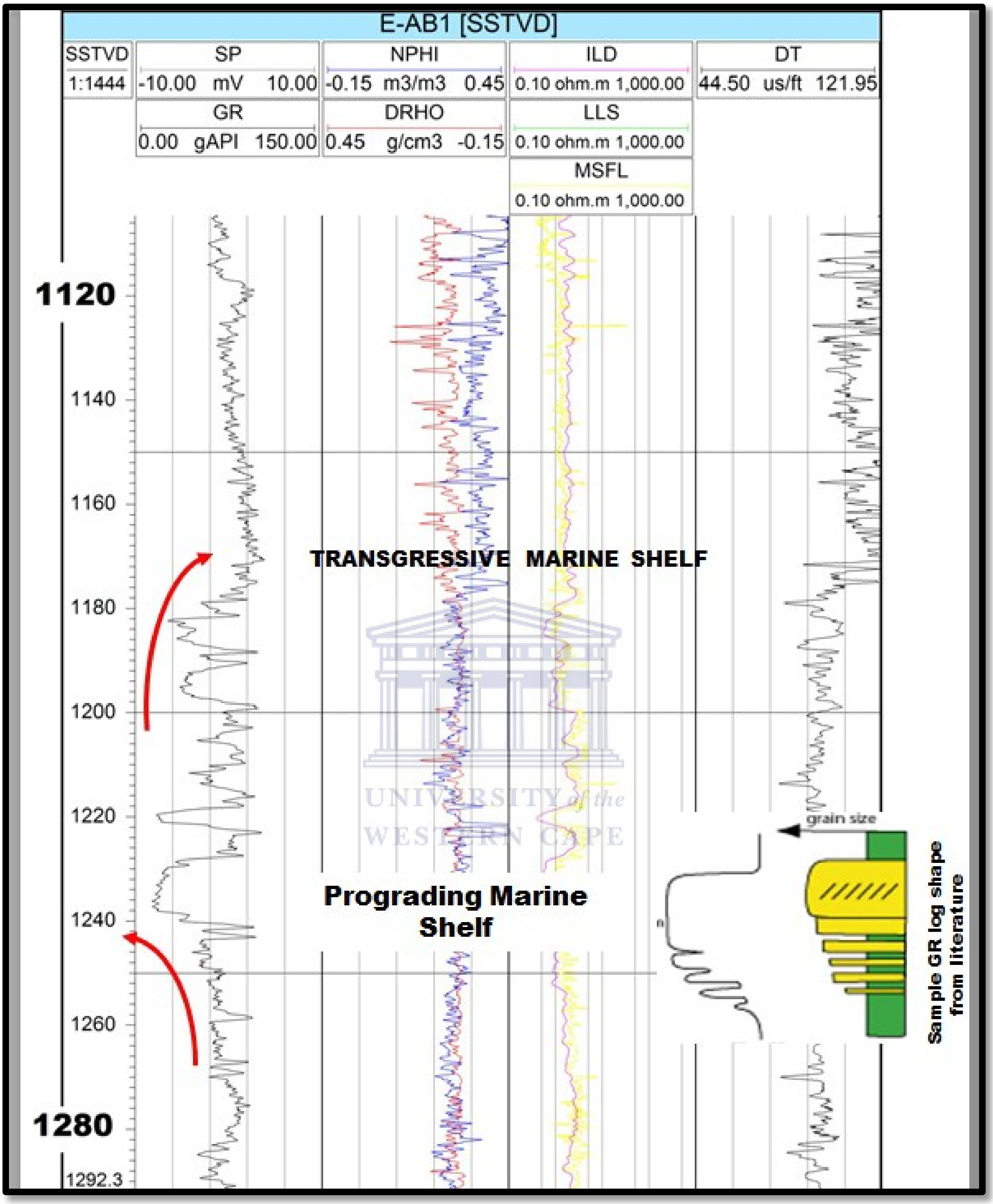


Figure 4.1.1: Well E-AB1 a progading marine shelf coarsening upward sequence into transgressive marine shelf.

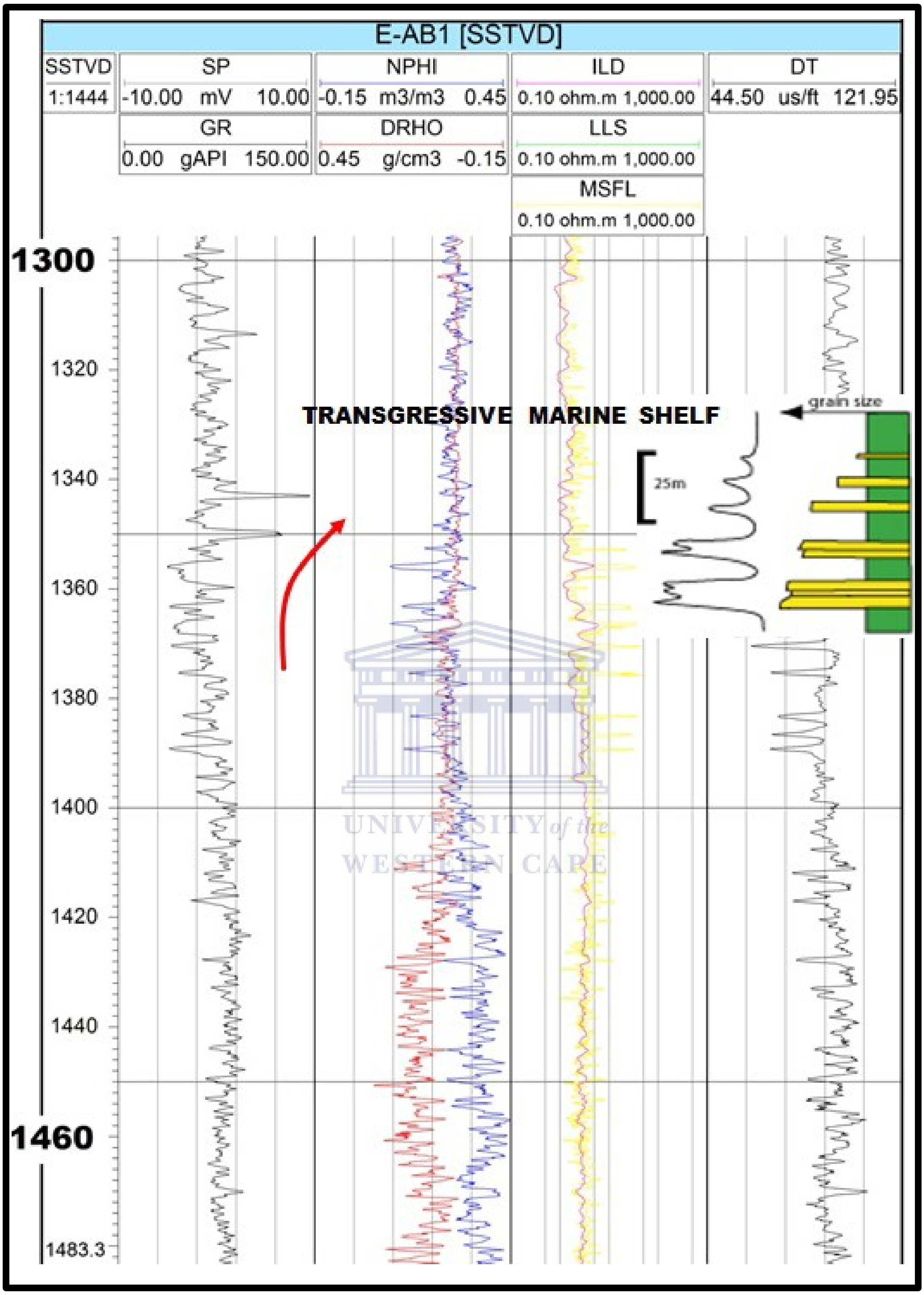


Figure 4.1.2: Well E-AB1 illustrates a transgressive marine shelf depositional environment.

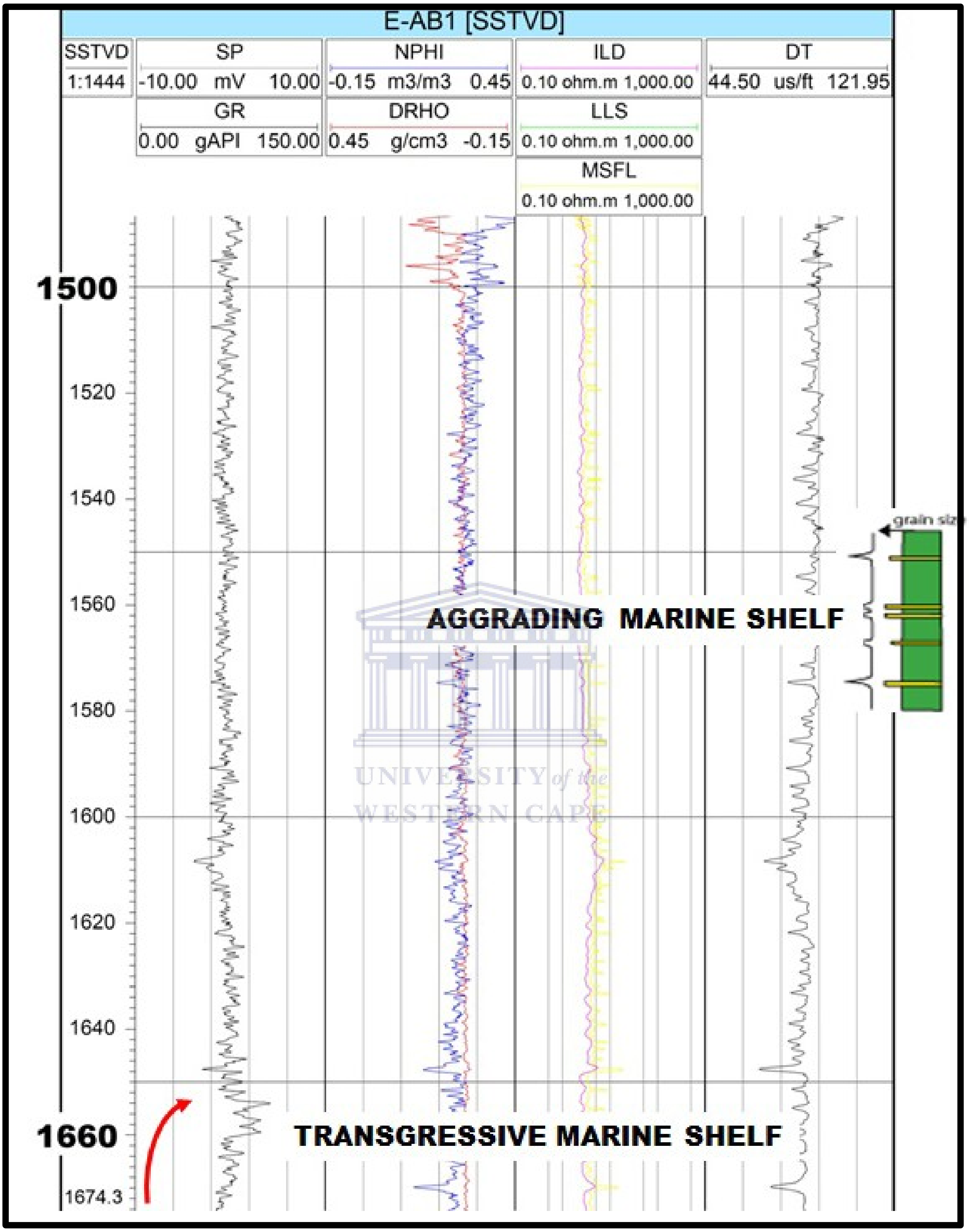


Figure 4.1.3: This portion of **Well E-AB1** illustrates a transgressive marine shelf into an aggrading marine shelf depositional setting.

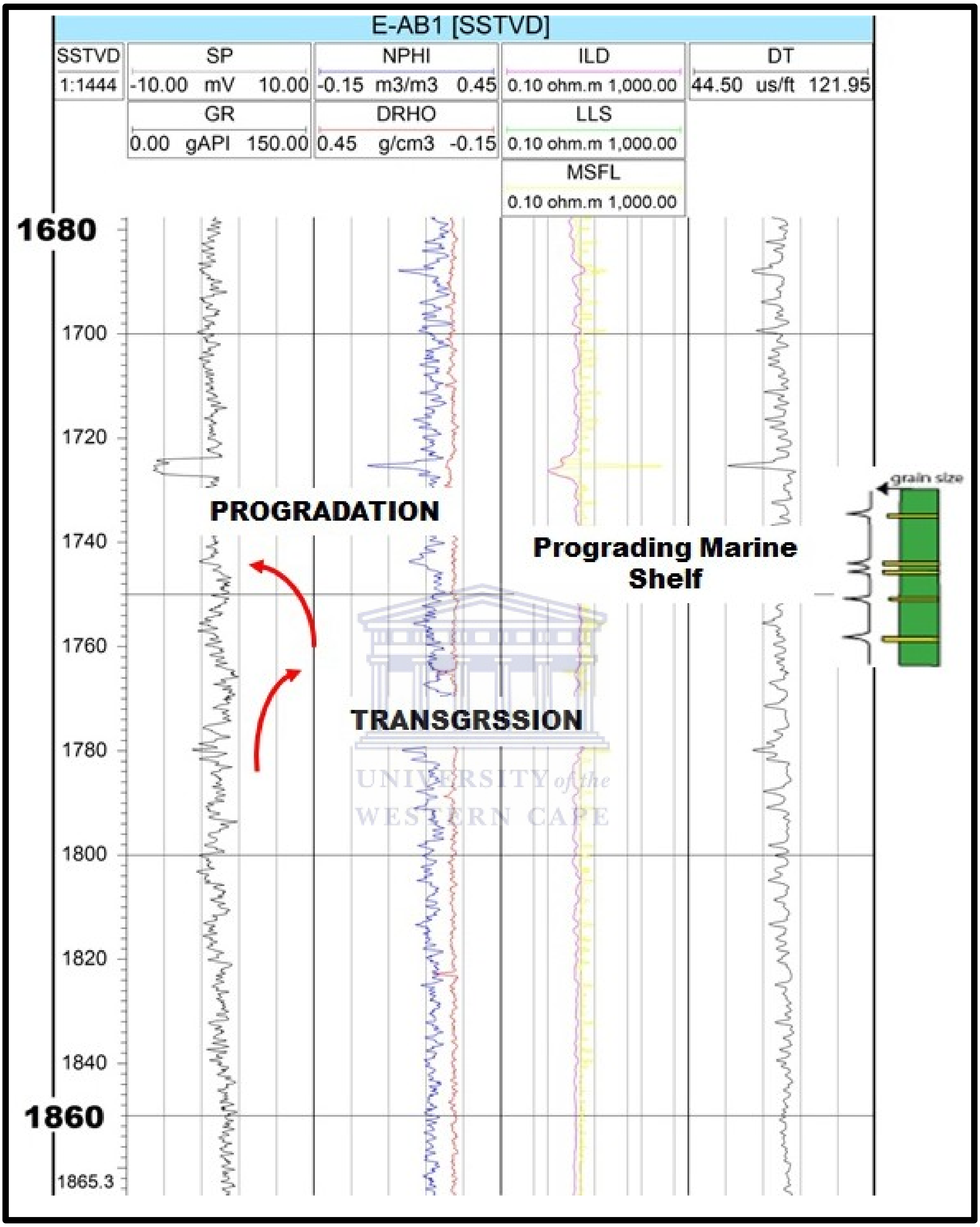


Figure 4.1.4: This portion of **Well E-AB1** displays a transgression into a prograding marine shelf environment

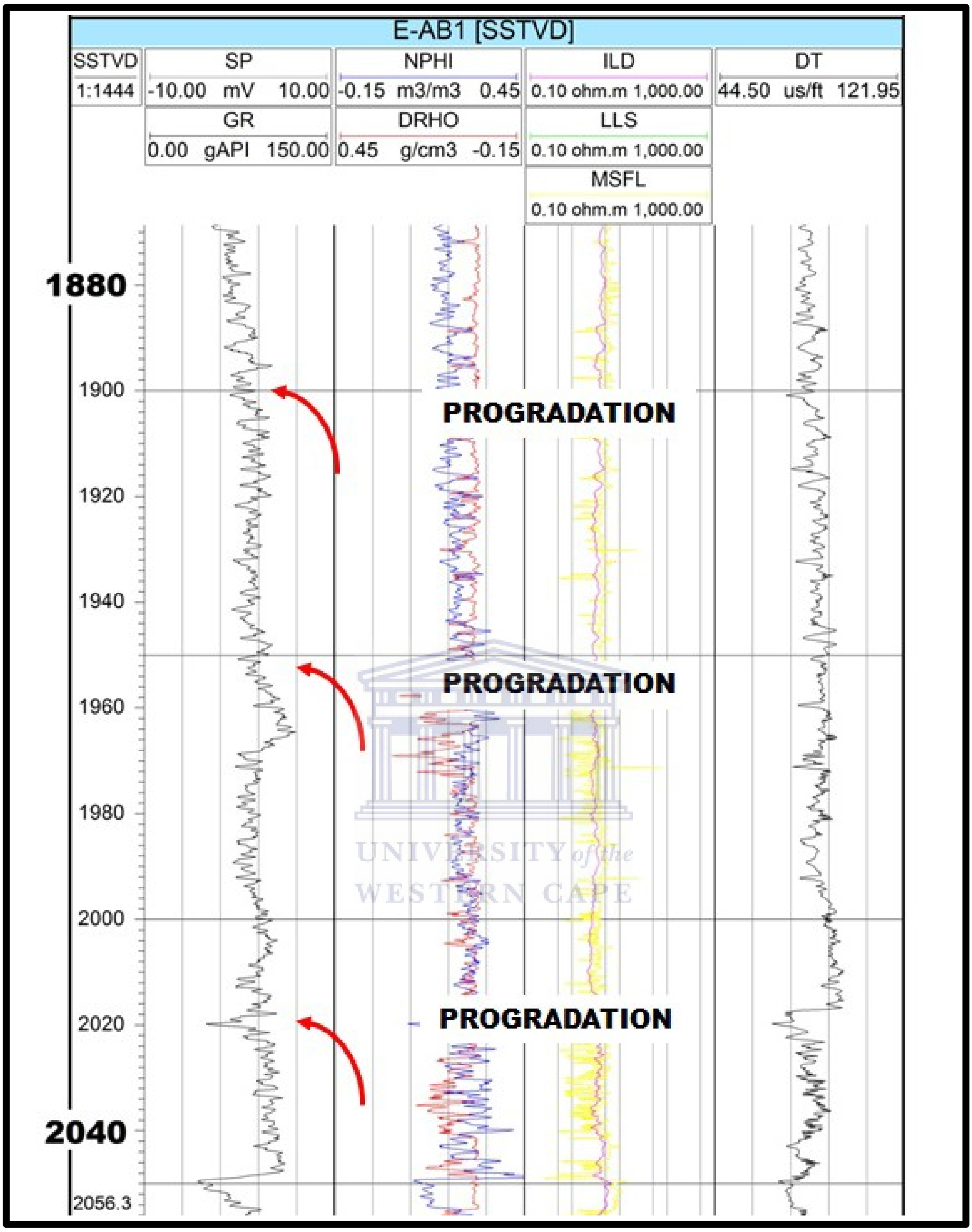


Figure 4.1.5: Well E-AB1 displays a coarsening upwards sequence of prograding marine shelf depositional environment.

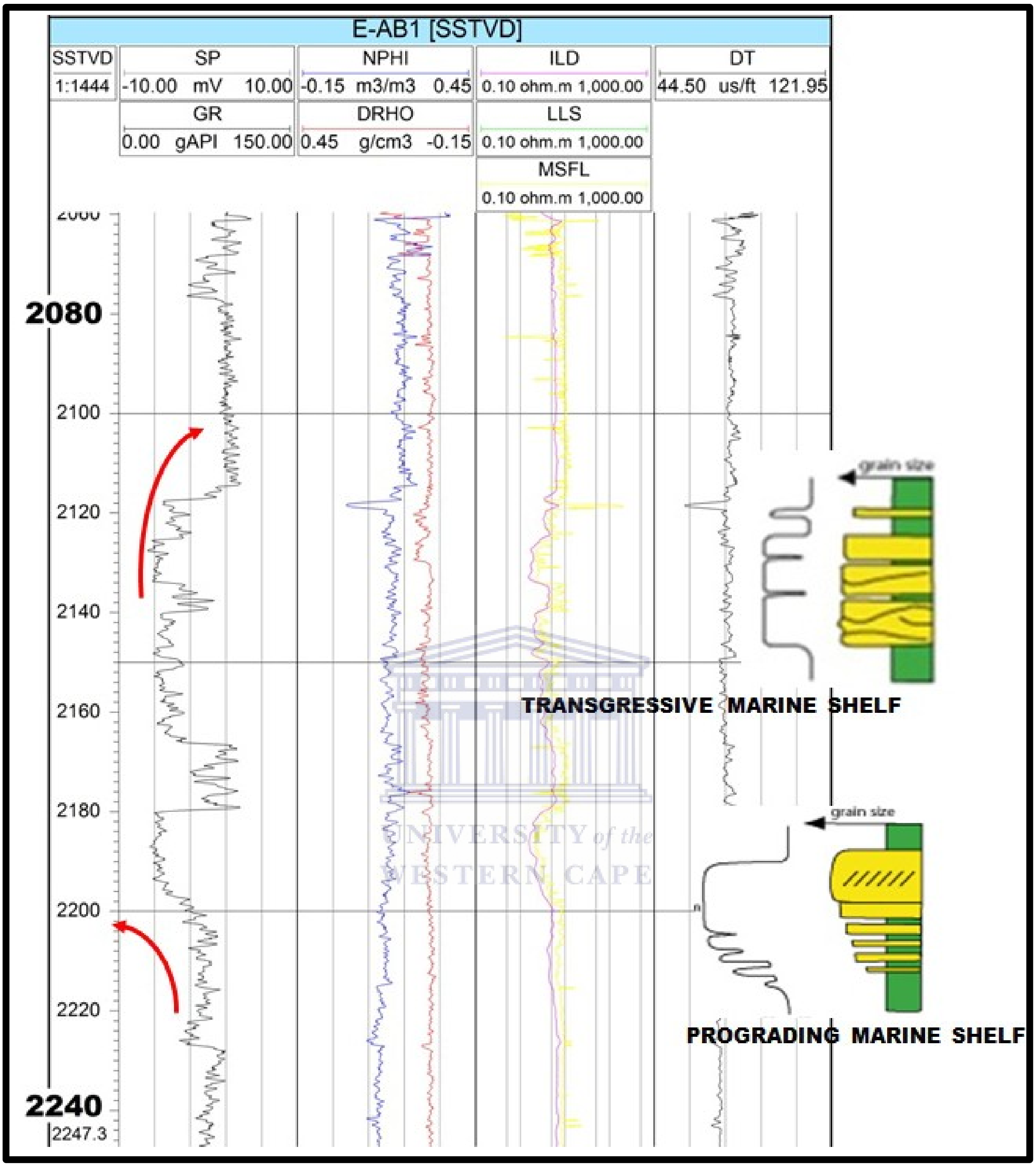


Figure 4.1.6: This portion of **Well E-AB1** illustrates a coarsening upwards progading marine shelf environment into a fining transgressive marine shelf depositional environment.

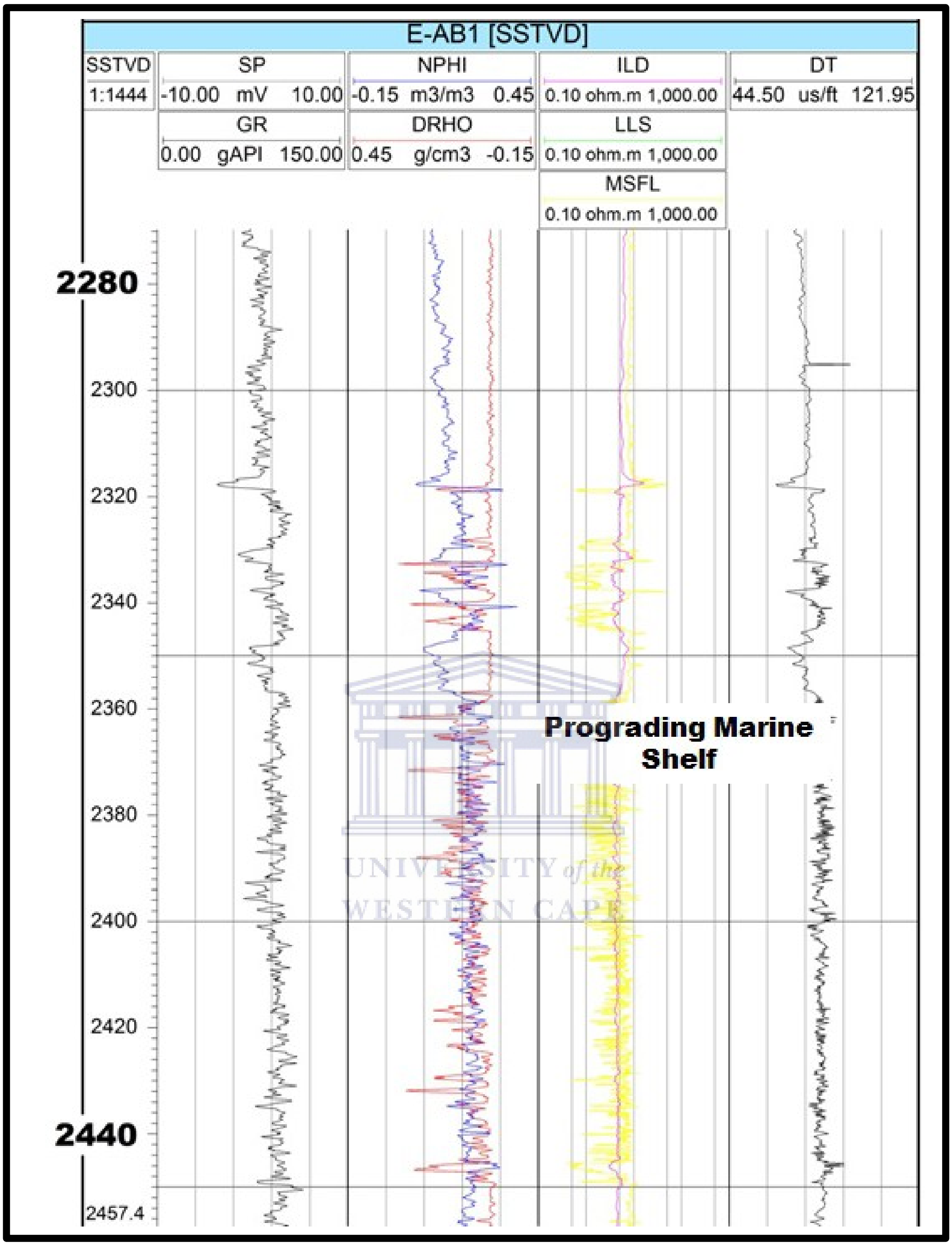


Figure 4.1.6: Well E-AB1 illustrates a prograding marine shelf.

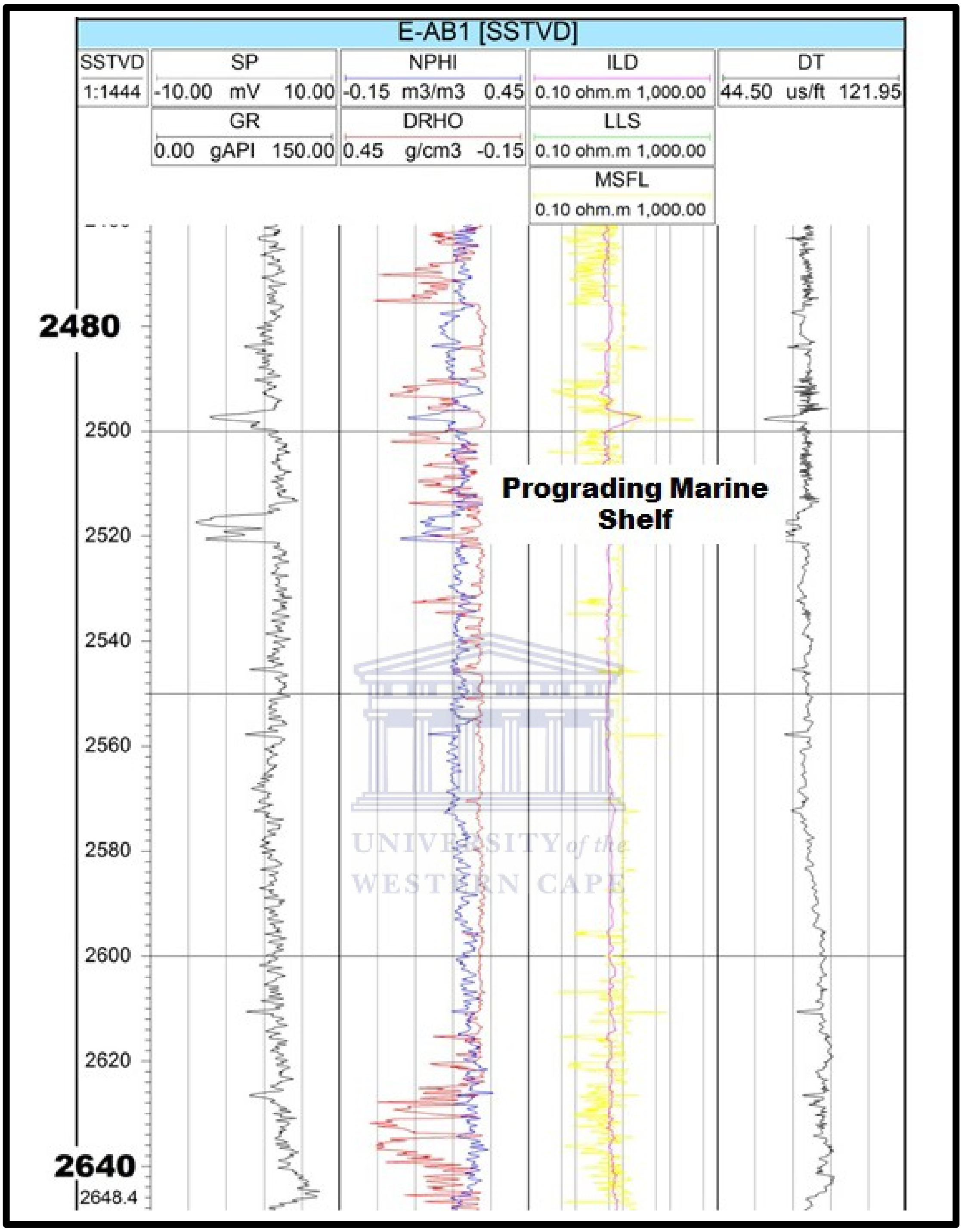


Figure 4.1.7: Well E-AB1 illustrates a prograding marine shelf depositional environment.

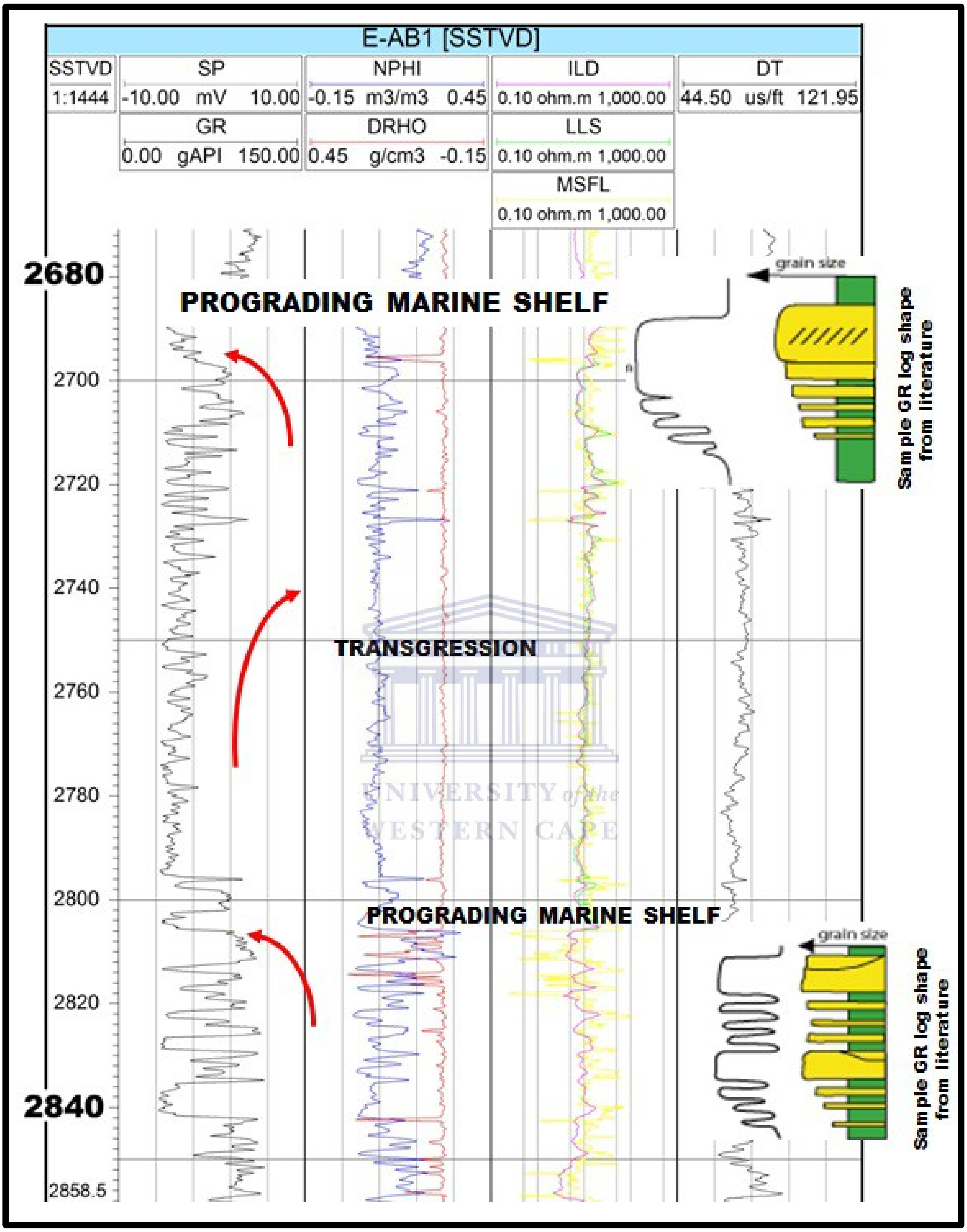


Figure 4.1.9: Well E-AB1 displays coarsening upwards progading marine shelf into a transgressive marine shelf environment and then a prograding marine shelf environment.

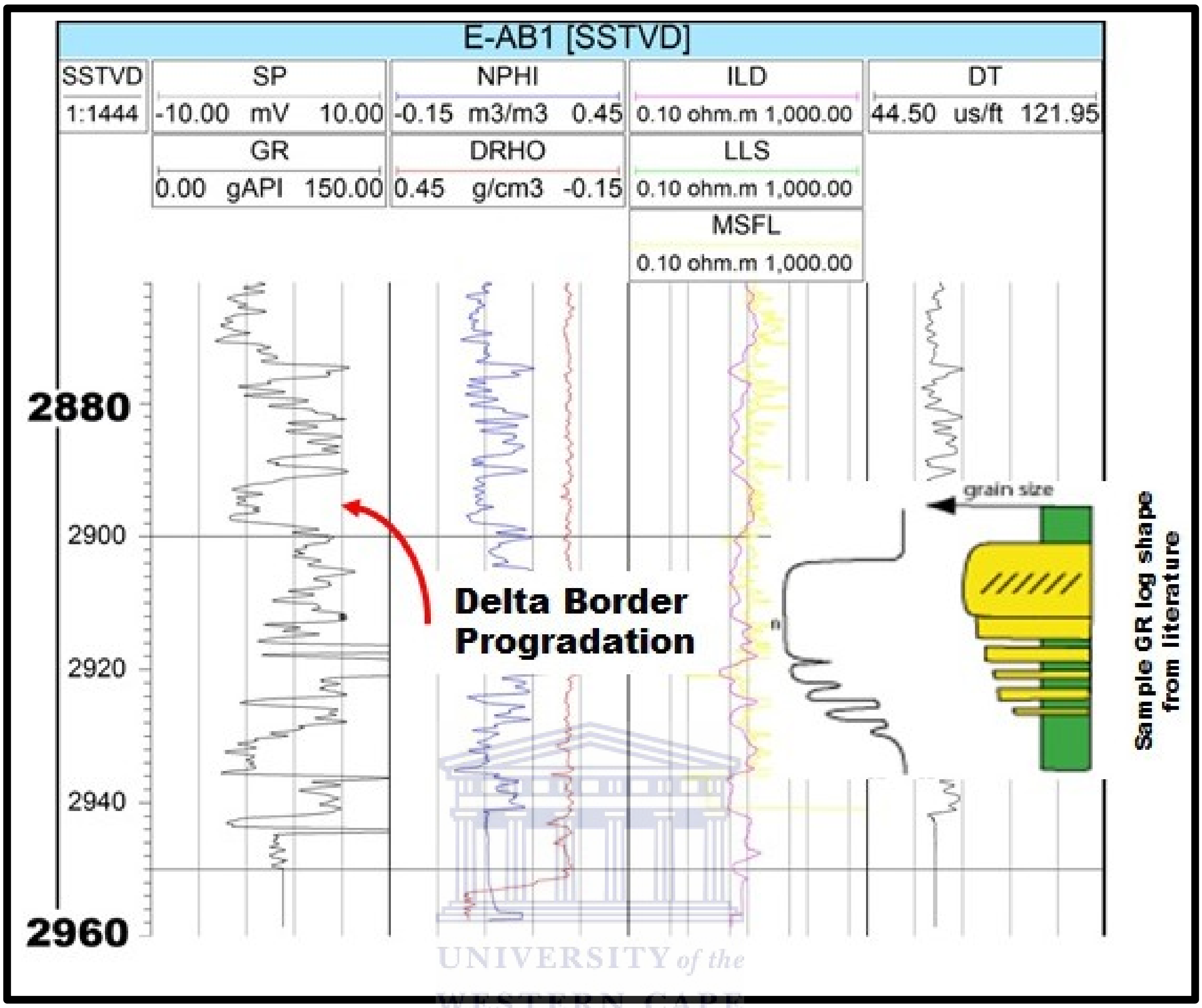


Figure 4.1.10: Well E-AB1 illustrates a coarsening upwards delta boarder progradation depositional environment.

In well E-AB1, from a total depth of 2960m to 2880m, the log shapes describe a coarsening upward delta border prograding depositional environment (Figure 4.1.10). 2840m to 2680m displays a prograding marine shelf transitioning into a transgressive marine shelf and then a prograding marine shelf (Figure 4.1.9), 2640m to 2280m illustrates a prograding marine shelf (Figure 4.1.8 and Figure 4.1.7). In Figure 4.1.6, well E-AB1 illustrates a prograding marine shelf from depth 2240m to 2180m. From 2180m to 2080m the depositional environment displaying fining upwards transgressive marine shelf. At a depths of 2040m to 1880m, well E-AB1 displays coarsening upward sequence of a prograding marine shelf (Figure 4.1.5). Figure 4.1.4, from depth 1860m to 1680m shows a fining upward transgressive marine shelf into a prograding marine shelf from depth 1660m to 1500m (Figure 4.1.3). Well E-AB1 illustrates a fining upwards transgressive marine shelf into an aggrading marine shelf. At a depth of 1460m to 1300m (Figure 4.1.2), well E-AB1 illustrates a transgressive marine shelf depositional environment. At a depth of 1280m to the top of the log 1170m, (Figure 4.1.1), well E-AB1 displays a coarsening upwards prograding marine shelf into a transgressive marine shelf.

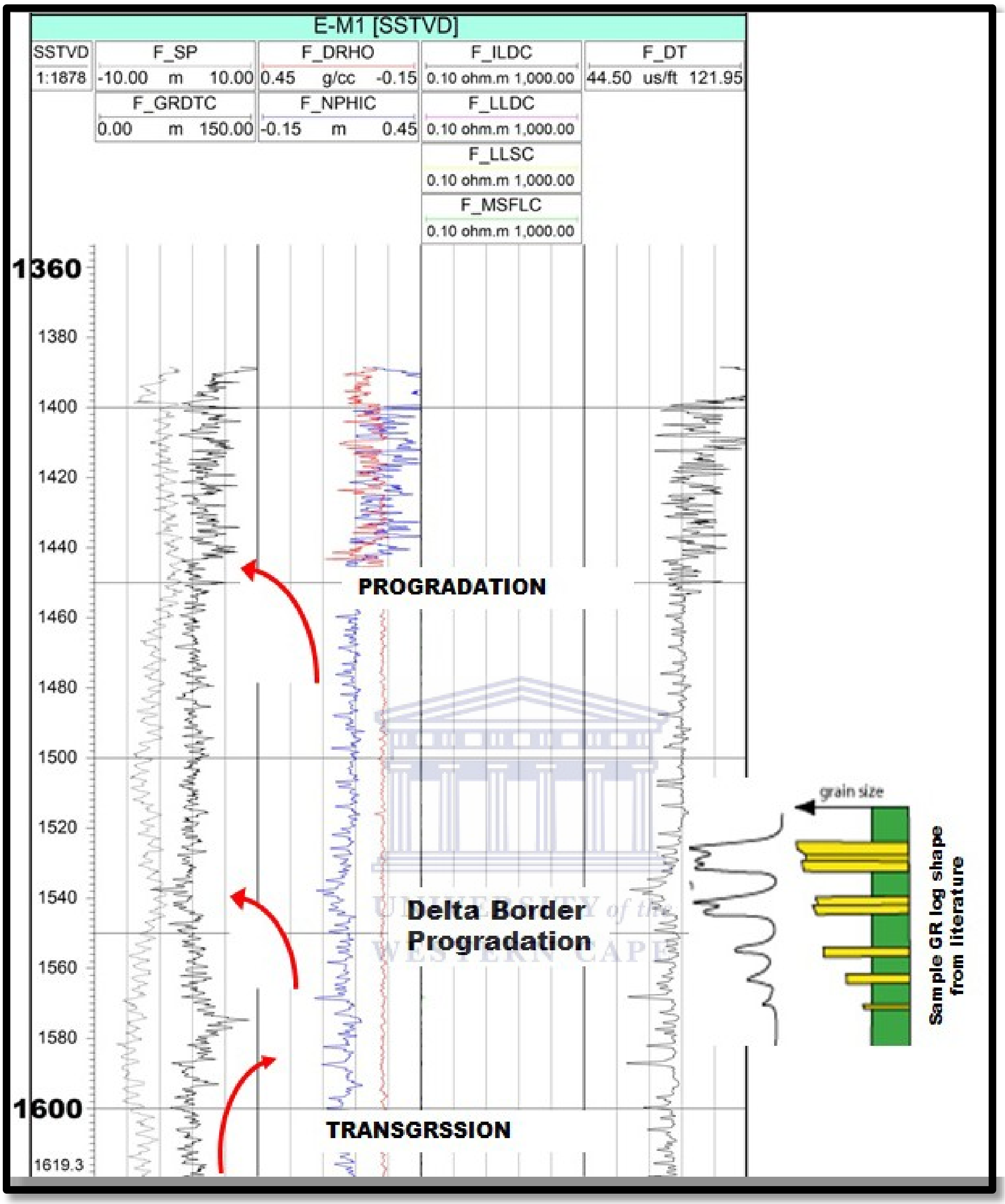


Figure 4.1.11: Well E-M1 illustrates a transgression, delta border progradation and a prograding marine shelf.

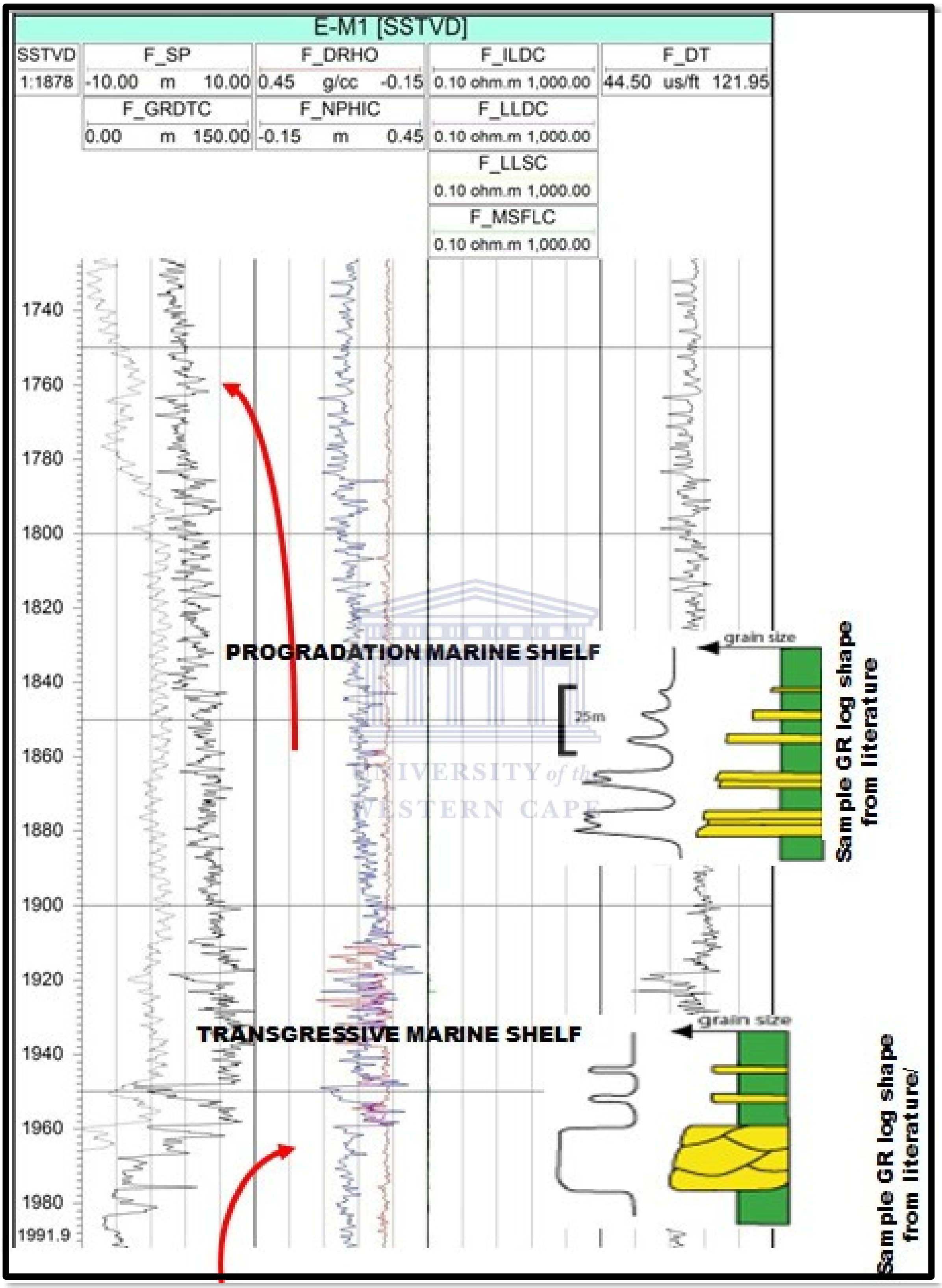


Figure 4.1.12: Well E-M1 shows a transgressive marine shelf into a prograding marine shelf.

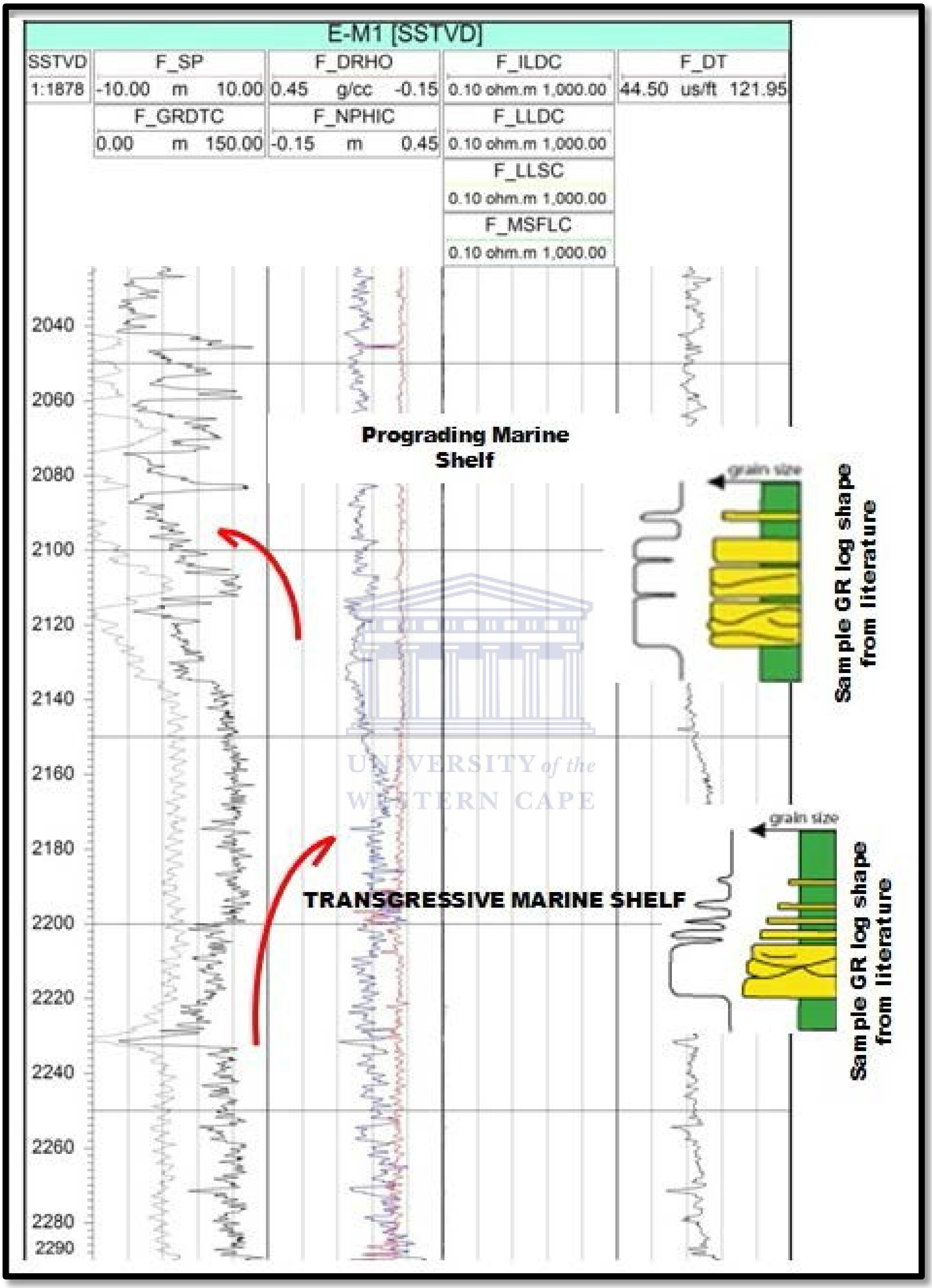


Figure 4.1.13: Well E-M1 illustrates a transgressive marine shelf into a prograding marine shelf

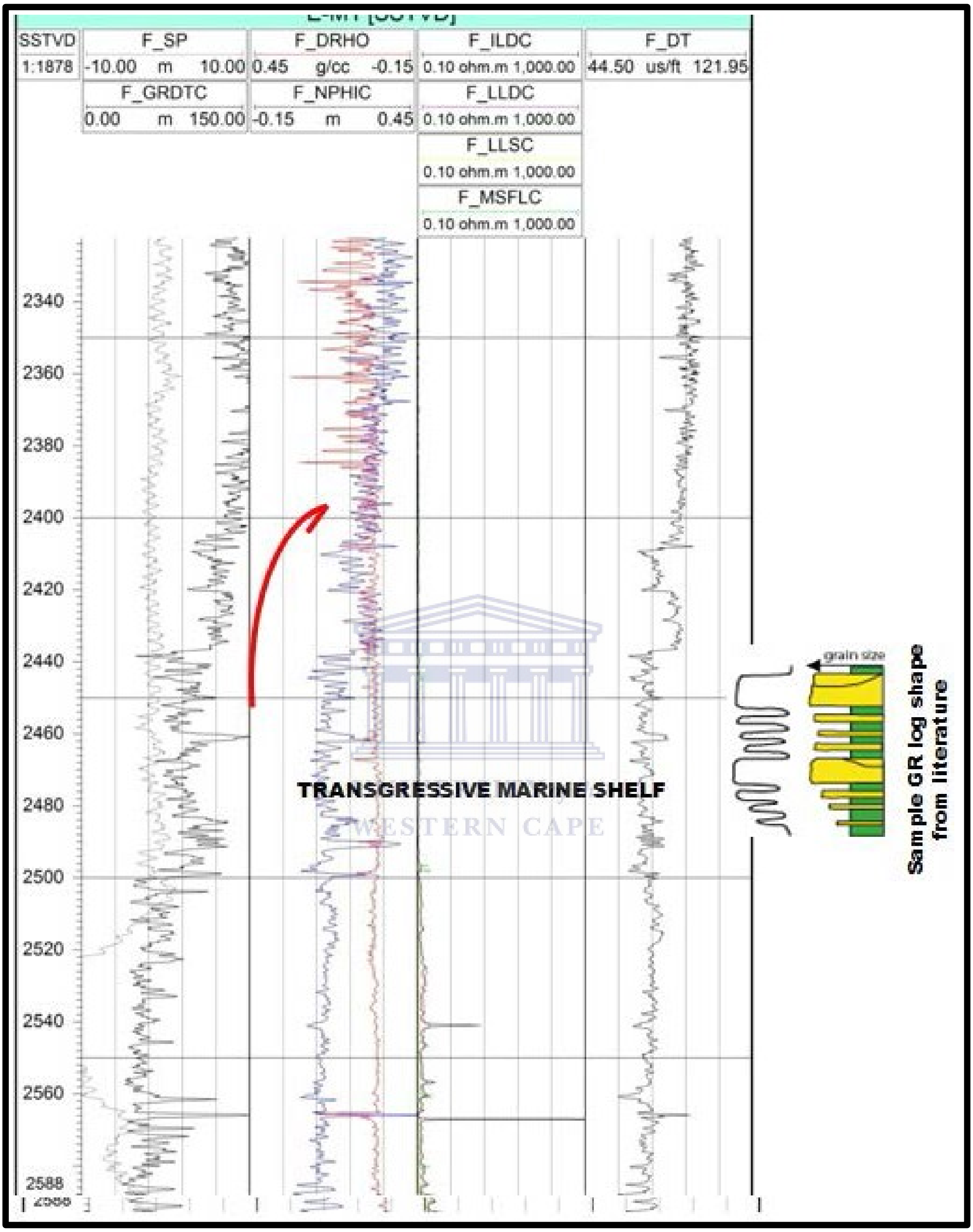


Figure 4.1.14: Well E-M1 illustrates a fining upwards transgressive marine shelf depositional environment.

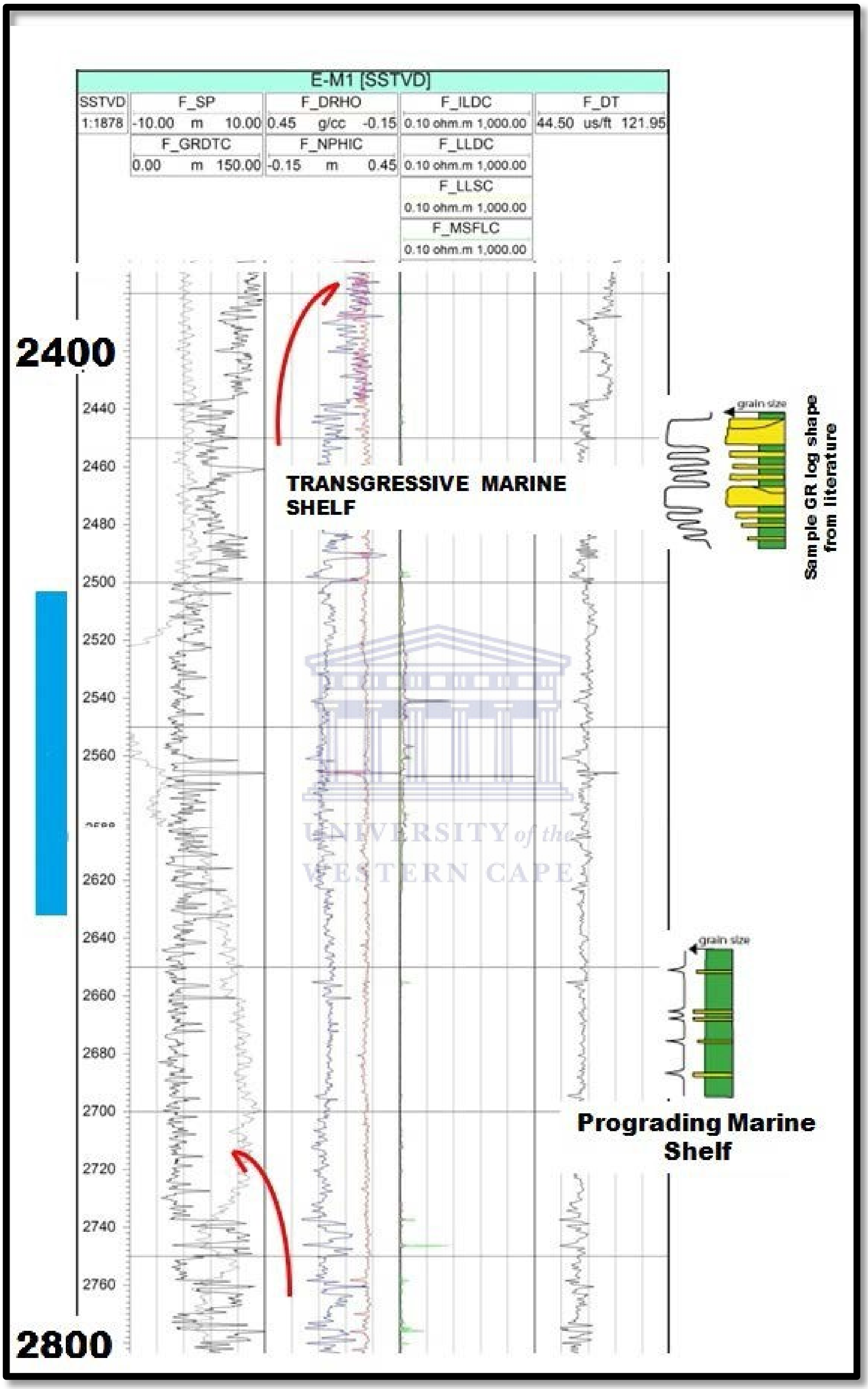


Figure 4.1.15: Well E-M1 illustrates a prograding marine shelf into a transgressive marine shelf.

Well E-M1 shows a coarsening upwards prograding marine shelf into a fining upwards transgressive marine shelf at depths of 2800m to 2400m, the blue area represents core extractions. See page 53 for core interpretations (Figure 4.1.15). In figure 4.1.14, well E-M1 displays a fining upwards transgressive marine shelf at a depths of 2588m to 2340m. From 2280m to 2040m (Figure 4.1.3), well E-M1 illustrates a transgressive marine shelf into a coarsening upwards prograding marine shelf. At a depth of 1980m to 1740 (Figure 4.1.12), Well E-M1 shows a transgressive marine shelf into prograding marine shelf environment. In figure 4.1.11, well E-M1 illustrates a transgressive marine shelf into a delta boarder progradation and then into a prograding marine shelf depositional environment.

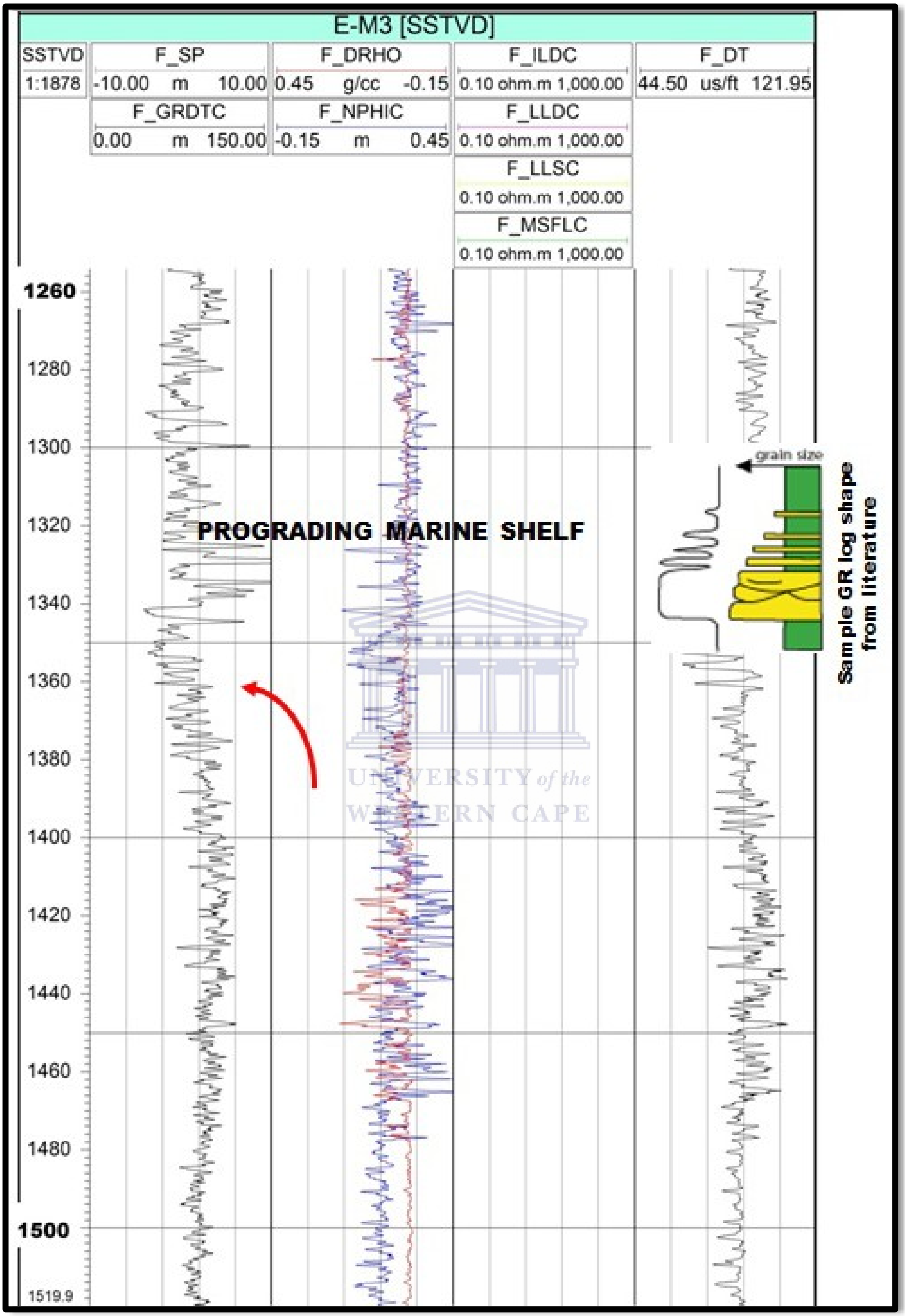


Figure 4.1.16: Well E-M3 prograding marine shelf depositional environment.

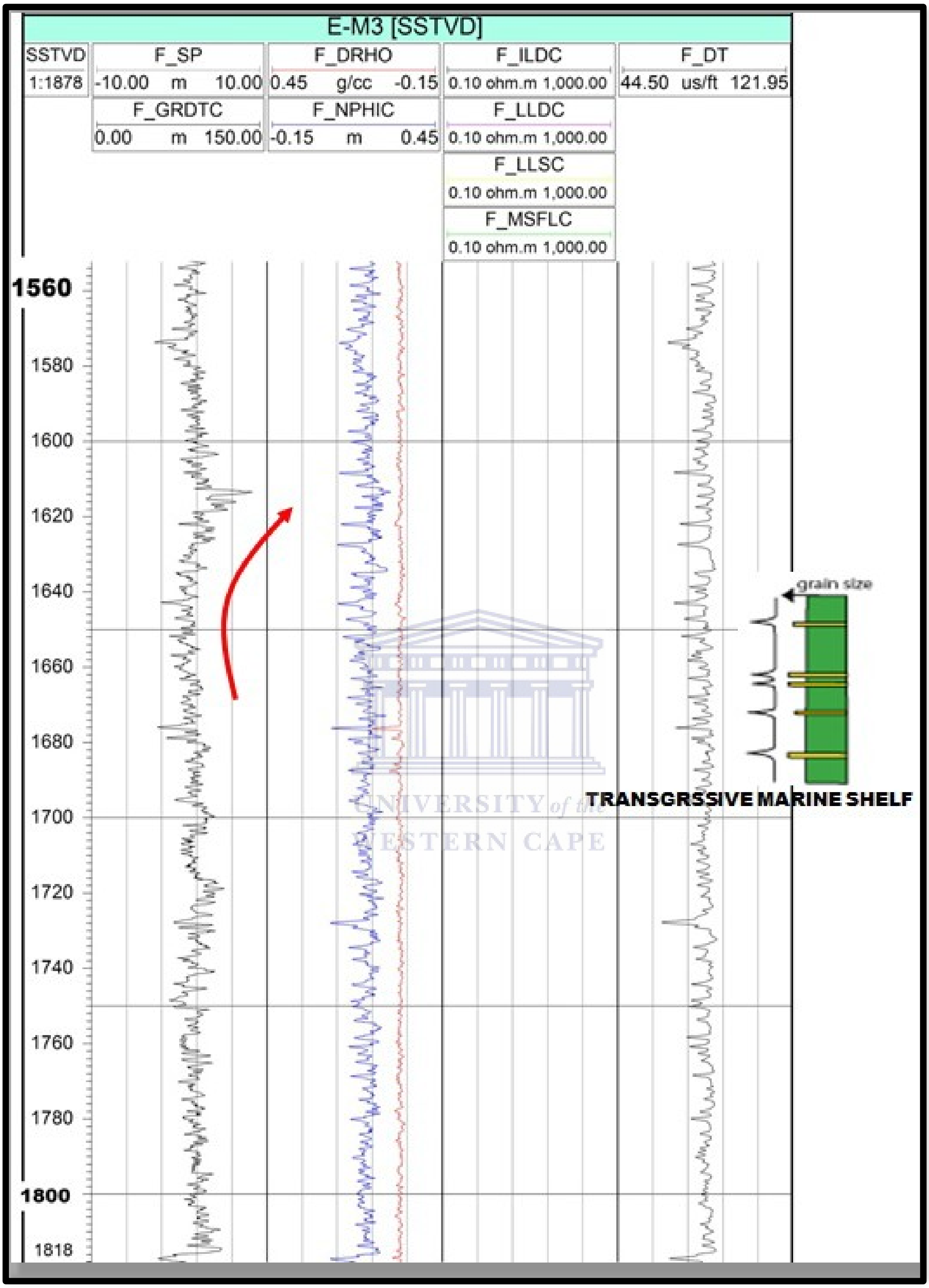


Figure 4.1.17: **Well E-M3** transgressive marine shelf depositional environment.

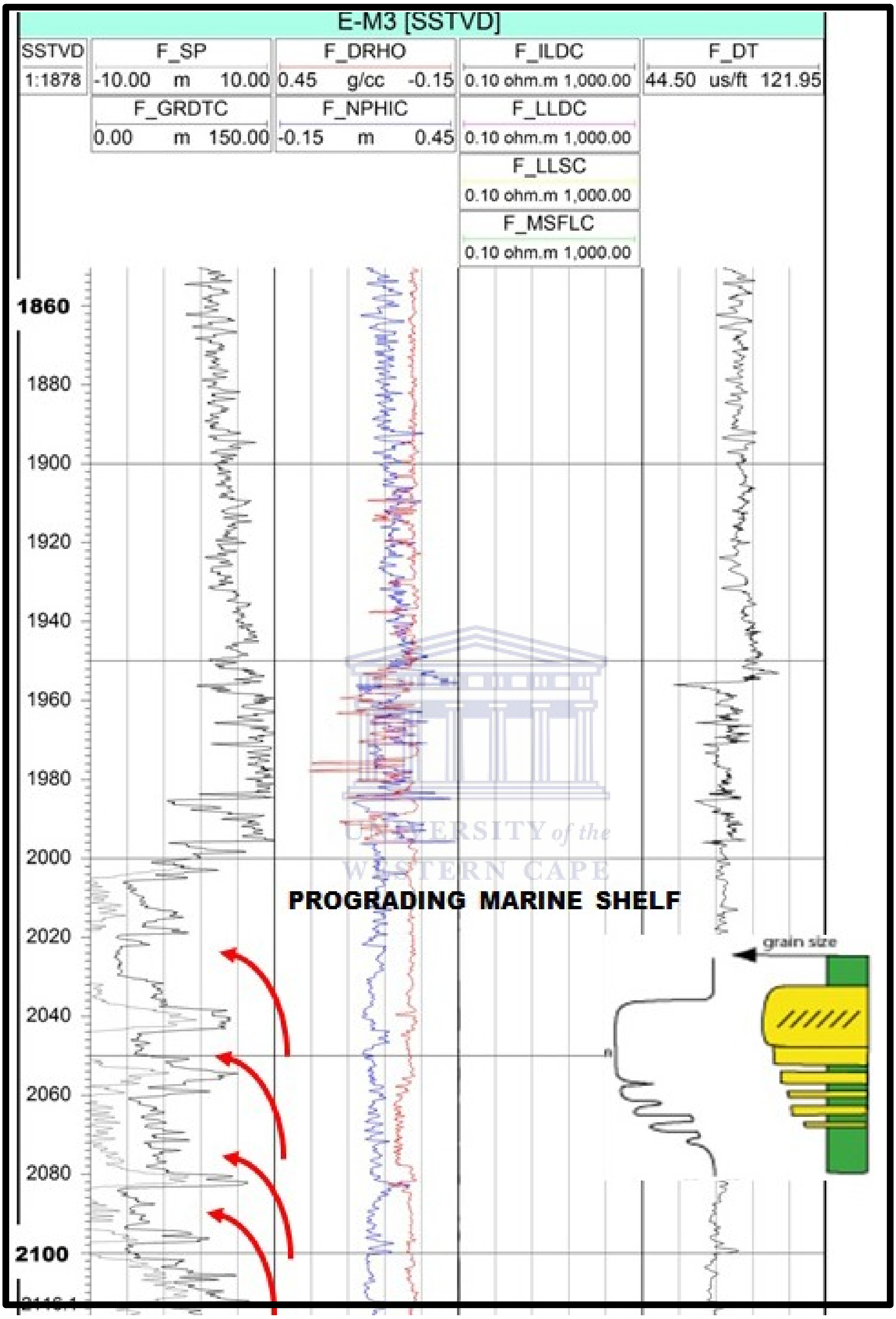


Figure 4.1.18: Well E-M3 illustrates a prograding marine shelf deposition.

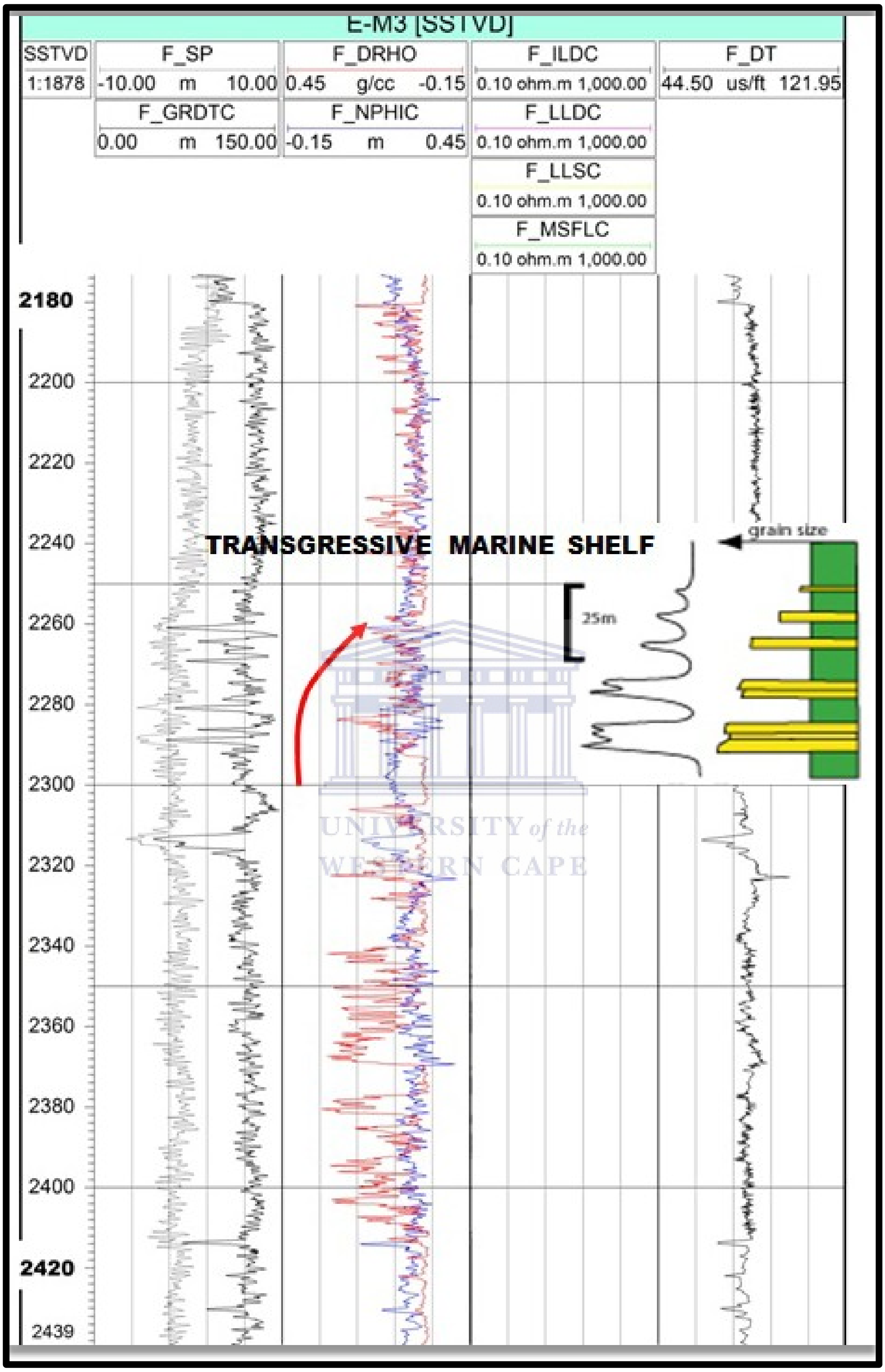


Figure 4.1.19: Well E-M3 illustrates a transgressive marine deposition

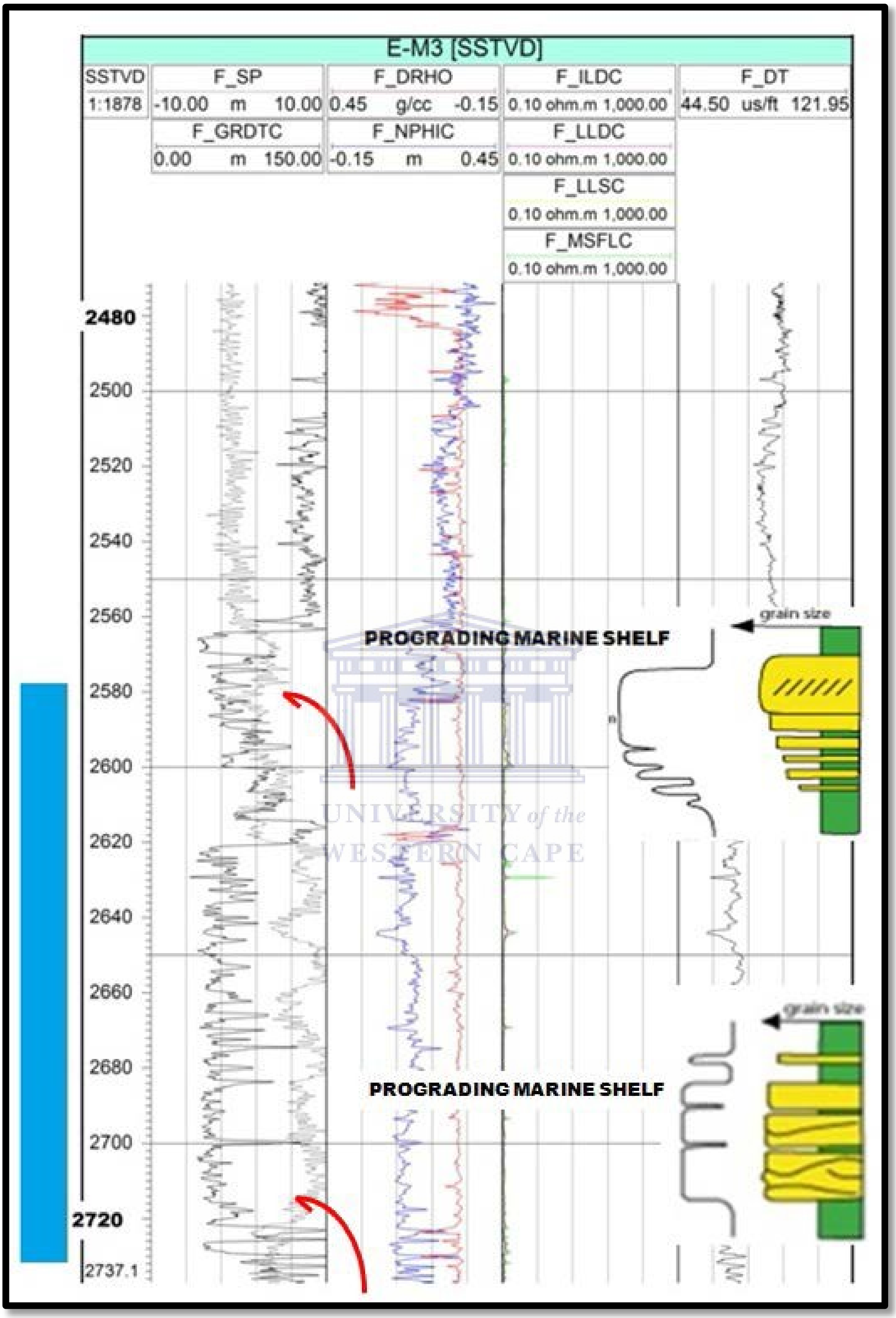


Figure 4.1.20: Well E-M3 displays a coarsening upwards prograding marine shelf environment depositional environment.

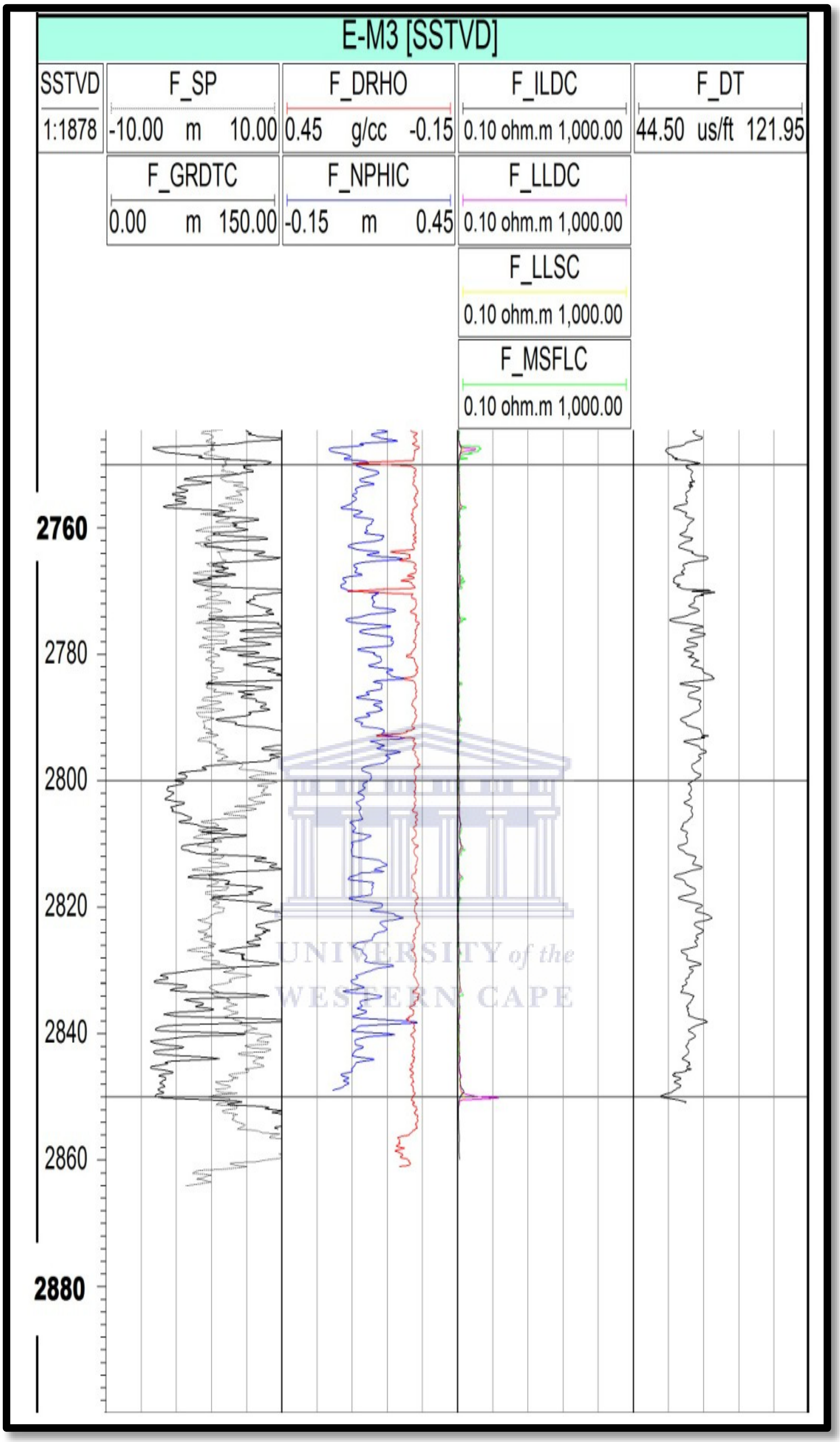


Figure 4.1.21: Well E-M3 displays a proximal shelf depositional environment.

From a depth of 2880m to 2760m (Figure 4.1.21), well E-M3 shows a gamma ray signal which suggests a proximal shelf depositional environment. In figure 4.1.20, well E-M3 from depths of 2737.10m to 2480m, displays a coarsening upwards prograding marine shelf environment depositional environment. At depths between 2580m and 2737m cores were extracted. See page 53 for interpretation.

In well E-M3, at a depth of 2420m to 2180m (Figure 4.1.19), the depositional environment displays a transgressive marine shelf. At a depth of 2100m to 1860m, well E-M3 displays a coarsening upwards prograding marine shelf (Figure 4.1.18). In figure 4.1.17, well E-M3 illustrates a fining upwards transgressive marine shelf from depths 1800m to 1560m. Well E-M3 (Figure 4.1.16) displays a coarsening upwards marine shelf depositional environment from a depth of 1500m to 1260m.

4.2) Interpretation of depositional environments

The interpretation of depositional environments for wells E-AB1, E-M1 and E-M3 will be based on core descriptions which were correlated to the gamma ray logs and on the shapes of the gamma ray logs in the studied wells and in deltaic and fluvial successions.

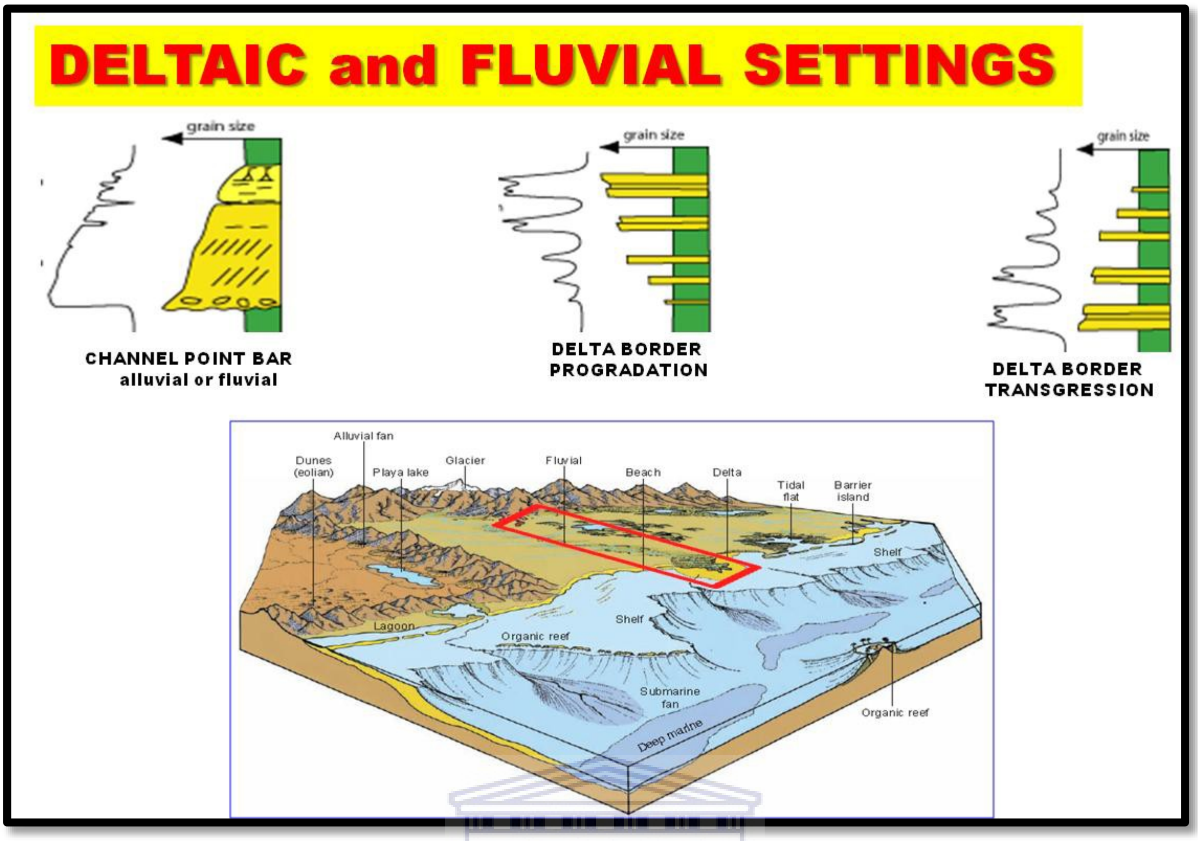


Figure 4.2.1: Illustrates the gamma ray log response and sedimentary log for deltaic and fluvial depositional settings, (Modified from Kendall, 2004)

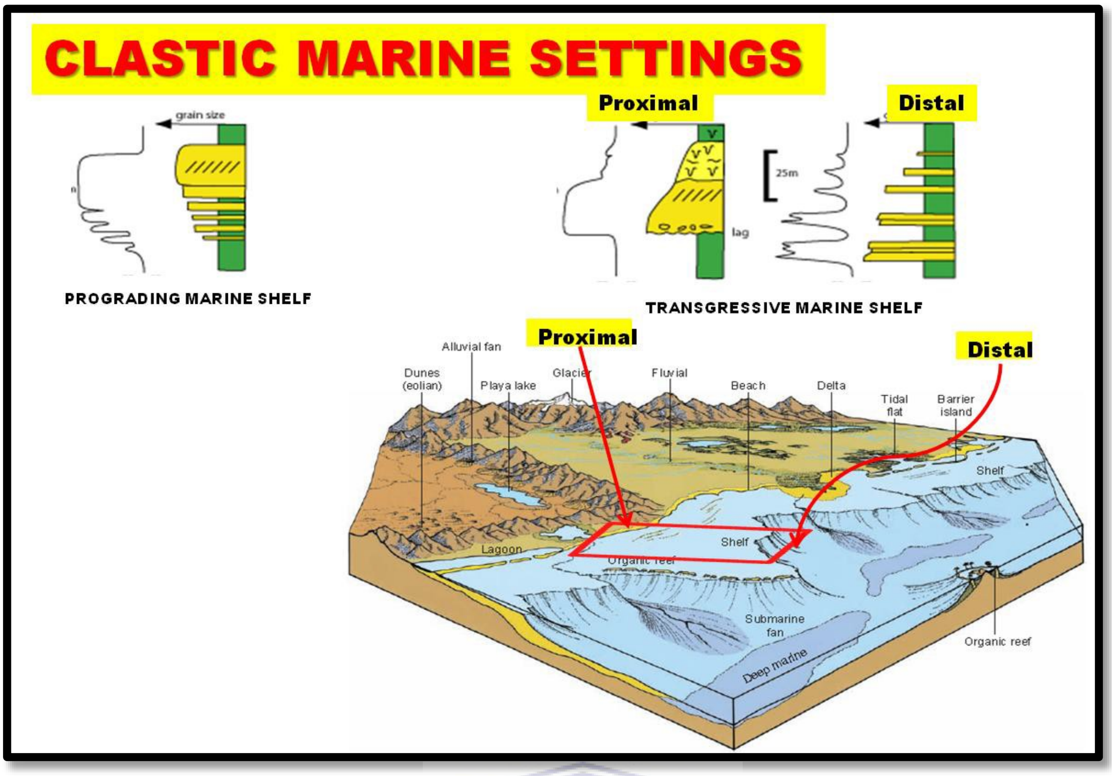


Figure 4.2.2: Illustrates the gamma ray response and depositional setting for clastic marine settings. (Modified from Kendall, 2004)

4.3) Depositional Environment

4.3.1) Depositional environment of well E-AB1

According to SOEKOR's wells reports, well E-AB1 displayed three main depositional environments. Zone 1; from the sea floor to 2684m, marine shelf sediments were penetrated. Zone 2 (2684m to 2795m) showed a transitional sequence with the base of the marine sediments at 2795m. Zone 3 was from 2795m to the total depth of 2952m which had continental environments such as fluvial sediments.

Zone 3: Continental environment

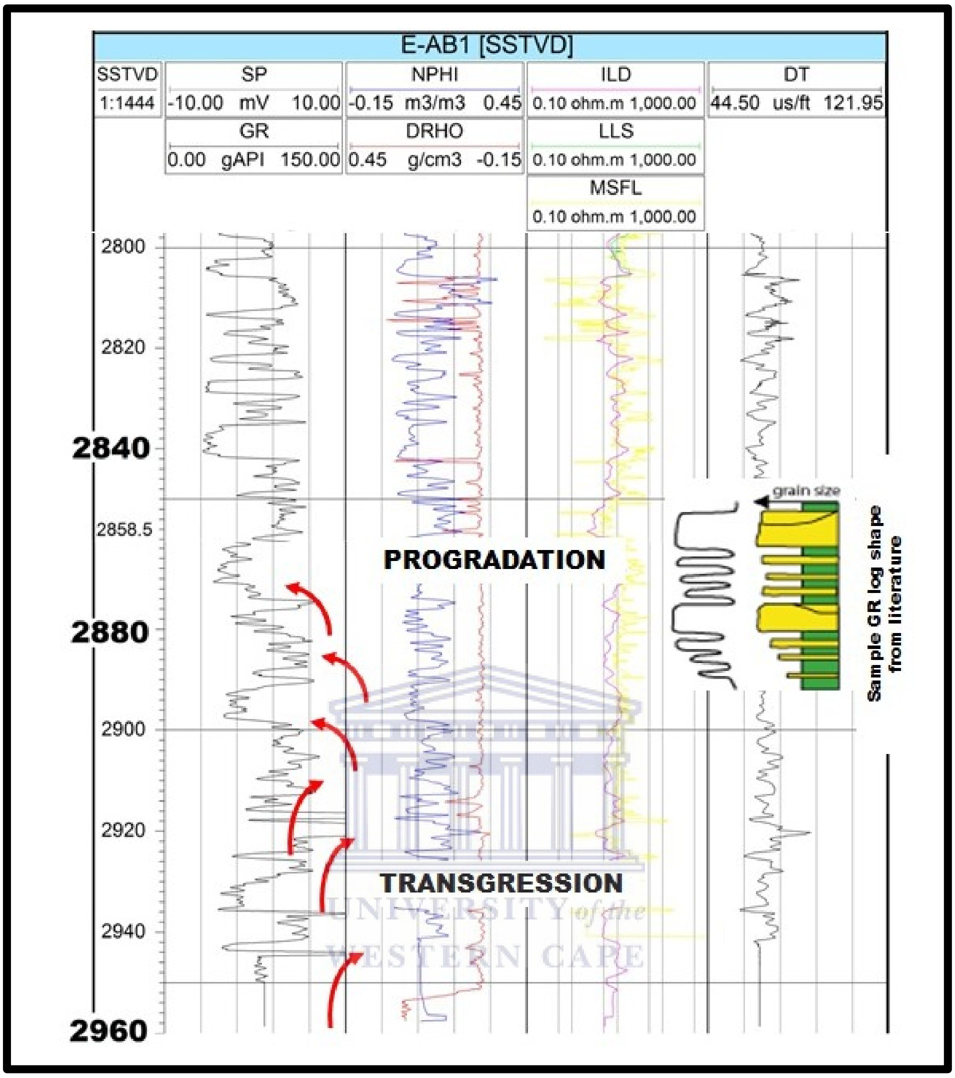


Figure 4.3.1: Depositional environment of well E-AB1, zone 3.

With respect to the lithology of interval 2962m to 2795m to (Figure 4.3.1), Zone 3 is described as a fining-upward and blocky sequence of medium to fine grained sandstones interbedded with red and green siltstones and claystones, interpreted as possible point bar or fluvial channel fills. (Jordaan, 1988). From a depth of 2960m to 2800m the well log illustrates a fining upwards transgressive channel fill sequence transitioning into a prograding marine sequence (Figure 4.3.1) defined fluvial environments

Zone 2 includes the transitional sequence (marine to continental environments). The interval 2795m to 2684m is described as a fining-upward sequence of medium to fine grained sandstone with interbedded grey claystones overlain by a coarsening- upwards succession of grey claystones, siltstone and sandstones (Jordaan, 1988), both typical of marginal marine or transitional environment (described as zone 2). The well log for depths 2789m to 2680m illustrates well E-AB1 as a coarsening upwards sequence shown by the red arrow. See pages 58 and 59 for description of cores.

Zone 2: Transition sequence

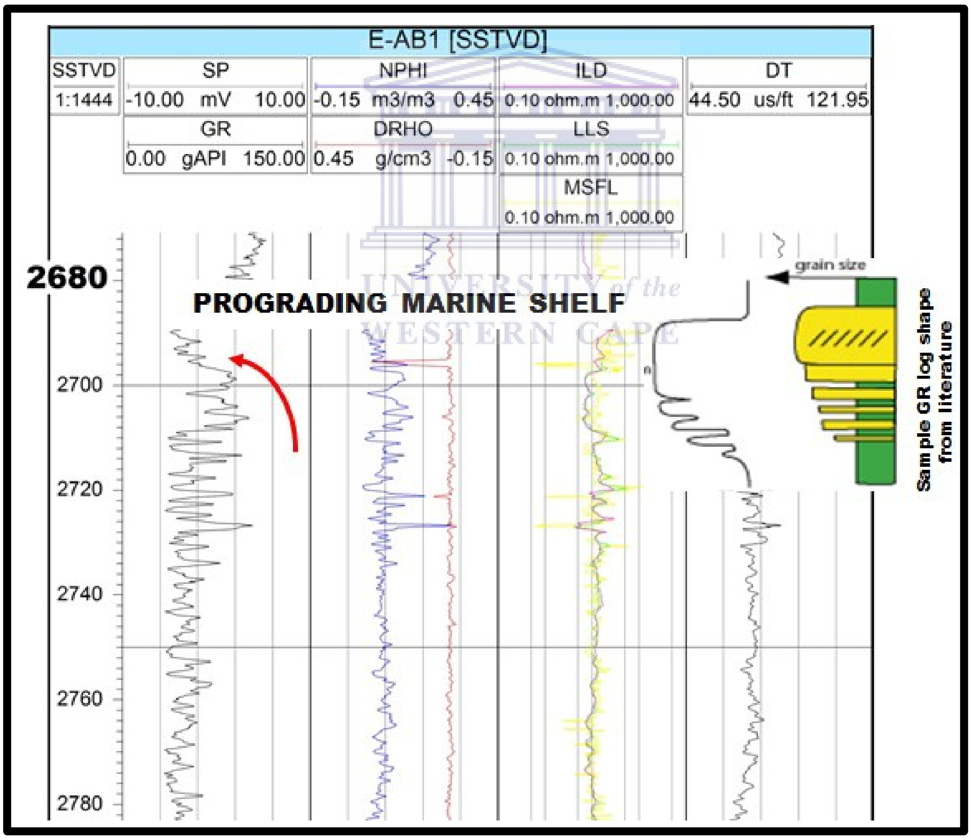


Figure 4.3.2: Depositional environment of well E-AB1 illustrating Zone 2.

Zone 1: Marine sediments

From horizon C (2684m) to 2321m, the succession is composed of basal grey claystones with thin sandstone and limestone interbeds, thus outer shelf sediments. From 2356m down to 2521m the lithology is grey claystones interbedded with thin limestone, sandstone and siltstone. This can be described as outer shelf sediments (Figure 4.1.8 and Figure 4.1.7), which illustrates a coarsening upwards prograding marine shelf. Interval 2356m to 2117m consists of coarsening upward sequences of grey claystone, sandstone and siltstone overlain by blocky, fine to medium grained sandstone, In Figure 4.1.6, well E-AB1 displays a coarsening upwards prograding marine shelf. From 2117m to horizon E (2017m) the lithology is fine to medium grained sandstone, interbedded with grey claystones and minor grey siltstones which occur as stacked tidal bars or thin sand sheets from typical middle shelf environments (nearshore). The well log for E-AB1, displays a coarsening upwards prograding marine shelf transitioning into a fining upwards transgressive marine shelf (Figure. 4.1.6).

4.3.2) Depositional environments for well E-M1

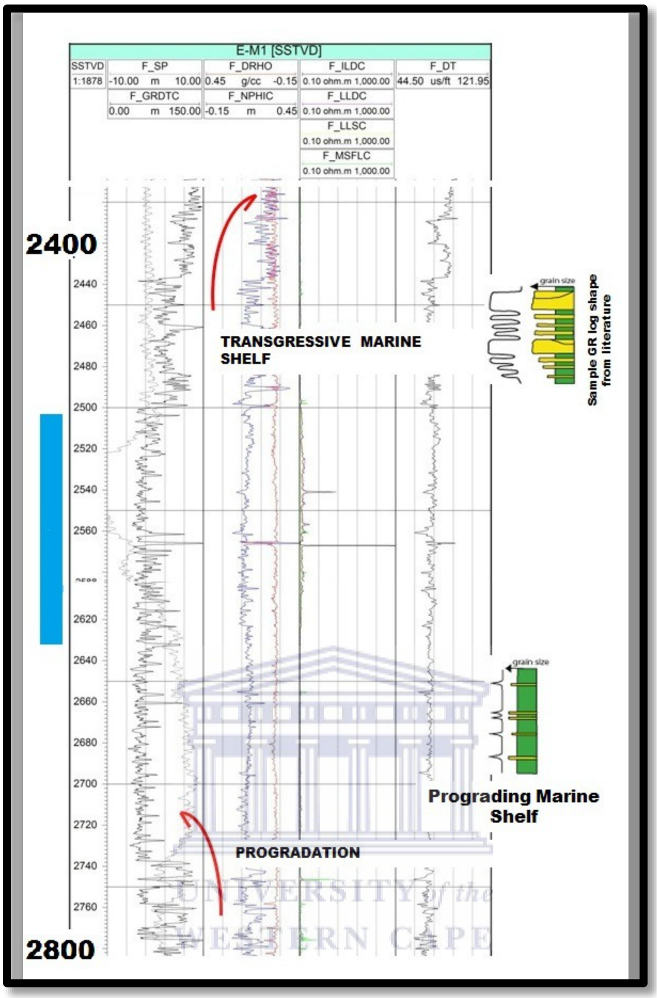


Figure 4.3.3: Illustrates the depositional environment for well E-M1.

From 2800m to 2738m, the lithology consists of interbedded red claystones and discrete pebbly sandstones indicating a continental depositional environment. From 2738m to 2643m consists of a massive fining upwards glauconitic sandstone section which is medium to pebbly at the bottom and very fine to fine at the top. This interval represents a shallow marine environment. From 2640m to 2556m the lithology consists of a fining upwards sequence deposited in a fluvial environment. In well E-M1 (Figure 4.3.3), the depositional environment indicates a fining upwards transgressive marine shelf. The blue section indicates the core extraction interpreted on pages 58 and 59.

4.3.3) Depositional environment of well E-M3

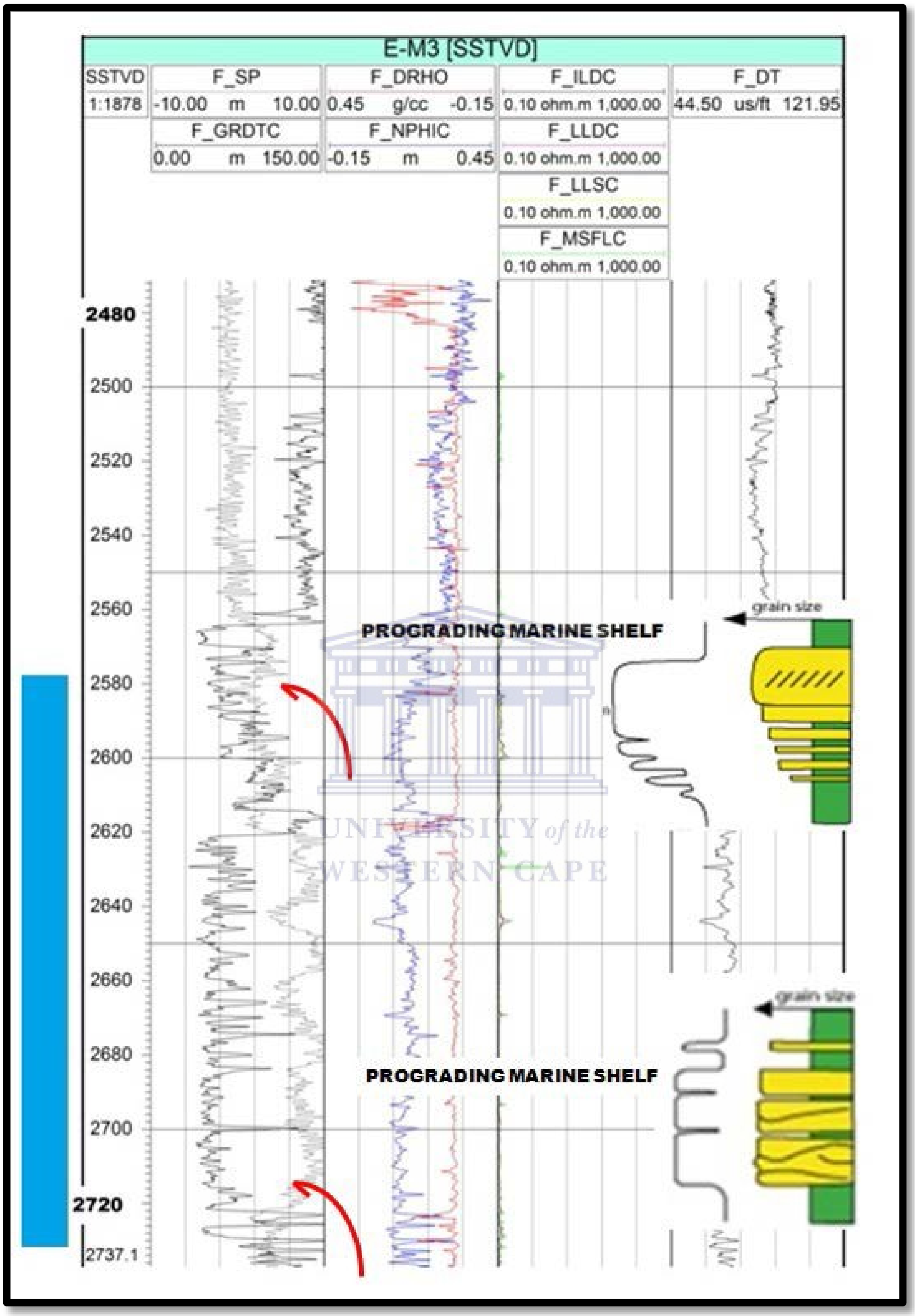


Figure 4.3.4: Illustrates the depositional environment of well E-M3

In well E-M3, the interval 2737m to 2722 indicates green claystones and siltstones common in continental environments, from 2737m to 2480m, the lithology consists of thick shallow marine sandstones with interbedded claystones and siltstones throughout. Well E-M3 illustrates a coarsening upwards prograding marine shelf depositional environment. Also see page 59 and 60 for the description of cores.

4.4) Interpretation of Cores

Information for interpretation of cores were provided by PASA's (1988) completion well reports of wells E-M1, E-M3 and E-AB1. For well E-M1, eight cores were cut back to back over the interval 2508m to 2643m in the sandstone just below horizon C to evaluate a drilling break and gas show at 2506m. Coring was suspended after core 8, when a sharp reduction in ditch gas values and on-site core analysis indicated penetration of the gas water contact.

Cores 1, 2 and 3 (2508m to 2550, 73m) consist of massive glauconitic sandstone. Sandstone beds are coarse to medium grained at the base and fine to very fine at the top. Small pebble lag deposits occur within core 1 and 2. Core 3 shows some crudely imbricate pebbly conglomerate from 2545, 5m to 2548m. Laminated siltstones and sandstones are present in core 1.

Scattered fossilized logs are also present at 2331, 75m in core 3, a sharp contact exists between overlying sandstones and a 30m thick claystone bed. Sediments beneath the contact consists of well-defined sandstone beds of a fining upward sequence illustrating a fluvial cycle. From 2558m to the end of coring, sandstones are non-glauconitic. The lower part of the fining upward sequence, within core 4-8.

Regarding well E-M3, the section at 2580m to 2723m, beneath horizon ‘C’, consists of a coarsening- and thickening-upwards interbedding of claystone, sandstone and conglomerate near the top. The lower half is made up of massive sandstones. Cores 1 to 6 were cut between 2586 and 2685, 54m. The sandstones were tight to slightly porous, light grey, fine to very coarse, with green claystone clasts and traces of pale yellow fluorescence which disappeared beneath 2615m. The conglomerate appeared between 2595m and 2600m and was brown-green-grey in colour and formed by clasts up to 15cm in a coarse sandstone matrix.

According to the core reports written by Muntingh (1987), from a total depth of 2790m to 2782m, the core of well E-AB1 is separated by erosional contacts and exhibits normal grading, cross bedding and is inclined to horizontal stratification in conglomerates. The well logs indicate a fining upwards sequence with conglomerates at the base. Lithologies are non-glauconitic displaying an inner shelf lower marine unit.

Pebbly sandstones and conglomerates become more prominent towards the base of this interval (2745m to 2730m), which indicates a lower shallow marine environment. From 2730m to 2721m, ripple and ripple cross lamination characterizes the top units. Parallel, horizontal bedding was present in coarse grained material contacts between units which are sharp and erosional. The well logs indicate an upward fining sequence, consisting of pebble lags grading into fine to medium sandstone and siltstone. The deposition suggests a lower transitional marginal marine environment. Units are compared to similar units in the E-M1 and E-M3 cores.

4.5) Biostratigraphy

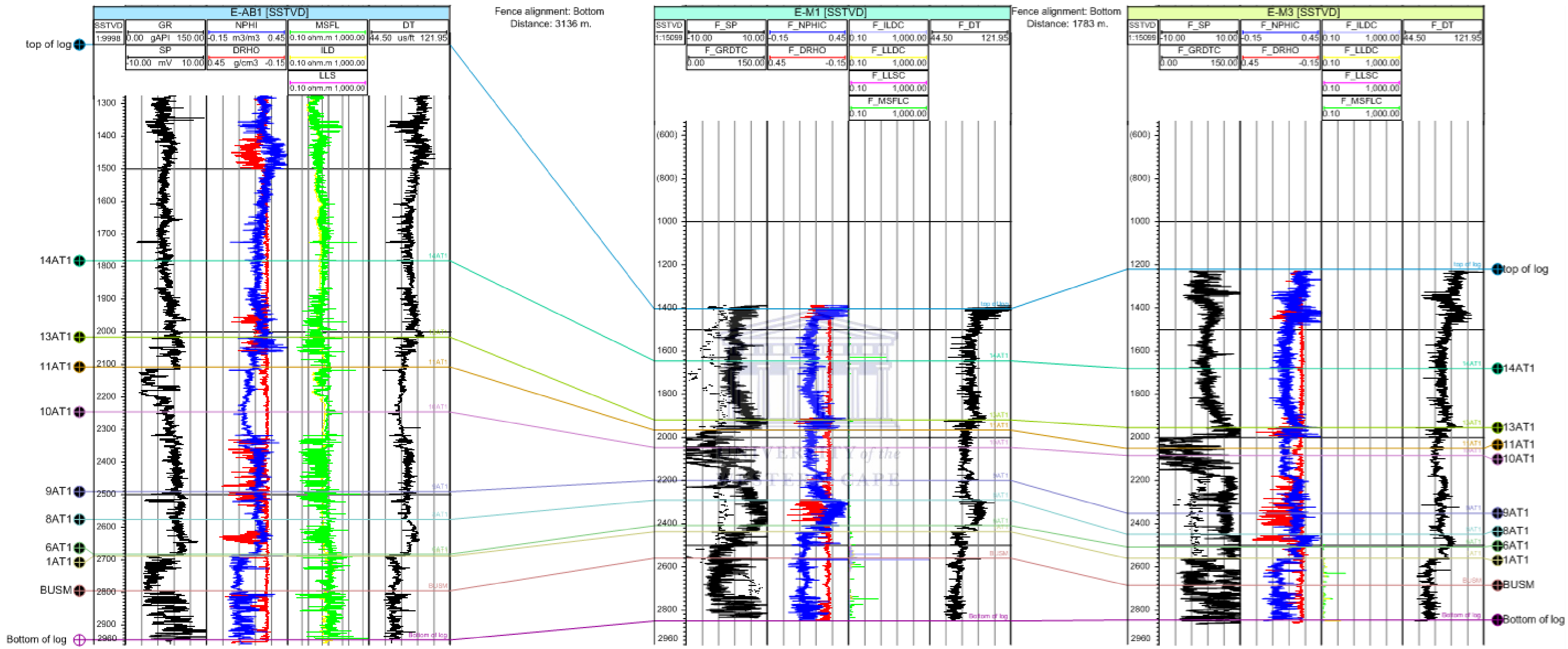
The objective of the biostratigraphy report is to correlate the biostratigraphic information with the geological modelling primarily in the region of the Pre 1AT1 (Horizon C) unconformity in well E-M3 (note that biostratigraphy reports for wells E-M1 and E-AB1 were unavailable). This correlation links the well data with the seismic data in order to establish sequence boundaries, which act as a key process to sequence stratigraphy.

The Pre- 1A interval contains typical Valanginian/Hauterivian fauna (Eoguttulina anglica). Because the condensed section found above the Soekor horizon 1AT1 has been dated as Late Valanginian (Petrie, 1995) elsewhere in the Bredasdorp Basin, it is therefore assumed that these Pre 1AT1 deposits here are Pre Late Valanginian in age.

Assuming some of the fauna to be in situ below the cored interval, it would then appear that the more claystone rich interval from 2862m drillers' depth (dd) to 2742m (dd) is inner marine shelf, shallowing to transitional at about 2700m (dd). Cores 6 to 3 are barren of foram fauna and are therefore also probably transitional or non- marine. Cores 2 to 1 show a coarsening upwards sequence indicating a shallow marine environment.

Post 1A, a major faunal change occurs at 2560m (dd) with the deeper water, fauna is normally found above the Pre 1A reservoir, which (Verneuilina cf. howchini, Gravellina australis) indicates a change to Post 1A. 6A sequence is characterized by low benthonic foram abundance and diversity, which indicate a middle to outer marine environment. A faunal change occurs at 2450m (dd) where a sudden increase in benthonic foram occurs, it is possible that the 8AT1 sequence occurs between 2460m and 2450m (dd). This sequence contains a high amount of red-stained Lenticulina.

4.6) Correlation of wells E-AB1, E-M1 and E-M3



Legend

1AT1- Horizon "C"
6AT1- Horizon "E"
9AT1- Horizon "Q"
13AT1- Horizon "K"
15AT1- Horizon "X"
22AT1- Horizon "L"

Figure 4.6: Showing the correlation of wells E-AB1, E-M1 and E-M3 with well tops on PETREL

4.7) Generation of synthetic seismogram

Well-seismic ties allows well data, measured in units of depth, to be compared to seismic data, measured in units of time. The process of synthetic seismogram generation relates horizon tops identified in a well with specific reflections on the seismic section and uses the sonic, density and velocity well logs to generate a synthetic seismic trace. The synthetic trace is compared to the real seismic data collected near the well location.

In order to display the well tops on the seismic section or line, a time-depth conversion was done to display a synthetic seismogram. To generate a synthetic seismogram, the velocity wireline log is required.

Seismic reflections are the result of the contrast of rock properties, particularly density and velocity. Velocity can be computed from any of the 3 types of logs: sonic, density and resistivity. A sonic log approximates a direct measurement of velocity by recording transit times between a downhole source and a receiver. Velocity is derived from density and resistivity logs mainly on the basis of observed correlations. However, since the data was poorly captured, the generated velocity log was not suitable to display the entire seismic section but it was still possible to use it for interpretation.

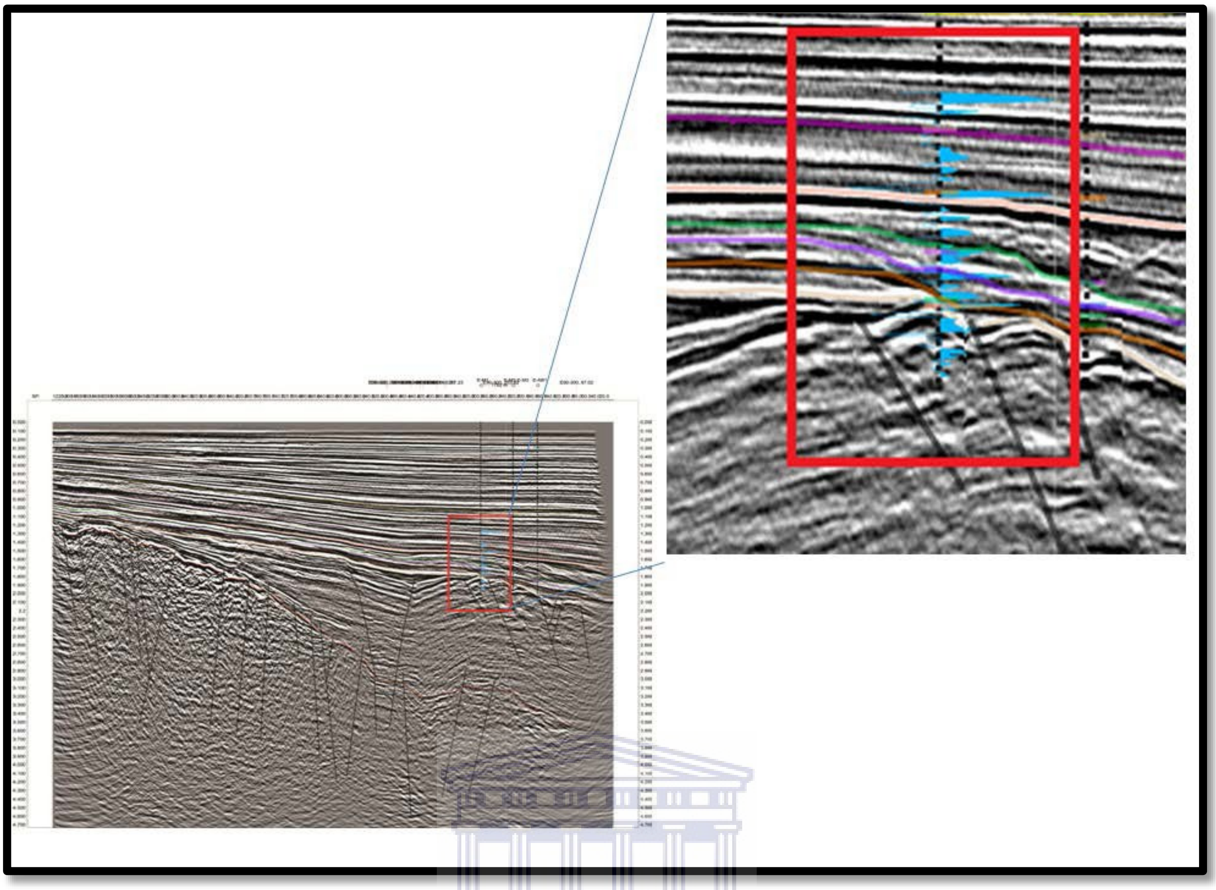


Figure 4.7: Displays the synthetic seismograph on the seismic line E-82-005 and wells E-AB1, E-M1 and E-M3.

The synthetic trace displays accordingly with the well tops as well as the bright peaks of the seismic section therefore, sequence boundaries could be picked with confidence. Figure 4.7.

4.8) Lithology

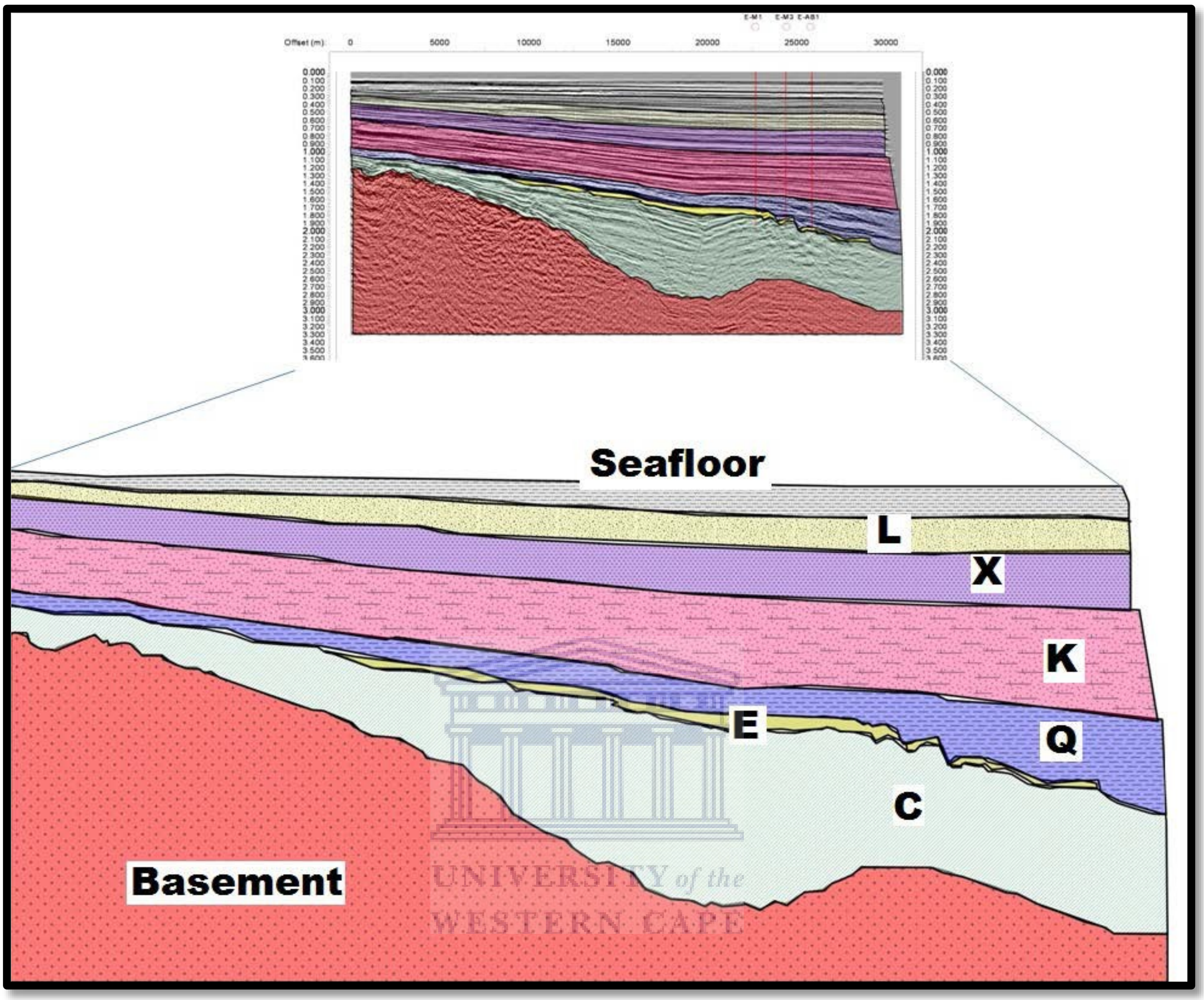


Figure 4.8: Illustrating the well tops from wireline logs on seismic section to display the lithologies of wells E-AB1, E-M1 and E-M3 on the seismic line E-82-005. See below for lithology interpretation.

Table 1: Horizon depths in wells E-AB1, E-M1 and E-M3

	Wells in depth (m)		
Horizons	E-AB1	E-M1	E-M3
Sea floor	124	124,5	123
L	unknown	430	360
X	329	529	540
K	710	unknown	760
Q	1178,5	1160	1170
E	2017	1965	1965
C	2684	2506	2560
total drillers depth (m)	2950	2865	2860

4.8.1) Description of lithology

Total depth to Horizon 'C'

The lithology consists of interbedded red claystone and discrete pebbly sandstone beds laid down in a continental depositional environment. The interval 2738m to 2643m in all three wells consists of fining upwards massive glauconitic sandstone which are medium to pebbly at the base and fine to very fine at the top. They are interpreted as a deepening upwards shallow marine environment.

Horizon 'C' – bottom of the last core

In all three wells E-AB1, E-M1 and E-M3, the approximate interval from 2643m to 2556m consists of a fining upwards cycle deposited in a meandering fluvial setting. From +/- 2556m down to the end of the coring, the sandstones are non-glauconitic. The approximate interval of 2566m to 2557m in all three wells are understood as representing the transition from a littoral setting (nearshore) to fluvial system which consists of two series of fining upward channels showing lateral accretion and limited marine influence. Horizon 'C' was picked at 2506m on the base of drilling breaks (23- 9mins/m) and a change in lithology. In this interval, 8 cores were cut. Cores 1-3 consist of massive glauconitic sandstones. The base of the fining upward cycle within core 4 – 8 is sharp and erosive, and draped with a pebble lag deposit.

Horizon 'E' to Horizon 'C'

From 2506m to 2250m in wells E-AB1, E-M1 and E-M3, the alternation of green non glauconitic sandstones and quartz sandstones is present. Depositional environment ranges down from nearshore/inner shelf at the section top to outer shelf/upper slope in the lower argillaceous portion. The lithology comprises of claystone and siltstone interbeds except for a sandstone interval between approximately 2255m to 2235m in wells E-AB1, E-M1 and E-M3. Claystone and siltstones are medium to dark grey in colour, slightly argillaceous and calcareous. From approximately 2450m to 2286m a good claystone sequence is encountered, which is considered to be a good source rock in the main stage of oil generation.

Horizon 'Q' to Horizon 'E'

From Horizon 'E' (1965m) to 1549m in wells E-M1 and E-M3 consists of mainly claystone with interbeds of siltstone and sandstone. The entire interval represents an upward coarsening sequence where an upper slope/outer shelf setting passes upward into a mid/inner shelf environment. From 1540m to 1140m, this interval consists of soft, sticky claystone that is slightly calcareous with minor siltstone interbeds. The upper interval (1400m to 1160m) entails mainly sandstone with occasional quartz pebble stringers and minor claystone interbeds.

Horizon 'X' to Horizon 'Q'

This interval is subdivided into 3 coarsening upwards units. The third unit is a medium to dark grey calcareous claystone. Very fine to fine, slightly argillaceous and calcareous sandstone stringers exist with siltstone intervals throughout, less towards the base. The interval is a typical upper slope/outer shelf environment ending in an inner shelf environment. The second unit consists of a soft, medium dark grey claystone, slightly calcareous and glauconitic with siltstone interbeds which occurs throughout the interval. The first unit consists of unconsolidated, fine to medium grained glauconitic sands with minor quartz sand interbeds. Interbedding of claystone of medium to dark grey colours is common.

Horizon 'K' to Horizon 'Q'

This interval is a massive claystone sequence with a thin coarsening upwards sandstone and siltstone unit in the lower part.

Horizon 'X' to Horizon 'K'

Consists of a glauconitic claystone sequence with minor siltstone and sandstone stringers towards the top of the interval.

Horizon 'L' to Horizon 'X'

For Horizon 'L', the base of Tertiary was picked up because of the first appearance of *Inoceramus* shell with a predominantly sandy top. It displayed an off-white to medium grey, very fine grained, slightly argillaceous, calcareous and glauconitic nature. Unconsolidated glauconitic and quartz sandstone interbedded with siltstone and sandstone was also observed. Shell fragments, bryzoa and echinoid spines occur throughout. Possible middle to outer shelf depositional setting is evident.

Horizon 'L'

Consists of fine to very fine calcareous, glauconitic and slightly argillaceous sandstones. Sandstones are interbedded with medium dark grey slightly calcareous and carbonaceous claystone. Unconsolidated glauconitic and quartz sands are common throughout the interval with occasional stringers of dolomite and limestone. Shell fragments, foraminfera, bryozoa and echinoid spines were abundant. The interpreted environment is a possible inner to mid shelf.

Seafloor to Horizon 'L'

Fine, medium grey quartz sand, abundant fossils.

4.9) Interpretation of sequence stratigraphy

4.9.1) Sequence stratigraphy framework

The type of basin and how the basin forms are fundamental controls on the sequence stratigraphy framework because each tectonic setting is unique in terms of subsidence patterns and depositional systems that fill the basin. The Bredasdorp Basin is classified as a rift basin, located on a passive margin due to the breakup of Gondwanaland in the Early Cretaceous period. The basin fill is strongly influenced by the displacement geometry on the bounding normal fault system, creating half grabens within the basin. (PASA, 2005; 2006) (Figure 4.7.1).

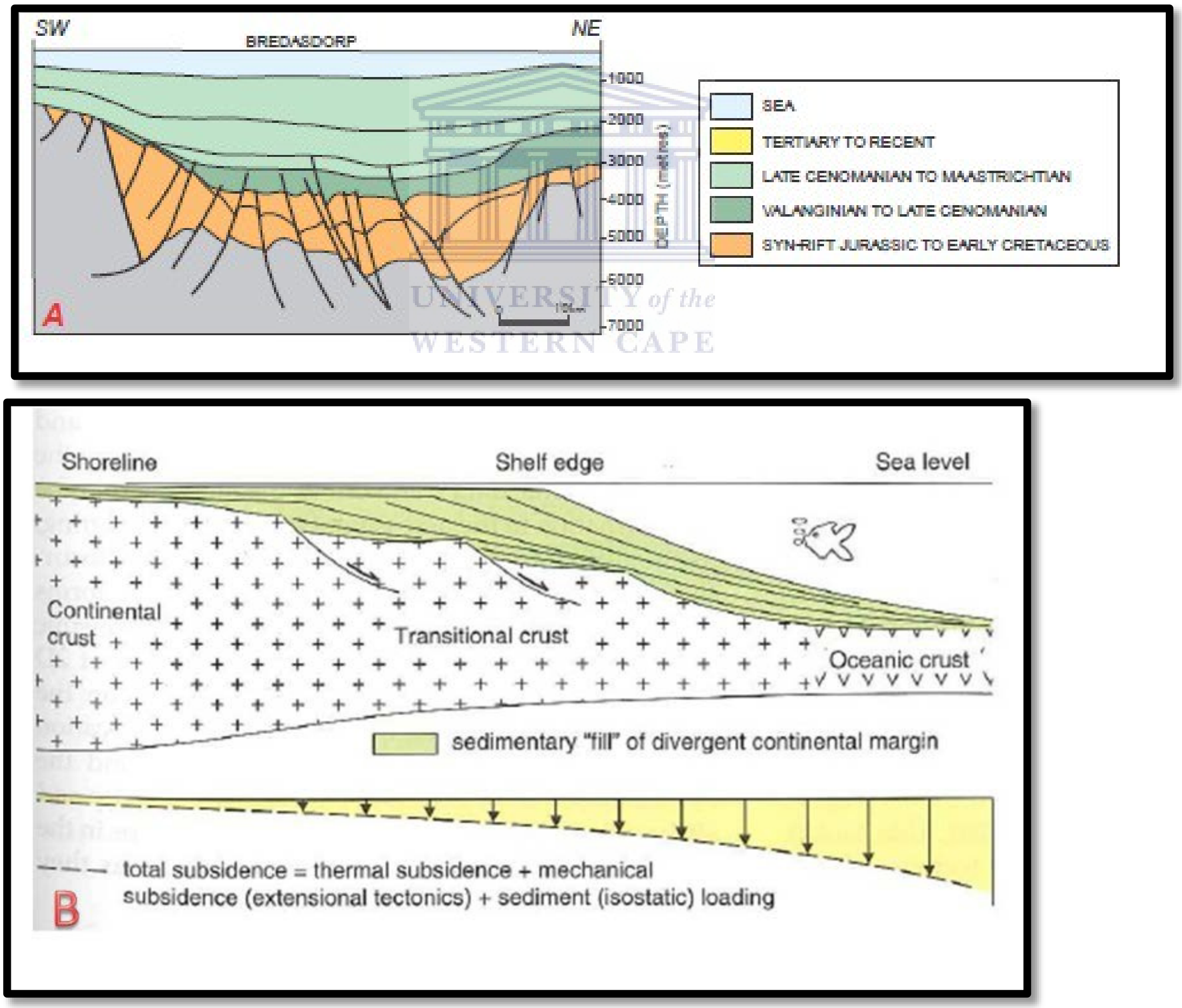


Figure 4.9.1: (A).Cross section of the Bredasdorp Basin illustrating the normal faults and half grabens. (B)Illustrating the dip orientated cross section through a divergent

continental margin, showing overall subsidence patterns and stratigraphic architecture. (Modified from Catuneanu, 2006).

The subsidence patterns represent another primary control on the overall geometry and internal architecture of the sedimentary fill, as reflected by the diverging trends displayed by the time-line horizon in the distal direction seen in Figure 4.9.1:(B) (Catuneanu, 2006). In this context the seismic line yields basic information in the strike and dip directions, location and type of fault, general structural style and overall stratal architecture of the basin fill (Catuneanu, 2006). The dip and strike are vital as it allows for inferring shoreline trajectory, lateral relationships of depositional systems and patterns of sedimentary transport. The seismic reflections reveal key information on subsidence patterns. Subsidence is different in most basins with rates varying mostly along the dip direction. (Figure. 4.9.1(B))

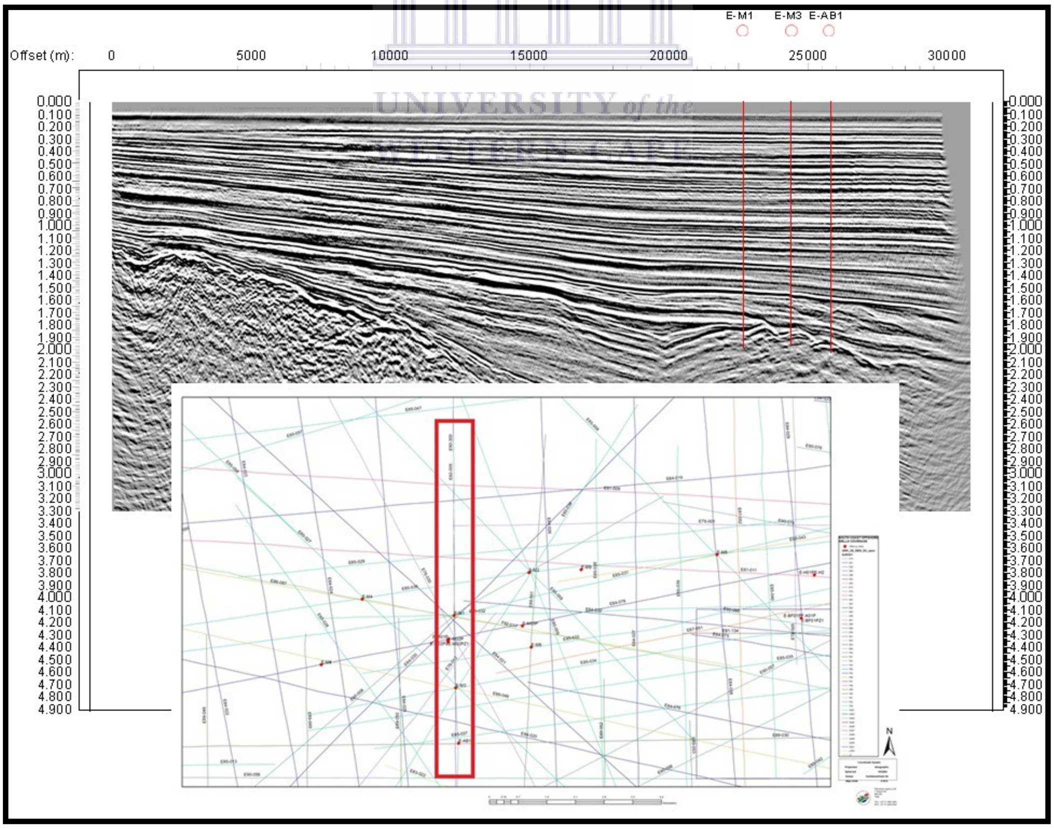


Figure 4.9.2: Base Map of Seismic line E82-005, together with Seismic line E82-005 within the Bredasdorp Basin also displaying the location of wells E-M1, E-M3 and E-AB1.

Paleodepositional reconstruction is important because the spatial and temporal relationships of depositional systems, including their shift directions through time, validate the interpretation of sequence stratigraphy surfaces and system tracts.

4.9.2) Seismic Interpretation

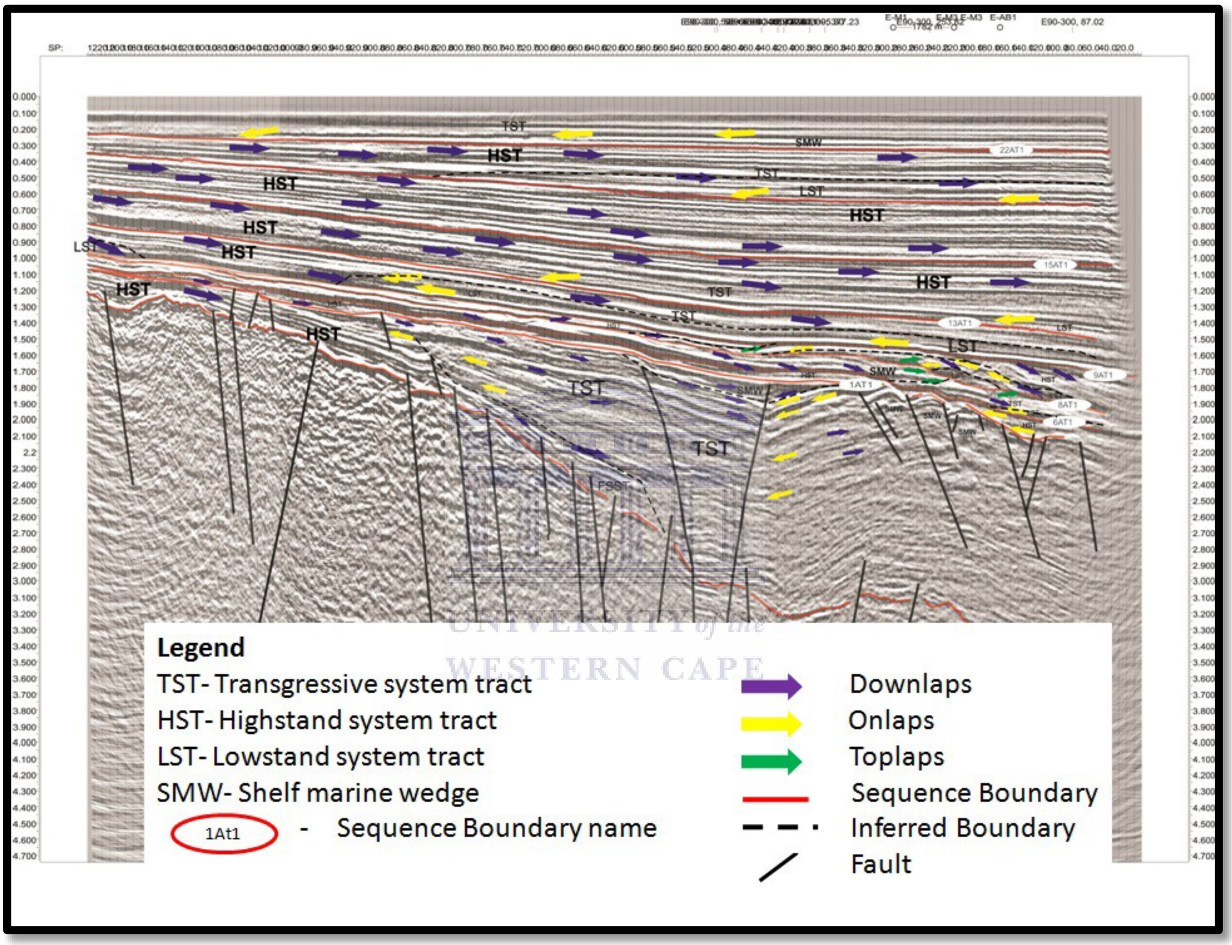


Figure 4.9.3: Showing seismic section E82-005, displaying system tracts and sequence boundaries interpreted in this thesis. See Appendix 3 for enlarged Figure 4.9.3

The current stratigraphy nomenclature of Bredasdorp Basin reflects a committed sequence stratigraphic approach in the seismic recognition of multiple unconformities within the syn-rift successions. Sequences initially defined by significant unconformities, as recognized on seismic sections, were assigned numbers (1-22)

(Brown et al., 1995). Third and higher order sequences, composite sequences and sequence sets recognized subsequently were designated by letters (A, B, C etc.)

Unconformities are named by sequences overlying them (e.g. 1A, 4B) and by their nature (Type1= t1), (e.g. sequence boundary 1At1) (PASA, 2012) as illustrated in Figure 4.9.3.

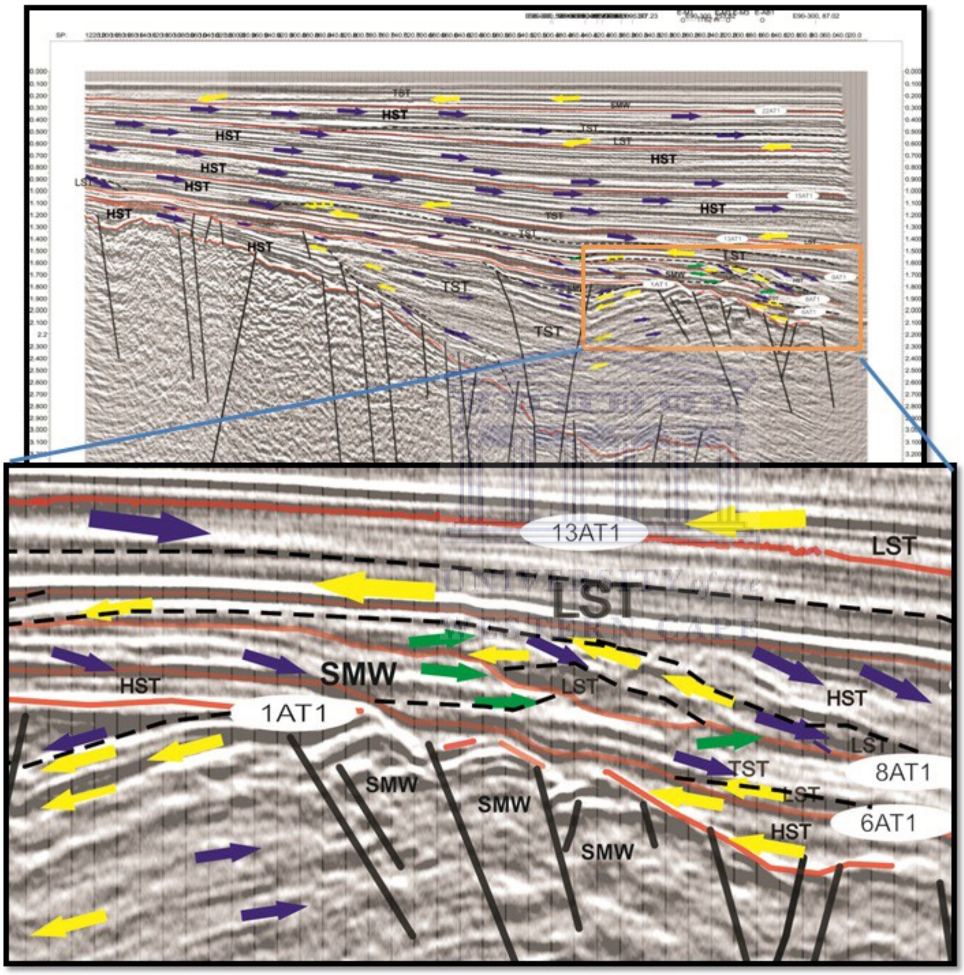


Figure 4.9.4: Illustration of system tracts and sequence boundaries.

The most important surface/sequence boundary is a Late Jurassic unconformity described as Horizon 'C' (1AT1 unconformity) in figure 4.6. This reflector is easy to match to the synthetic seismogram and easily picked with confidence on the seismic line. Its correlation across faults is also reliable in most places but becomes less certain to the south of the area where the fault patterns become more complex and the seismic event becomes slightly more difficult to pick (SOEKOR, 1985). The top of the reservoir was not possible to pick due to lack of information from the synthetic seismograph and sonic log due to the fact that the level was only some tens of meters lower than the strong Horizon 'C'.

Yellow arrows (Figure 4.9.3) indicate coastal onlaps which show a transgressive shoreline shift associated with a rise in base level. The blue arrows indicate downlaps which occur from normal/forced regression associated with fall of the base level. The green arrows could either be toplaps/offlap, however both are associated with a normal regression or forced regression shoreline shift when there is a fall within the base level.

System tracts are interpreted based on strata stacking patterns, position within sequences and types of bonding surfaces and are assigned to an inferred curve of relative base level or to the eustatic sea-level curve when it is possible.

The Lowstand System Tract (LST) is formed by sediments that accumulate after the onset of relative sea-level fall, when the sea level stabilizes in a low level during regression. When the sea level falls below the shelf break (type 1 sequence boundary), the former marine shelf is eroded away by fluvial systems that carry most of the sediment directly to the abyssal plain, at the base of the slope. The LST deposits include the submarine fans laid down on the abyssal plain and slope and the fluvial sediments that fill partially or completely the valleys incised in the marine shelf (previous highstand deposits).The LST is bounded at the base by a type 1 unconformity, and on top by the transgressive surface.

Conversely, if the sea level falls down to a position above the shelf break (type 2 sequence boundary), the sediment is transported to the shelf edge rather than the abyssal plain, so a Shelf Marginal Wedge (SMW) is formed. SMW is bounded at the base by a type 2 unconformity, and on top by the transgressive surface.

The Transgressive System Tract (TST) is formed by sediments which accumulated during the sea level rise until the time of maximum transgression or sea level, which is represented by the Maximum Flooding Surface (MFS) formed when marine sediments reached their most landward position. The TST lies directly on the transgressive surface and below the MFS and internally shows a retrograding/onlapping pattern.

Finally, the Highstand System Tract (HST) is formed when the relative sea level is high and constant, so the sediment accumulation rates exceed the rate of increase in accommodation. Therefore the HST deposits show prograding and aggrading clinoforms that commonly thin downdip and are capped by a topset of fluvial sediments. The HST is bounded by the MFS at the base and a sequence boundary at the top.

Chapter 5

Discussion

The overall sequence stratigraphy of the three studied wells in Bredasdorp Basin is discussed in this section, by detailing the sequence stratigraphy framework and depositional environment derived by using electro sequence analysis.

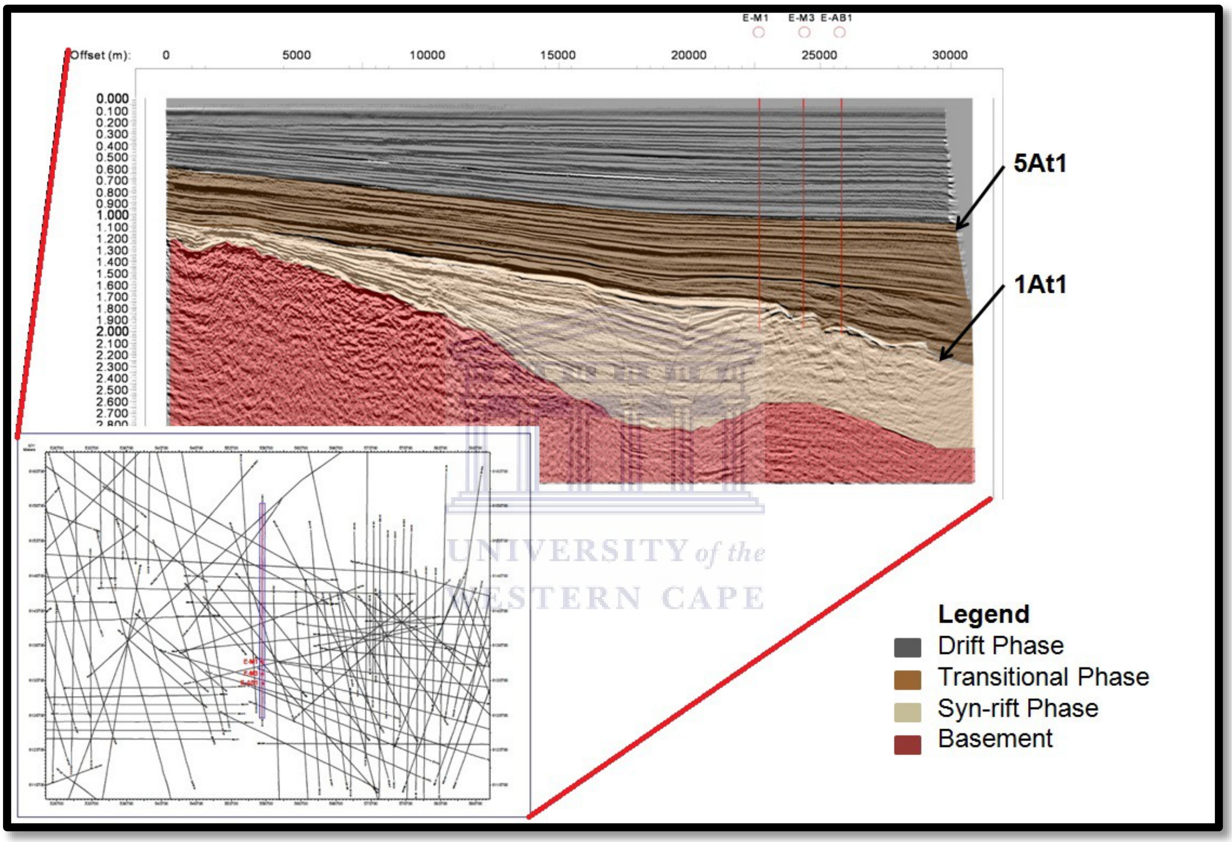


Figure 5.1: Seismic line E82-005, from base map of the southern coast of Bredasdorp Basin, with wells E-M1, E-M3 and E-AB1, illustrating the syn-rift phase, drift phase and transitional phase.

Syn-rift phase

Two phases of syn-rift sedimentation have been recognized in the Bredasdorp basin by Jungslager (1996). Syn-rift 1 sedimentation which began in the Middle Jurassic Period comprises four lithogenetic units.

a) Lower fluvial interval, which represents the initial graben-fill and is comprised of claystones, sandstones and conglomerates deposited in alluvial fans and fluvial environments (Broad et al., 2006). According to the SOEKOR well completion reports, the lower fluvial sequence for E-M wells consists of non-glauconitic, feldspathic sandstones and interbedded red and green coloured shales. Shale beds are interpreted as overbank/flood plain shales and sandstones represent mainly channel deposits and minor flood sandstones (crevasse splay deposits).

   Well E-M1 (depth 2738m to 2685m) lithology consists of interbedded red claystones and discrete pebbly sandstone beds representing a continental depositional setting which corresponds to the description of Broad et al. (2006) description. Well E-M3 and E-AB1 correlates to E-M1 with interbedded continental green claystone/siltstone and pebbly sandstones with red lithologies below depths of 2734m.

b) Lower shallow marine interval, representing the first marine incursion into the basin comprising of glauconitic fossiliferous and stones representing prograding beach deposits hosting foraminifera of Portladian age (Kimmeridgian) (Broad et al., 2006). Well E-M1 (depths 2506-2556m) consists of a massive glauconitic sandstone unit. Well E-M3 has a 31m interval of green claystones, siltstones and pebbly sandstone, the latter is a thick massive shallow marine sandstone sequence. Well E-AB1 has a transitional/marginal (also known as estuarine environments) marine unit of 24m overlying a sub-wave base marine sandstone with clast interbeds deposited in a high energy shelf environments (SOEKOR well reports)

c) Upper fluvial interval, consisting of alluvial floodplain and meandering fluvial deposits (Broad et al., 2006). This sequence is encountered wells E-M1, E-M3 and E-AB1, characterized by interbedded sandstones and shales. Sandstones are coarse to very fine grained, poorly size-sorted, with common pebbly lags at the base of some units. Argillaceous clasts and wood debris are common constituents of the sideritic sandstones which are non-glauconitic and common within the Bredasdorp Basin.

d) Upper shallow marine interval, characterized of massive glauconitic fossiliferous sandstones of Late Valanginian age. All 3 wells E-M1, E-M3 and E-AB1 intersected mainly sandstones with minor shales in this interval. Towards the base, sandstones are mainly fine-medium grained and some parts pebbly and glauconitic. Bedding units commonly fining upwards from erosive bases with cross bedding. Sedimentary and petrographic characteristics indicate a decrease in depositional energy regime indicating a transgressive sequence. The coarse grained basal part of the sequence is interpreted as middle and upper shoreface.

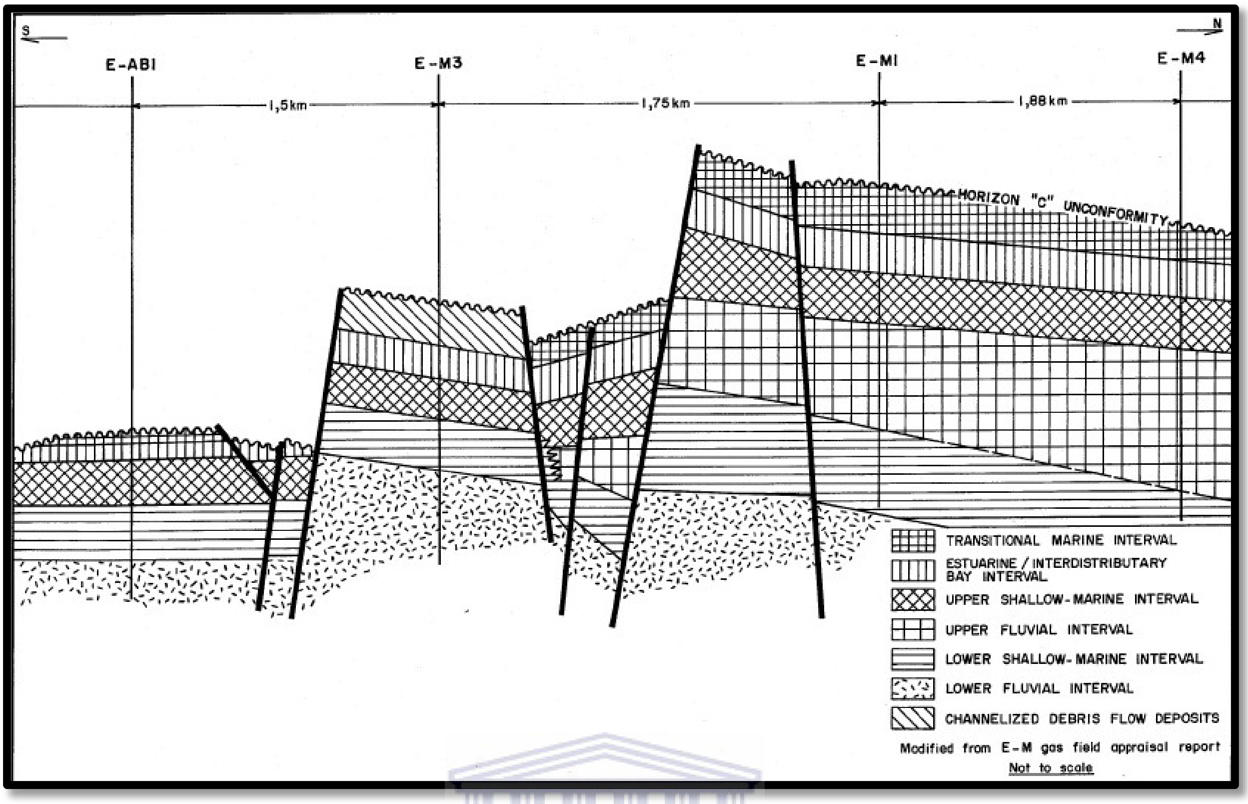


Figure 5.2: Schematic representation of lithofacies correlation in E-M1, E-M3 and E-AB1 wells below the Horizon 'C' unconformity. (Taken from SOEKOR well report, Muntingh, 1986)

The syn-rift 1 succession is truncated by the regional Horizon 'C' (1At1) unconformity. According to Jungslager (1996), the Horizon 'C' unconformity (Figure. 4.9.3) represents the onset of a renewed phase of rifting (rifting 2) which was initiated as a consequence of initial movement along the Agulhas Falkland Fault Zone (AFFZ) at Valanginian-Hauterivian boundary time (121Ma). During this period of regional tectonism, renewed block faulting, reactivation of faults, local inversion and folding provided structures for oil and gas accumulations (Van der Merwe and Fouché, 1992). Further turbidite sedimentation began at those times covering the older nearshore sandstone beds and making the Horizon 'C' (1At1) unconformity a very noticeable regional unconformity. Thus the Horizon 'C' (1At1) unconformity marks the onset of the transform motion along the AFFZ and of the rifting 2 phase

(PetroSA 2003, see Figure. 2.1.4). Syn-rift 2 interval contains Hauterivian deep marine shales which drape over tilted fault blocks and indicate rapid subsidence and widespread flooding. The end of phase is marked by the 6At1 unconformity (in Figure. 4.9.3).

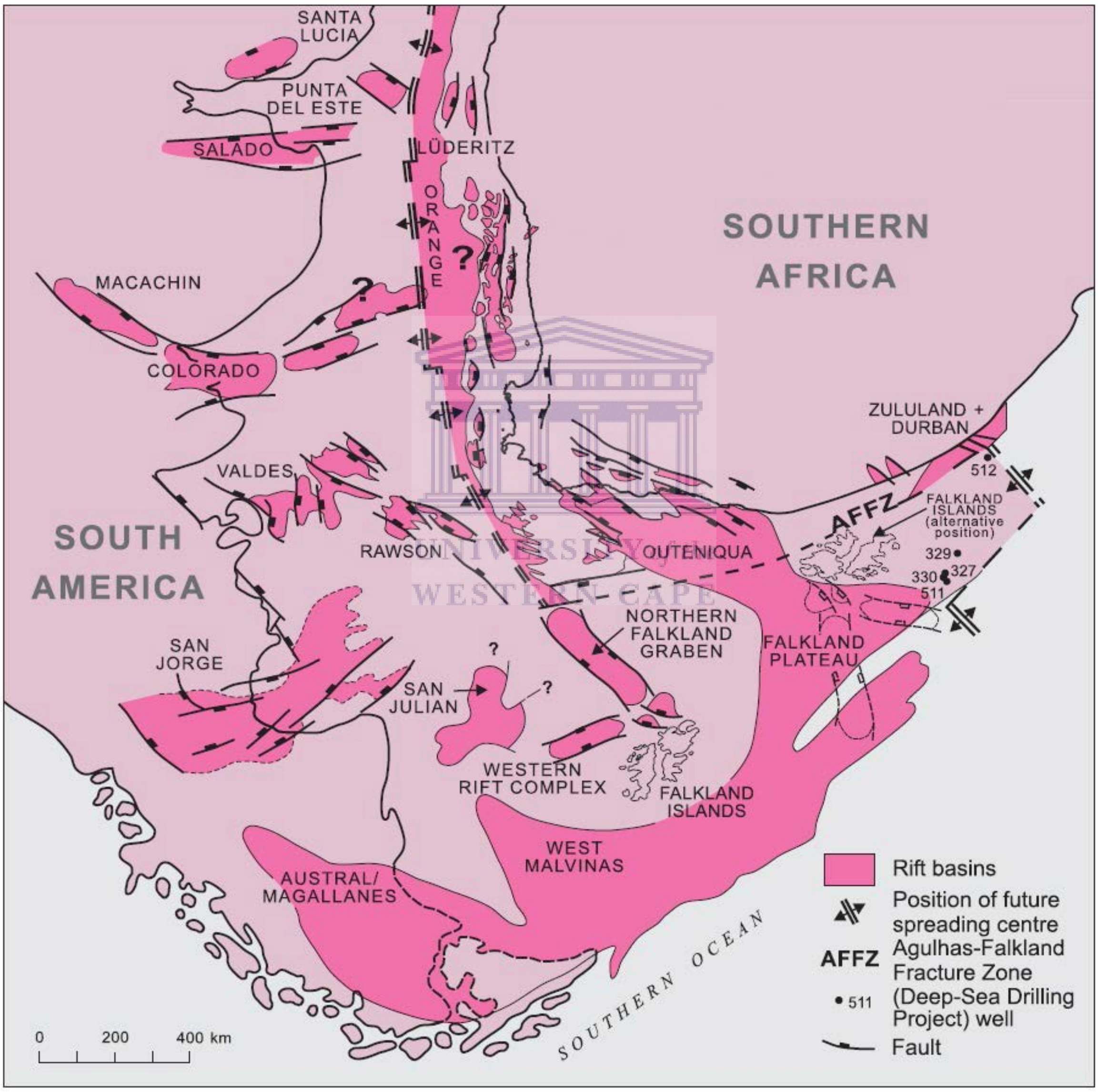


Figure 5.3: Plate reconstruction illustrating the pre-break-up configuration of Late Jurassic to Early Cretaceous rift basins. Also illustration the Falklands microplate might have undergone clockwise rotation of 180º (from Jungslager, 1999a).

Between Horizon 'C' and 'E' (1At1 and 6At1) in the syn-rift phase 2, well E-M1 consists of well sorted, clay free, very fine to medium grained, sandstone with pale yellow fluorescence cut from 1765m to 2080m. From 2265m to 2586m the lithology consists of alternating claystone and siltstone except for an interval 2235 and 2255m. The sedimentary environment ranged from nearshore-inner shelf for the top of the sandstone section to outer shelf-upper slope towards the base. The interval for well E-M3 has a less sandy upper part, composed mainly of claystone with poorly developed shelf sandstone interbeds. Well E-AB1 has a predominantly claystone succession with stacked coarsening upwards shelf sandstones just below the 6At1 unconformity (in Figure 4.9.3).

Transitional phase

The transitional phase (Figure 5.4) of sedimentation was influenced by tectonic events, eustatic sea-level changes and thermal subsidence and characterized by repeated episodes of progradation and aggradation (Broad et al., 2006) that could be correlated with the eustatic sea level curve (Appendix Figure 2) (Brown et al., 1996).This phase is characterized to occur between 121Ma to 103Ma, from the top of the Horizon 'C' 1At1 unconformity to the base of the 14At1 unconformity, which marks the onset of thermal sag (also known as the drift phase).

Drift phase

The beginning of the drift phase (Figure 5.5), is marked by the Middle Albian14At1 unconformity. By the Late Albian time, the trailing edge of the Falkland Plateau had cleared the Columbine-Agulhas Arch (Figure 5.3) and thermally driven subsidence became effective (Broad et al., 2006). The deep water submarine fan sandstones associated with the 14At1 unconformity are economically important as oil reservoirs. The 15At1 sandstones are the last significant sands deposited in the basin where later the infill consisted of claystones and siltstones. During the Turonian (15At1 unconformity), a world-wide highstand led to the deposition of thin organic-rich shales (Figure 4.9.3).

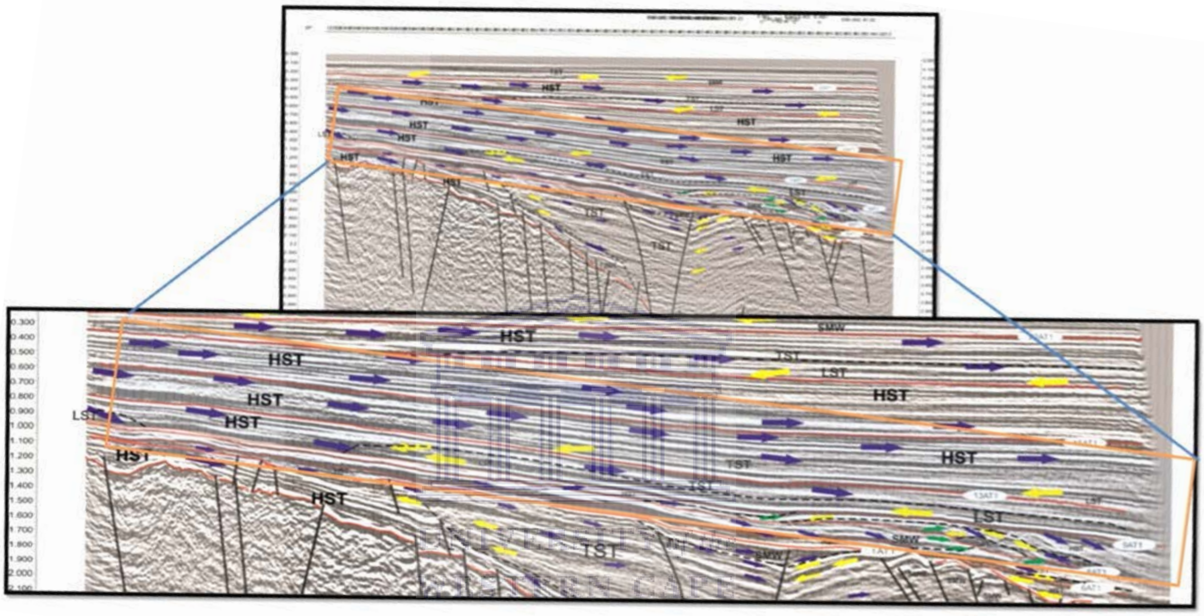


Figure 5.4: Illustrating the transitional phase on seismic line E82-005 between unconformities, Horizon 'C' (1At1) and (15At1). See Appendix 4 for enlarged Figure 5.4.

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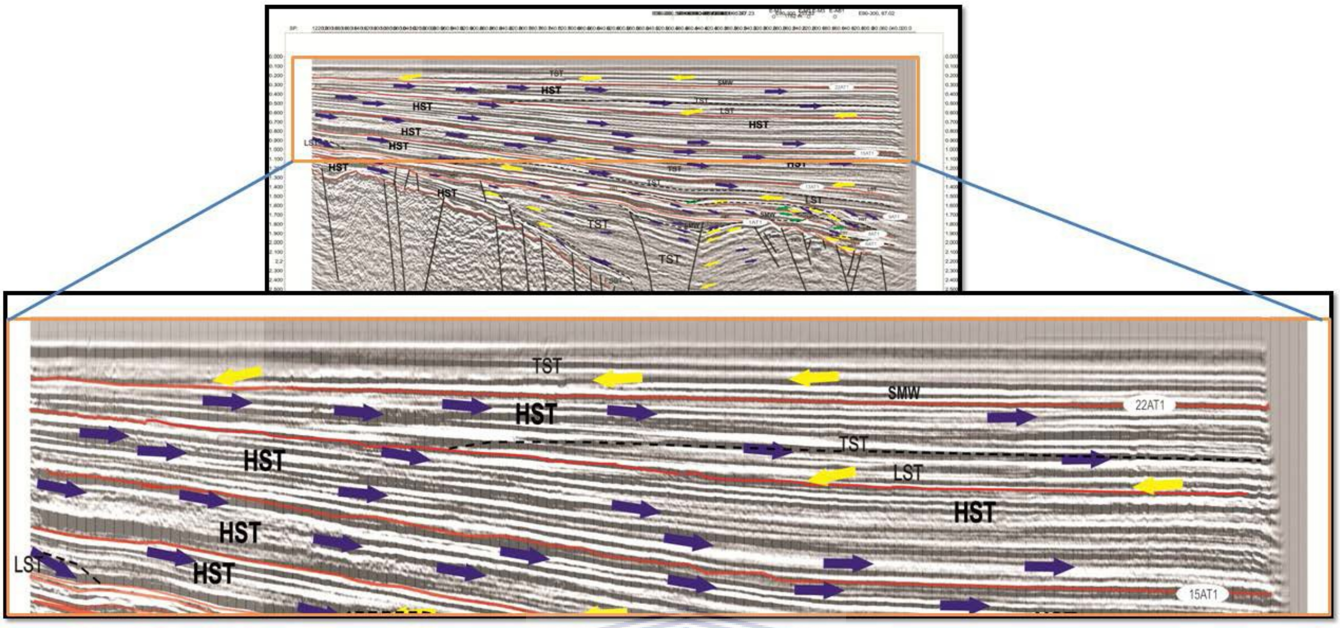

Figure 5.5: Showing the drift phase on seismic line E82-005 between unconformities 15At1 and 22At1. See Appendix 5 for enlarged Figure 5.5

Chapter 6

Conclusion

The E-M1, E-M3 and E-AB1 structure forms a local high in the Bredasdorp Basin. The basin formed as a response to movements along the Agulhas Fracture Zone during the separation of the South African plate and Falklands Plateau. The structure forms a fairly low relief faulted dome structure. Towards the north and east, the structure is gently dipping, but more steeply dipping towards the south and west. Faulting is mainly east-west and down throwing towards the basin centre has produced an elongated graben area between wells E-M1 and E-M3.

In the studied wells, this interval refers to the Upper Shallow Marine, the dynamic alternation of coastal estuarine and non-marine alluvial deposition is mainly controlled by progradation. Initially in the E-M area, sandstone, siltstone and shales of the lower fluvial sequence were laid down. Local warping (in response to tension stress associated with rifting along the AFFZ) led to marine incursion to the north, though the area around the E-M3 well continued receiving fluvial sedimentation due to the local influence of an estuary. The marine deposits of this incursion, from the lower marine sequence were affected by tectonic movements that subsequently led to the return of fluvial deposition (upper fluvial sequence) in the region of the northern wells. Downwarping in the area of well E-M3 resulted in a new marine incursion and commencement of deposition of the upper marine sequence together with fluvial sequences. General thermal basin subsidence led to this sequence eventually spreading across the whole area.

The top of the upper marine succession marks the top of the reservoir. In this context, the pebble conglomerates found in wells E-M3, E-M1 and E-AB1 above the upper marine sequence are thought to have resulted from local fault controlled sedimentation.

To conclude, the electro sequence log shape trends gave a key understanding to each well and their depositional environment. Well E-AB1, E-M1 and E-M3 displayed a continental/ fluvial setting at a depth below Horizon ‘C’. Horizon ‘E’ indicated a transitional marine setting and above the Horizon ‘K’, a shallow marine setting was established.

According to the E-M3 well report, stated by Petrie, (1995), definite age breakdowns are not possible using the foram fauna present although typical Valanginian/Hauterivian fauna is found below 2520m and typical Pre 13A fauna higher up in the studied interval. Because of this, definite sequence name assignments on biostratigraphic grounds are not possible and the Soekor sequence terminations have been adopted. Eg, Horizon “C” instead of “1AT1”. The general depositional environment rangers from Inner Neritic to Transitional in the Pre 1A reservoir with the uppermost coarsening upwards interval, above the 5AT1 the depositional environment ranges between Middle and Outer Neritic.

5AT1 appears to occur close to the sample at 2560m with the 5A MFS (Maximum Flooding Surface) occurring at 2540m. 6AT1 occurs between the sample at 2500m and 2510m with the 6A sequence being characterized by low benthonic foram abundance here. 8AT1 occurs between the samples at 2450 and 2460m with the 8A MFS possibly occurring at 2410m. 9At1 occurs between the samples at 2340m and 2350m. The sequence stratigraphy boundaries could therefore be picked at certain depths and seismic analysis could commence establishing the syn-rift phase, transitional phase and drift phase, through this whole process the objective the thesis was reached.

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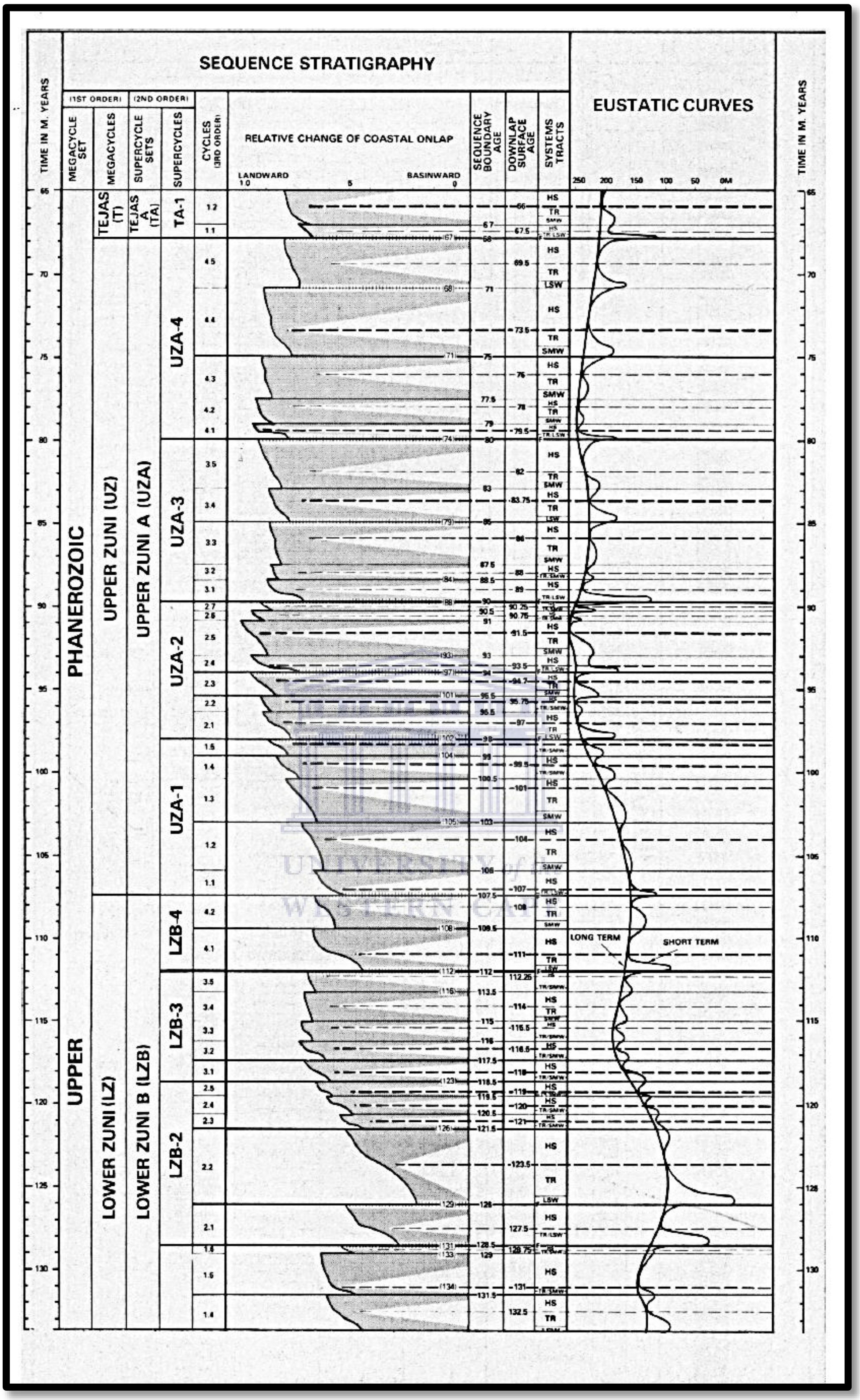
Appendix

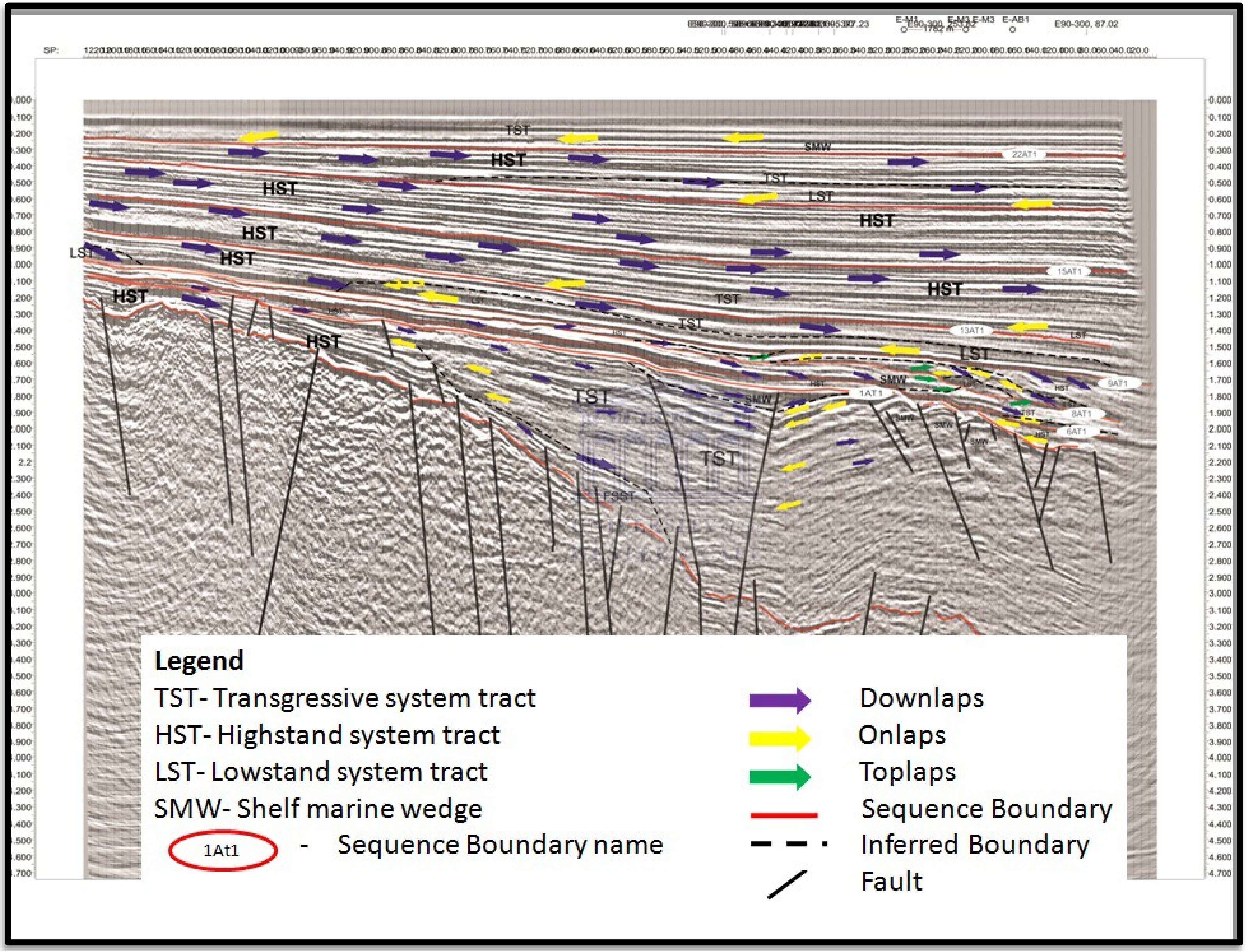
Classification of geophysical wireline Logs

Log	Property measured	Units	Geological interpretation
Spontaneous potential	Natural electric potential (relative to drilling mud)	Millivolts	Lithology, correlation, curve shape analysis, porosity
Conventional resistivity	Resistance to electric current flow (1D)	Ohm-metres	Identification of coal, bentonites, fluid types
Micro resistivity	Resistance to electric current flow (3D)	Ohm-metres and degrees	Borehole imaging, virtual core
Gamma ray	Natural radioactivity (e.g., relater to K, Th, U)	API units	Lithology (including bentonites, coal), correlation, shape analysis
Sonic	Velocity of compressional sound wave	Microseconds/metre	Identification of porous zones, tightly cemented zones, coal
Neutron	Hydrogen concentration in pores (water, hydrocarbons)	Per cent porosity	Porous zones, cross plots with sonic and density for lithology
Density	Bulk density (electron density) (includes pore fluid in measurement)	Kilograms per cubic metre (g/cm^3)	Lithologies such as evaporites and compact carbonates
Dipmeter	Orientation of dipping surfaces by resistivity changes	Degrees (azimuth and inclination)	Paleoflow (in oriented core), stratigraphic, structural analyses
Caliper	Borehole diameter	Centimetres	Borehole state, reliability of logs

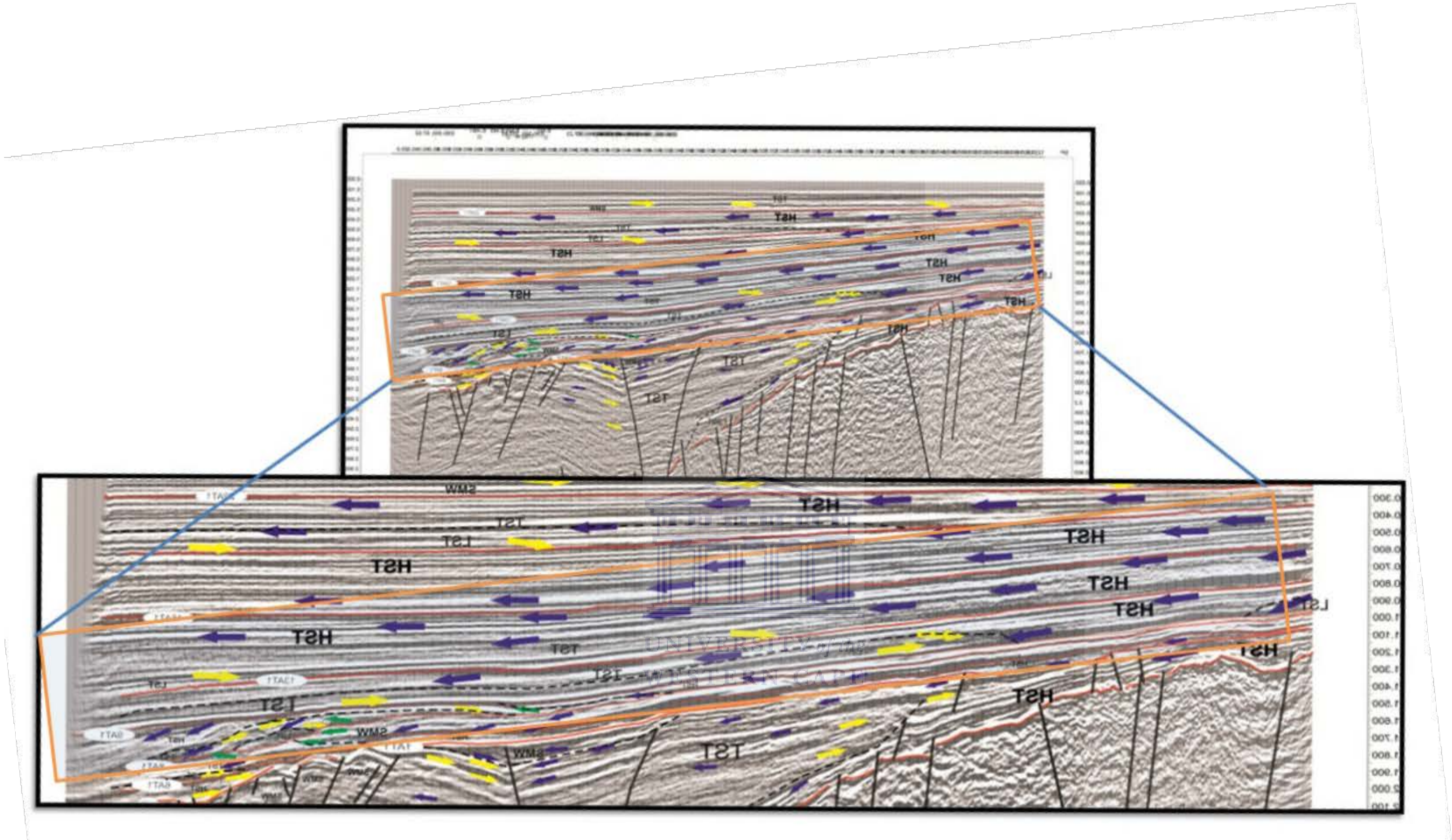
Appendix 1: Types of well logs, properties they measure, their use for geological interpretations (Modified from Cant, 1992).



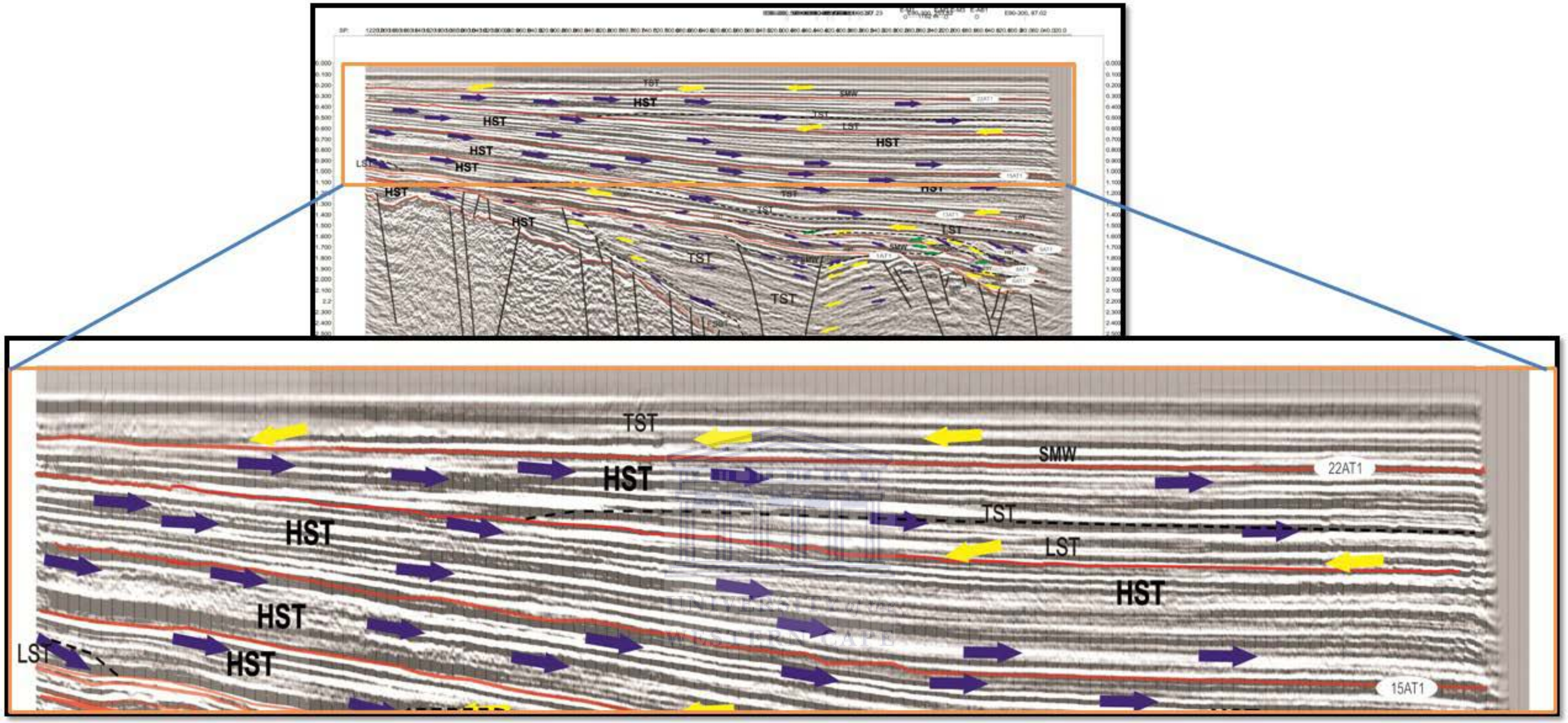
Appendix 2: Illustration the eustatic sea level curve. (Taken from Haq et al., 1987)



Appendix 3: Enlarged Figure 4.7.3: Showing seismic section E82-005, displaying system tracts and sequence boundaries interpreted in this thesis



Appendix 4: Enlarged Figure 5.4: Illustrating the transitional phase on seismic line E82-005 between unconformities 1At1 and 15At1



Appendix 5: Enlarged Figure 5.5: Showing the drift phase on seismic line E82-005 between unconformities 15At1 and 22At1