A thesis in Petroleum Geosciences

The palaeo environment and depositional facies of the drift section of Block 3A/4A in the Orange Basin, west coast offshore South Africa

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A thesis submitted in partial fulfilment of the requirements for the degree of Magister Scientiae in the Department of Earth Sciences, University of the Western Cape

RESPICE PROSPICE

UNIVERSITY of the
WESTERN CAPE

Supervised by: Dr Opuwari

August 2017

ABSTRACT

The Orange Basin is underexplored and has shown proven hydrocarbon reserves with the potential for further discoveries. This study is aimed at describing the depositional facies and palaeoenvironment of the drift section in Block 3A/4Aby doingdesktop studies, using seismic analysis, wireline logs and biostratigraphy data.

The proximal side of the study area shows structural highs and stratigraphic features such as onlaps, downlaps and pinchoutsin sequences. These structures were mostly observed on the 13A sequence. The 13A sequence is suggested to have been from the Aptian age, which was deposited in transitional inner shelf to pro-deltaic environments. The biostratigraphy data also suggest that the 15A sequence was deposited during the Cenomanian on an outer shelf environment. The 15A sequence, together with the 14 and 16A sequences have faults towards the west, validating the shelf collapse event that took place during the Late Cretaceous. Towards the east of the block there is thinning of sequences which thicken towards the shelf. This could also be observed in the youngest succession, the 22A sequence.The thicker successions reveal similarlog patterns in some wells and sequences; this could be an indication of simultaneousdeposition. The overall picture of the drift sequences in the wells is that they contain sandstones with interlaminated silt which could serve as possible reservoirs and seals in hydrocarbon entrapments.

DECLARATION

I declare that Palaeo environment and depositional facies of the Drift section of Block 3A/4A, Orange Basin, Offshore South Africa, West Coast is my own work; it has not been submitted before any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references.

Letshela Latoya Tlomatsana August 2017

Signature

ACKNOWLEDGEMENTS

I am grateful to God Almighty for showing me once again that I can and that I am not a quitter. Glory Be Unto You!

I am so privileged to have had a great supervisor like K.B Trivedi, thank you for your words of wisdom, encouragement, for pushing me each time I needed a push. Thank you for believing in me, for taking out the time to look at my work and give advice. Thank you for your constructive criticism, corrections and friendship. I will forever be grateful to have met and worked with someone of your calibre, I appreciate you.

I am extremely grateful to my father (Harold Tlomatsana), mother (Buhle Tlomatsana) and siblings (Randy and Fidel Tlomatsana) for their support, their pride in me, words of encouragement and for always being advocates of education. I am happy to have made you proud.

I would also like to thank my friends for their support, especially RoxzannePrinsloo for reviewing my work, always being available to help, listen, correct and criticize where necessary. I thank you all for being my number one supporters and cheerleaders.

My immense gratitude goes towards PetroSA for providing me with all the data and software I needed to carry out this study, especially the West Coast team for always willing to listen, encourage, correct and assist with the software and data. I thank you all from the bottom of my heart for the technical and emotional support, I will forever be grateful to you all.

I wish to thank pastors At Boshoff and Aiden Jeffrey from the Christian Revival Church (CRC) for their wise teachings, encouragement and instilling positivity in me. I thank my homecel group for their prayers, encouragement and support. You are all highly appreciated.

Lastly, I would like to thank the Earth Science department of the University of the Western Cape, Bellville, South Africa, Dr Opuwarifor the great opportunity. Many thanks to Professor Jan van BeverDonker for taking the time to review my work, I appreciate it a lot.

DEDICATION

I dedicate this thesis to my Abba Father, who is God Almighty. I would not have done this without His word, encouragement, love, beautiful promises and His faithfulness.

“*I can do all things through Christ who strengthens me”* Philippians 4:13

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CHAPTER 1INTRODUCTION

The Orange Basin lies on the west coast passive margin of Southern Africa offshore of a major river system. It covers an area of 130 000 square kilometres and was formed as a result of the breakup of south-western Gondwana around 132Ma.

It has growth faults, large scale slumping and compressional thrusting that developed due to aggradation during the Late Cretaceous. The basin is situated off the western continental margin of South Africa which is a passive volcanic margin and is characterised by organic and chemical sedimentation with enormous siliciclastic input. It contains continental to paralic and marine sediments of Mesozoic to present day age overlying the stretched African continental crust. Its sediments are derived from the Orange River(PASA, 2012).

The Orange Basin is underexplored and has shown proven hydrocarbon reserves and has the potential for further discoveries. With this project, an area will be chosen comprising a limited number of seismic lines and 4 wells where depositional facies, paleo-environment and seismic stratigraphy of the block 3A/4A will be determined, which, hopefully will to shed some light on the depositional events of the basin and the sequences present, thus helping with exploration for hydrocarbons in the basin.

The main goals of this project are to determine the deposition of sequences, to correlate sedimentary sequences, to do a regional seismic interpretation and a regional correlation. The deliverable is to put together the analyses to resolve the depositional facies, seismic stratigraphy and then construct a depositional model of the basin.

The dataset available for this project consists of wireline logs, core data, seismic data and biostratigraphy data. The process of the project leading to writing up a report will be through core analysis, interpretation of petrophysical logs, seismic interpretation, looking at work done on the biostratigraphy of the area and then lastly, constructing a depositional model of the area.

1.1. AIM AND OBJECTIVES OF THE STUDY

1.1.1. AIM

As stated above, the study is aimed at describing the depositional facies and palaeo environments of the drift section in Block 3A/4A in the Orange Basin using seismic analysis, wireline logs and biostratigraphy data.

1.1.2. OBJECTIVES

The objectives of this research project are:

1. Provide a summary of the study area and wells to be studied.
2. Describe the biostratigraphy of the wells.
3. Determine the depositional facies using seismic data.
4. Correlate sedimentary sequences using wireline logs.

1.2. HISTORY OF HYDROCARBON EXPLORATION IN SOUTH AFRICA

South Africa has a coastline of approximately 2800 km in length and an Exclusive Economic Zone that comprises approximately 650km (648.2km) of water bordering the country and inlands that are owned by South Africa. The Exclusive Economic Zones of South Africa add up to 1 535 538km².

South Africa has very limited reserves of conventional oil and natural gas (see table 1); most of the liquid fuels demand is satisfied by imports of crude oil and finished products, whereas the minority is met by local production from coal and gas. South Africa is exposed to very high political and economic risks as a result of this high dependence on imported fuel products (SAMSA, 2010).

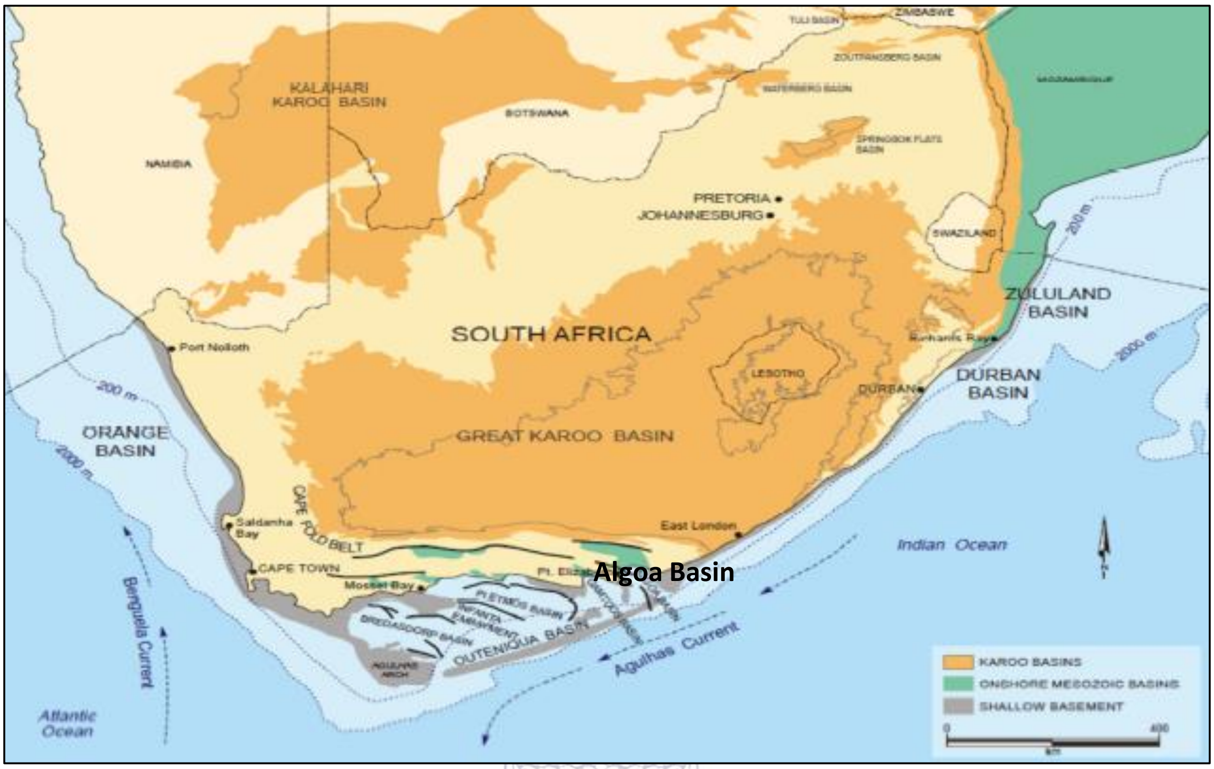


Figure 1: South African oil and gas basins (PASA, 2010)

The initial structured hydrocarbon exploration in South Africa was taken on by the Geological Survey of South Africa in the 1940's. In 1965, the government of South Africa formed SOEKOR (Pty) Ltd and began hydrocarbon exploration in the Karoo, Algoa and Zululand Basins (see figure 1). The first offshore well was drilled in 1969 after a new Mining Rights act was passed; granting offshore concessions in 1967, (SOEKOR, 1994).

From the mid 1970's to the late 1980's, the national oil and gas company of South Africa (SOEKOR) was the only explorer operating the whole of South African offshore projects; until international investors gained access to offshore areas in 1994.

The number of appraisal and production wells in offshore South Africa now exceed 300; 233 00 km of 2D seismic and 10 200 km of 3D seismic profiles have been acquired since the inception of offshore exploration (PASA, 2010).

Table 14: An illustration of oil and gas reserves and production in South Africa

South Africa	Production/Reserves	Share of World
Oil Production (barrels per day)	190 000	0.22%
Proven Oil Reserves (million barrels)	15	0.00%
Gas Production (cubic meters per day)	97 000 000	0.03%
Proven Gas Reserves (cubic meters)	27 160 000	0.00%

In the Orange Basin, the exploration of hydrocarbons started in 1974; where the Kudu borehole, 9A-1 was drilled (south of Namibia). Gas was discovered in the well, thus resulting in more wells being drilled in the area. The basin is estimated to contain very large amounts of gas reserves. However, it is still underexplored.

The number of exploration wells drilled following the gas discovery in well 9A-1 is approximately 30 (Muntingh, 1993), of which a few were discoveries and others had encouraging oil and gas shows, see figure 2. The region is covered by a wide seismic dataset that consists of different vintages acquired throughout the years since exploration of the basin started in 1974. Exploration wells were drilled by SOEKOR between 1976 and 1991. Most of the wells that were drilled are on the continental shelf where the water depths are less than 400m. The wells that are not on the continental shelf are located on the shelf break where the water depths reach 750m. Most of the wells that were drilled are deep, with most of them exceeding 3000m and more than half going beyond 4000m. Of all these wells, over 60% were cored and approximately 25% were tested.

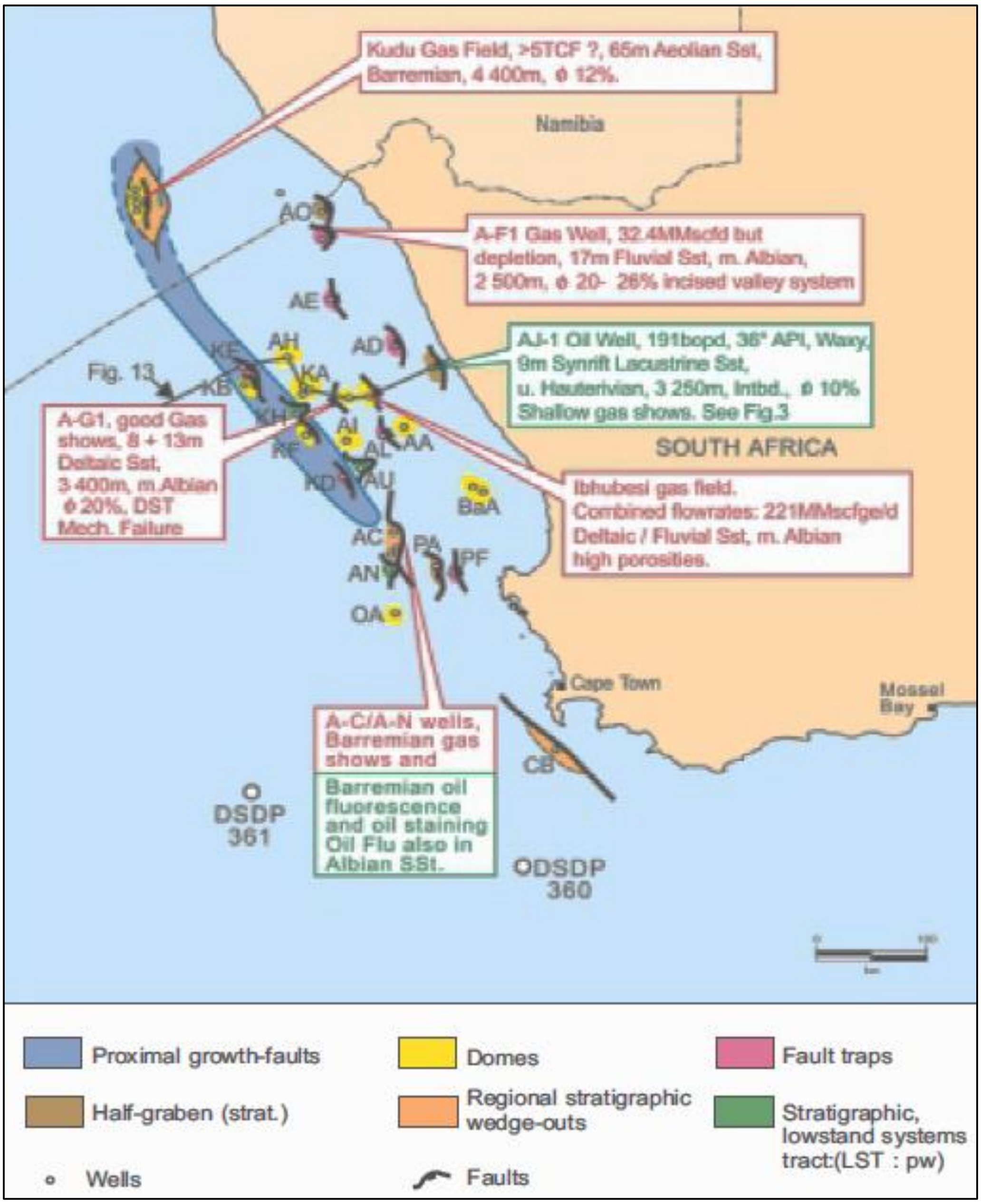


Figure 2: The main petroleum discoveries and shows in the Orange Basin (Jungslager, 1999)

The AJ-1 well, (see figure 3)in block 2A, north of block 3A/4A was an oil discovery and yielded excellent results. In this well, 6 cores were taken and 4 tests were done. This well tested oil in what is deemed to be a gas province. The well intersected a deeper, isolated, oil-bearing petroleum system than what was tested by the wells that intersect younger sediments. The oil was contained in an upper syn-rift graben succession dating from the Hauterivian and produced from lacustrine sandstones.This is totally different compared to the gas shows in the other wells in that the gas in the otherwells is trapped influvio-deltaic sand bodies in domal closures that are faulted, in mid-Albian successions of the post-rift succession.

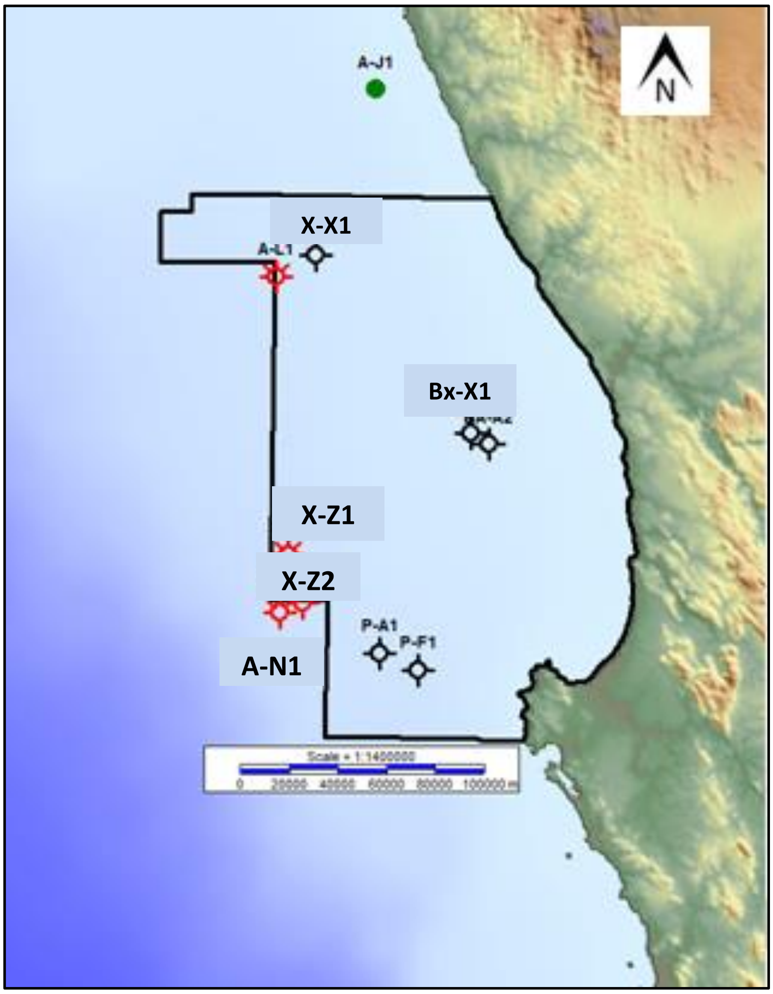


Figure 3: Block 3A/4A

Wells X-Z1 and X-Z2(see figure 3), were drilled in the southwest of block 3A/4A, these wells were drilled to test for gas and condensate trapped in Synrift and early post-rift, Lower Cretaceous, transitional to shallow water marine sequences with structural and stratigraphic closures. All three wells did not yield good results and had very poor gas shows.

Well A-N1(see figure 3), was also drilled to test for gas and condensate trapped stratigraphically in Aptian, Albian and Turonian sequences in lowstand shelf systems; it was drilled southeast of block 3A/4A. Potential reservoirs were found to be water saturated and the sandstone very poorly developed. This well was classified as a dry well.

Table 15: Blocks surrounding Block 3A/4A

Block	Operator Name	Contract Type	Rights Type	Area (km^2)	Stage Events	Ownership
3A / 4A	PetroSA	Exploration Right	Exploration / Production	21409	Application Accepted	Petro SA 50%, Sasol 50%
2A	Sunbird Energy (Ibhubesi)	Production Lease	Development / Production	4974	Valid Extension Granted	Sunbird 76%, PetroSA 24%
1	Cairn India	Exploration Right	Exploration / Production	19922	Application for Renewal	Cairn India 60%, PetroSA 40%
Central Orange Basin	Sungu Sungu Petroleum	Exploration Right	Exploration / Production	20644	Official Award	Sungu Sungu Petroleum 100%
2C	Anadarko Petroleum	Exploration Right	Exploration / Production	6223.73	Application Filed	Anadarko Petroleum Corp. 100%
3B / 4B	BHP Billiton Petroleum GB Ltd	Exploration Right	Exploration / Production	18218	Renewal	BHP Billiton Petroleum 100%
2B	Thombo Petroleum Ltd	Exploration Right	Exploration / Production	5614	Application for Renewal, New interests	Simbo Petroleum 40.50%, Thombo Petroleum 34.50%, Main Street 840 25%

1.3. STUDY AREA

The location of the study area is on the west coast of South Africa, as seen in figure 4,and is parallel to the coastline. The basin has an areal extent of approximately 145 000km². The Orange Basin is sub-divided into different blocks that are individually being explored for hydrocarbons.

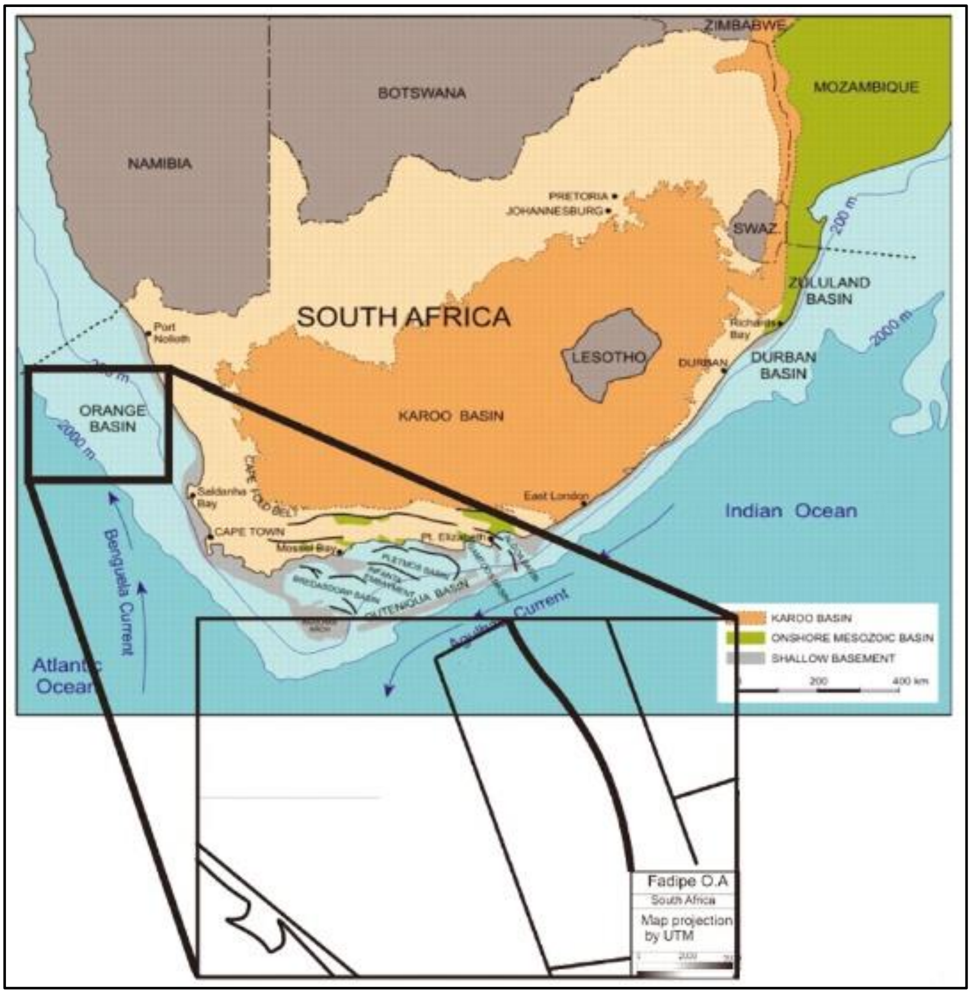


Figure 4: Location of the Orange Basin(Oil and gas technology, 2014)

The block of interest in this study is block 3A/4A and is located approximately 115km north of Cape Town and 280km south of the border of South Africa and Namibia. It is located at the centre of the Orange Basin and covers an area of 21409 km², see figure 4. It is licensed in equal shares to the national petroleum company of South Africa, known as PetroSA and Sasol.Block 3A/4A has seven wells in it and two that were drilled on the block boundary.

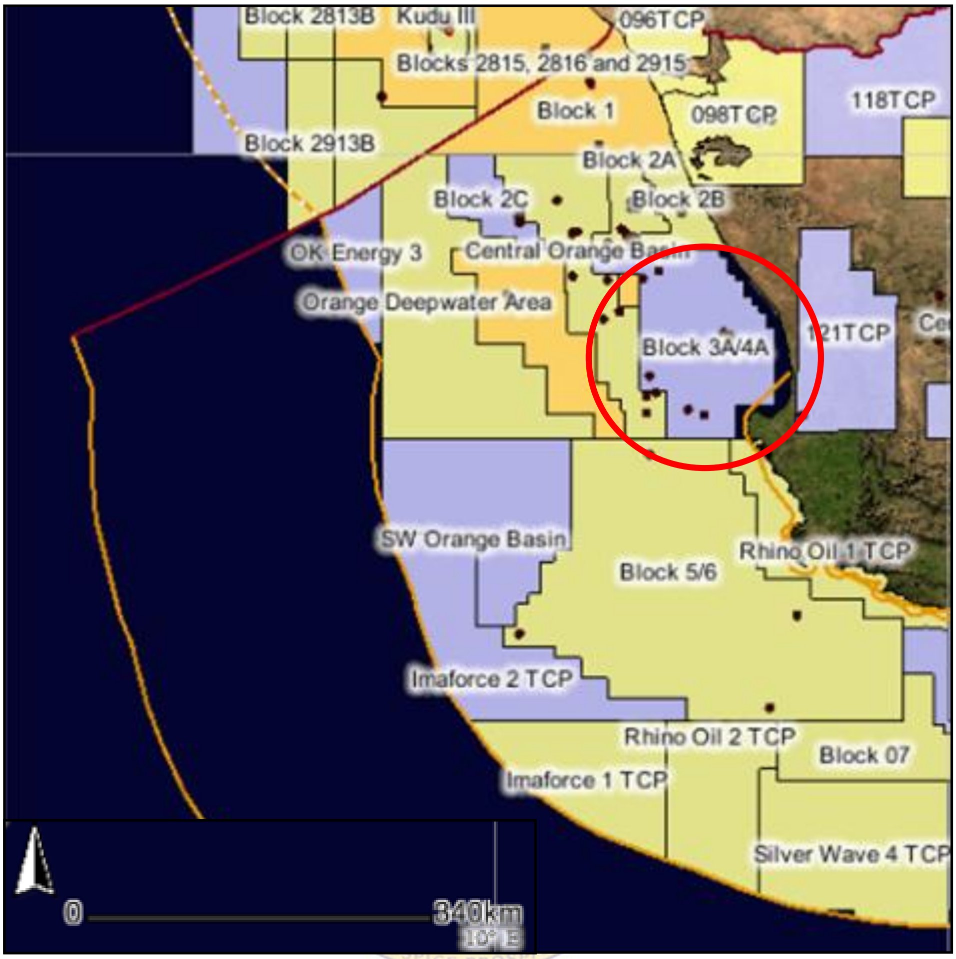


Figure 5: Location of Block 3A/4A (IHS Energy Group)

The wells that are inside the block are wells X-X1, BX-X1, Ba-A2, P-A1, P-F1, X-Z1 and X-Z2; and those that sit on the block boundary are A-L1 and A-C3, refer to Figures 5 and 6.

However, this study only focuses on four wells that are inside the block and they are wells X-X1, X-Z1, X-Z2 and BX-X1, refer to table 3. These four wells were chosen because they all sampled the drift sequence and their data quality is better. Surrounding Block 3A/4A are blocks 3B/4B, 2A, 2B, 2C1 and the Central Orange Basin Block, see Figure 5.

Table 16: The four wells of interest in Block 3A/4A under investigation

Well Name	Water Depth (m)	Total Depth (m)
X-X1	235.3	3805
X-Z1	324.9	4139.2
X-Z2	319.7	3613.4
Bx-X1	141.7	1699

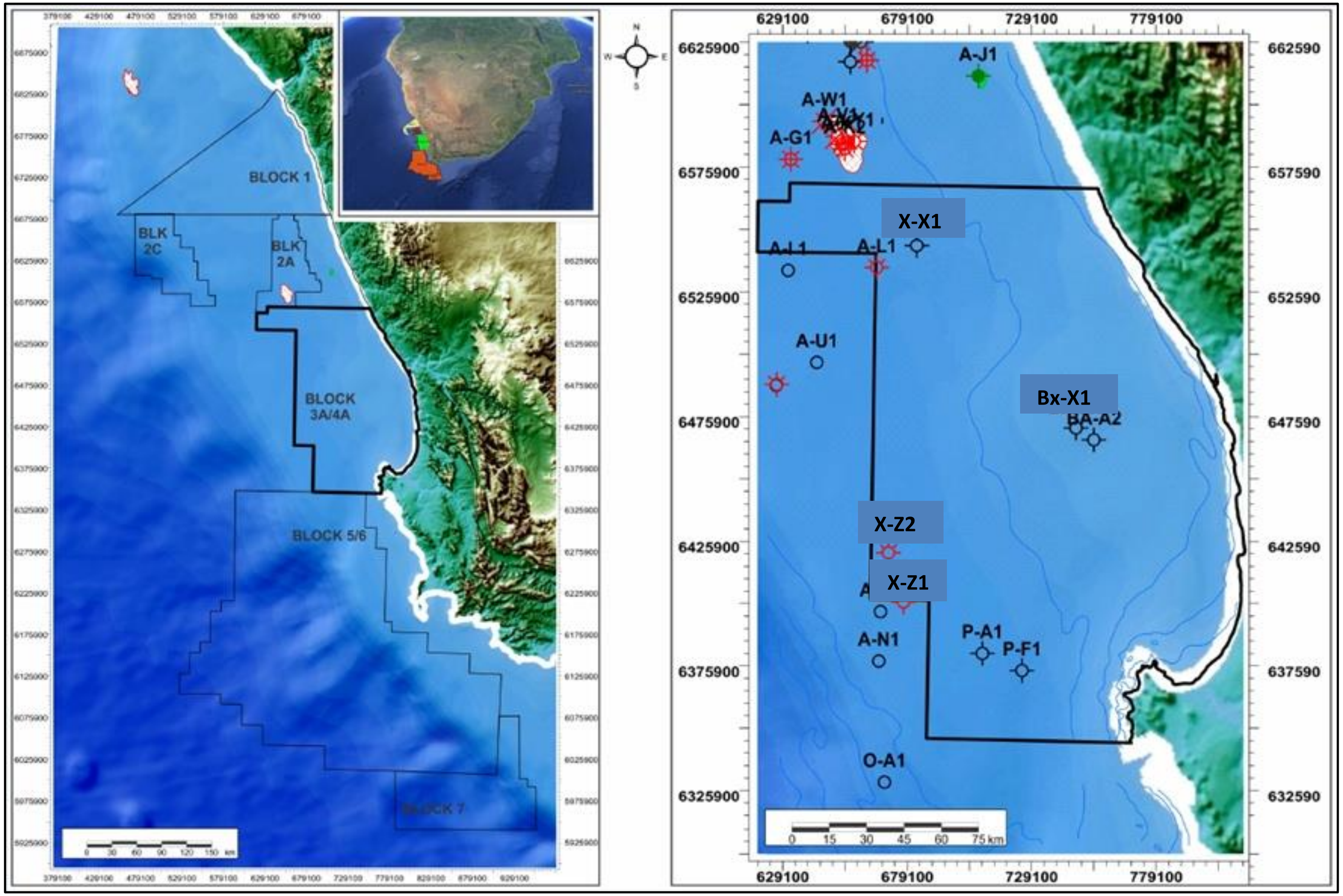


Figure 6: Maps illustrating the location of Block 3A/4A and the location the wells of study (PetroSA)

1.4. REGIONAL SETTING OF EASTERN, SOUTHERN AND WESTERN COASTS OF SOUTHERN AFRICA

1.4.1. West Coast

The Orange Basin forms a portion of the southwest African coastal basin which is located in the western parts of South Africa. It is underexplored and is the largest offshore basin in South Africa, PASA, 2012. The Orange Basin extends from the Walvis Ridge in the North to the Agulhas Falkland Fracture Zone in the south; see figure 7. The basin covers an area of 145 000 km² and has one well for every 4000 km².

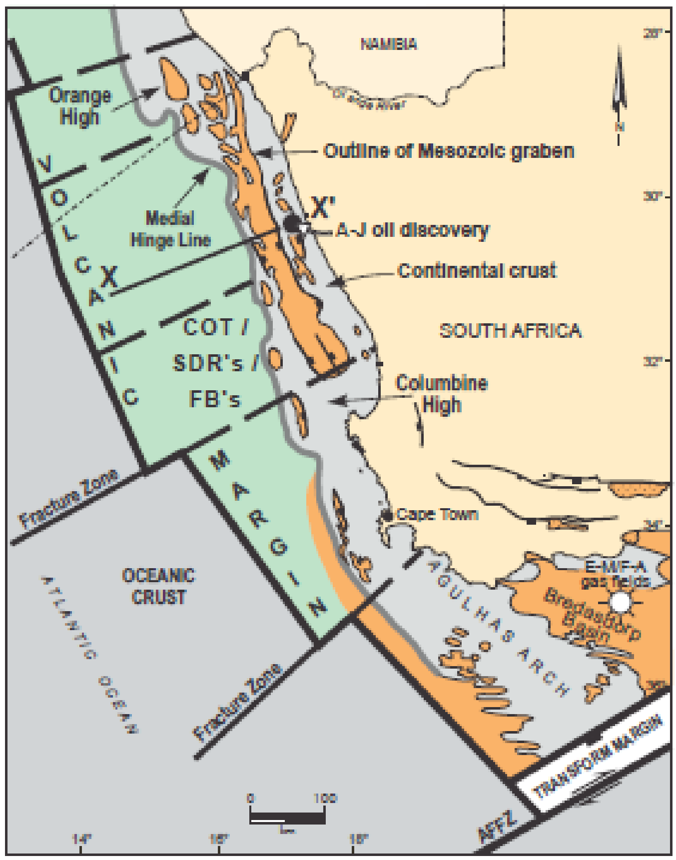


Figure 7: Major tectonic elements of the western margin of South Africa (Jungslager, 1999)

The Orange Basin formed following the break-up of Gondwana during the Late Triassic to Early Jurassic and the sea-floor spreading associated with the opening of the South

Atlantic Ocean. There are four main phases that were formed as a result of the rifting episode; the Syn-rift, Post-rift (transitional), Drift and Late-Drift (Cretaceous and Tertiary), (PASA, 2010).

The Hauterivian marks the end of rifting and beginning of the Drift phase when the Proto-South Atlantic Ocean was established. The South Atlantic was very shallow and restricted during this period, thus; a transitional depositional setting between the rift and drift phases (Broad *et al*., 1996).

1.4.2. East Coast

The south eastern offshore extends from the Mozambique border in the north to the Port Alfred Arch in the south. The eastern coast is subdivided into the Zululand Basin, Durban Basin and the Transkei Swell, see figure 8. Just like the west coast, the east coast is also underexplored (PASA, 2012).

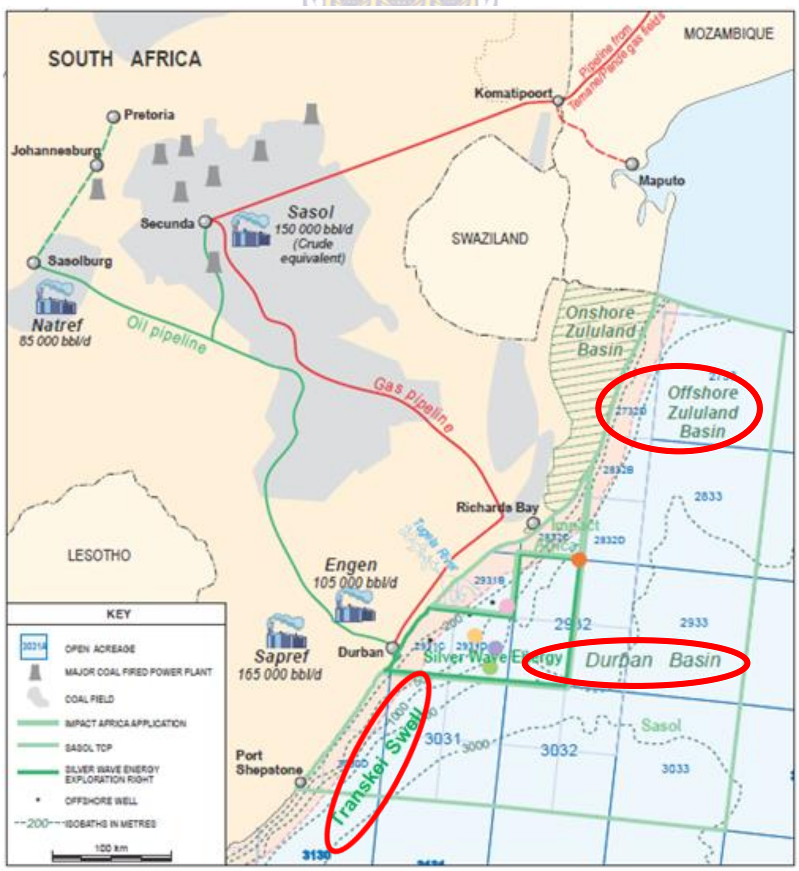


Figure 8: East Coast Basins (PASA, 2012)

The Zululand Basin covers an area of approximately 13500 km ^{2} with only 10 wells drilled between 1960 and 1970. In these wells, no hydrocarbon shows were observed; only porous sandstones and Late Cretaceous source rocks. It was deduced from wells drilled in Mozambique that Late Cretaceous source rocks could be developed extensively and that they could be oil prone.

The Durban Basin covers an area of approximately 4000 km^2 and is borded in the north by the Zululand Basin and by the Port Shepstone Arch in the south. Thick Tertiary successions overly the continental slope and shelf; whereas thinner Early Cretaceous sediments are seen overlying the basement of Jurassic to Palaeozoic age. The grabens have a north-south orientation and are understood to have significant thicknesses of Synrift sediments, with numerous large structural traps outlined in water depths between 400m and 600m (Oil and gas technology, 2014.

The Transkei Swell has a steep slope and thin continental shelf which have Tertiary sediments lying on the basement. This basin runs from the south of Durban to the Port Alfred Arch.

1.4.3. Southern African Basins

There are a number of sub-basins in Southern Africa and they are located in the southernmost offshore part of South Africa. They are the Bredasdorp, Pletmos, SouthernOuteniqua, Algoa and the Gamtoos Basins as shown in figure 9.

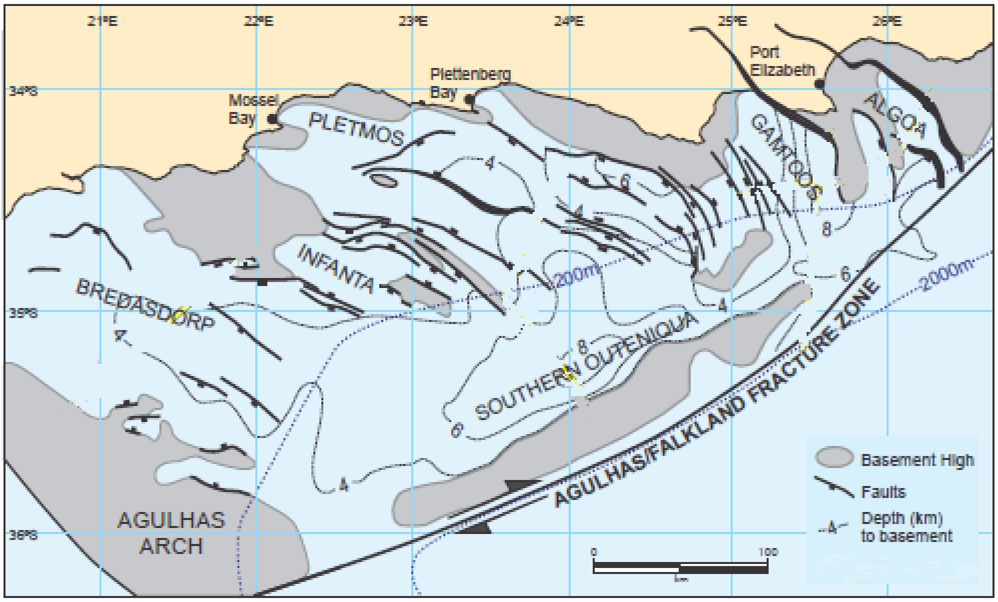


Figure 9: Southern Basins and their major tectonic elements (adapted from PASA, 2012)

The sub-basins have grabens and are bounded by faults that were significantly influenced by the Cape Fold Belt.

The Pletmos and Bredasdorp Basins have the most proven hydrocarbons and are believed to have even more than has been discovered to date. There are projects that are presently undergoing appraisal stages in these basins (SAMSA, 2010).

The Southern Outeniqua Basin is extremely underexplored due to its very strong deep water ocean currents. According to 2D seismic data that was acquired in 2001 and 2005 by Canadian Natural Resources, there are Synrift structures believed to contain gas and are said to be within the oil window. The Southern Outeniqua Basin is ranked highly to contain oil in the southern and central parts of the basin and likely to contain gas towards the north.

The Gamtoos Basin is gas-prone while the Algoa Basin is more oil-prone; with good source rocks of Kimmeridgian age. These two basins have proven petroleum systems. With the Gamtoos Basin being more gas-prone, it is possible that the basin floor drift sandstones contain oil sourced from the Hauterivian (PASA, 2012).

1.5. SEQUENCE STRATIGRAPHY

Sequence stratigraphy is an effective tool for the hydrocarbon exploration and development industry. Galloway (1989) defined it as “the study of rock relations within a time – stratigraphic framework of recurrent, inherently related strata confined by unconformities or conformities”.

This study is important because it puts sediments into an expected or rather predictable; chronostratigraphic structure agreeing to Walther’s law that correlates surfaces and states that facies that are adjacent to one another in a continuous vertical sequence also accumulated adjacent to one another laterally; however, an exception to this law is if there are faults and unconformities.

Each sequence is made up of a succession of system tracts and each system tract has a relationship with coeval depositional systems, (Brown and Fisher, 1977). There are four system tracts that can be identified; lowstand system tract (LST), highstand system tract (HST), transgressive system tract (TST) and shelf margin.

Sequence stratigraphy can be used both in academic and industry applications. It can be used academically to determine the origin and internal architecture of sedimentary basin fills inasmuch as it can be used industrially for the exploration of hydrocarbons.

Explorationists using sequence stratigraphy can lessen the risks in reservoir, seal and source rock prediction. By pursuing a systematic method for the integration and interpretation of geologic data and by using seismic reflection profiles to infer information into areas that are not drilled (Armentrout, 1990).

As the regional patterns are most clearly identified on seismic reflection profiles, sequence stratigraphy interpretation focuses on seismic data (Vail et al., 1977). According to Brown and Fisher (1980) a key to seismic stratigraphic interpretation is an understanding of the geologic factors that generate seismic reflections. They again said that the seismic-stratigraphic approach allows explorationists to extrapolate subjective stratigraphic relationships, to interpret depositional processes and environments as well as to come up with lithofacies models.

The application of sequence-stratigraphic analysis relies on the identification of a hierarchy of units of strata as well as beds, bedsets, parasequence sets and sequences confined by chronostratigraphicallysignificant surfaces of erosion or non-deposition / unconformities or their comparative surfaces (Ryer, 1983, Busch and Rollins 1984, Busch et al., 1985 and Galloway, 1989) in Van Wagoner et al., 1991.

1.5.1. Identification of parasequences

Parasequences are comparatively conformable successions of generally related beds or bedsets confined by marine flooding surfaces and their counterpart surfaces and are defined by the vertical stacking / occurrence of repeated upward fining or coarsening cycles. Sequence stratigraphic interpretation also uses wireline logs to determine parasequences stacking patterns, that is; to identify low system tracts (LST), high stand system tracts (HST) and transgressive system tracts (TST), (see figure 10) that are covered by the Maximum Flooding Surface, TS and SB. The stacking patterns are usually determined on the foundation of the difference in grain size (Olowoyo, 2010).

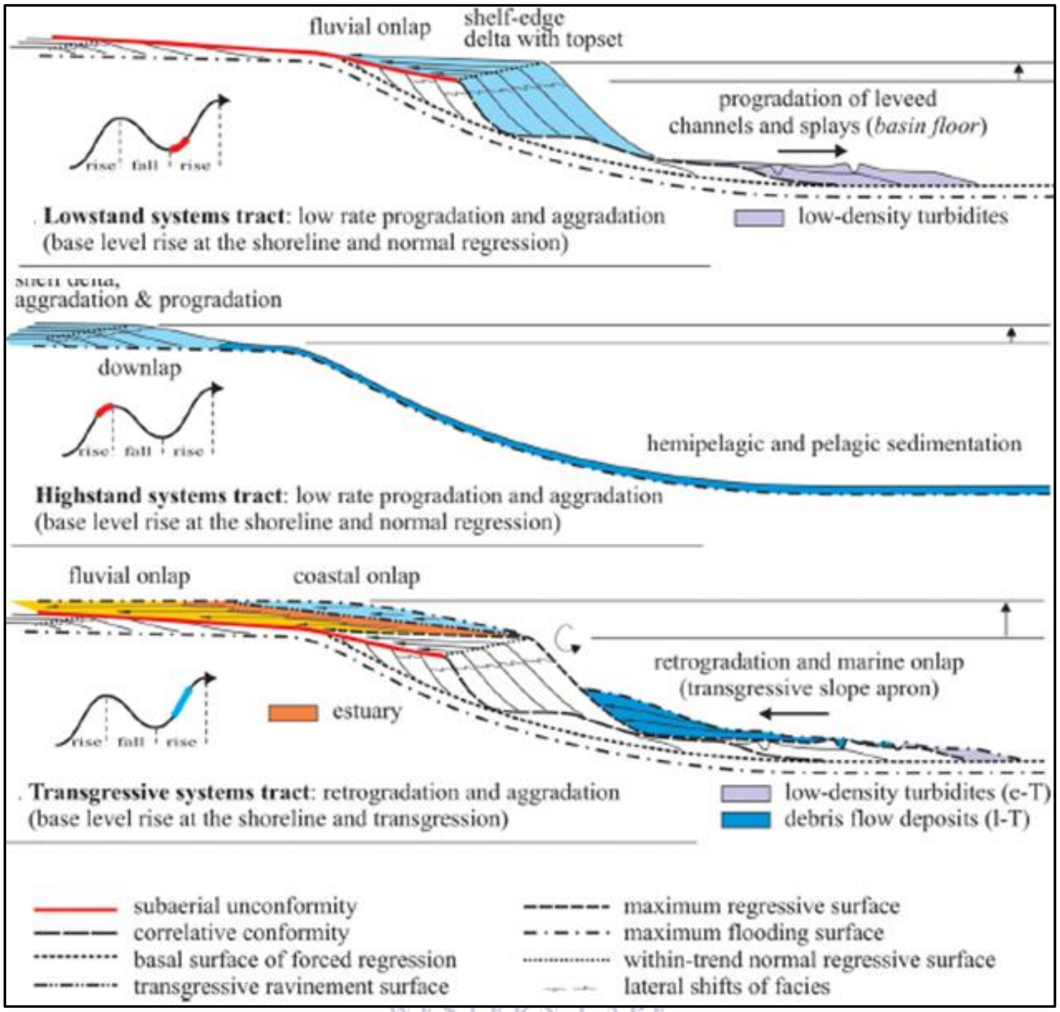


Figure 10: Lowstand, Highstand and Transgressive System Tracts (Hunt and Tucker, 1992)

Retrogradation – Occurs when the coastline moves towards the land in response to a transgression. This happens when there is low sediment supply with a rise in sea-level. A retrogradationalset of parasequences displays back stepping patterns due to younger parasequences deposited landward; this is all because the rate of sediment deposition is less than the rate of accommodation (Armentrout, 1990).

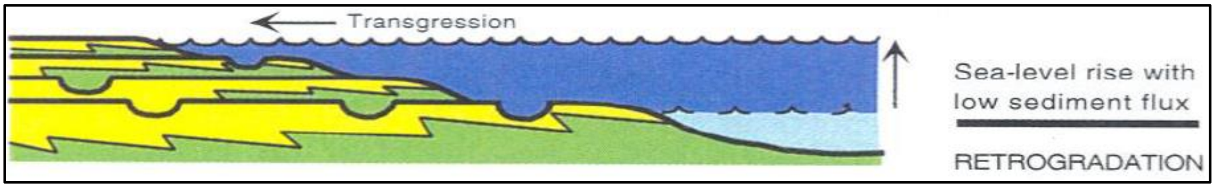


Figure 11: Retrogradation (Posamentier and Allen, 1999)

Aggradation – Takes place when sedimentary sequences build up vertically due to a rise in sea-level resulting from eustacy or / and subsidence. The rate of sediment supply is enough to maintain the depositional surface at or near sea-level; thus, producing aggradational stacking patterns in parasequences when facies patterns at the top of every parasequences are significantly similar (Catuneanu *et al*, 2011).

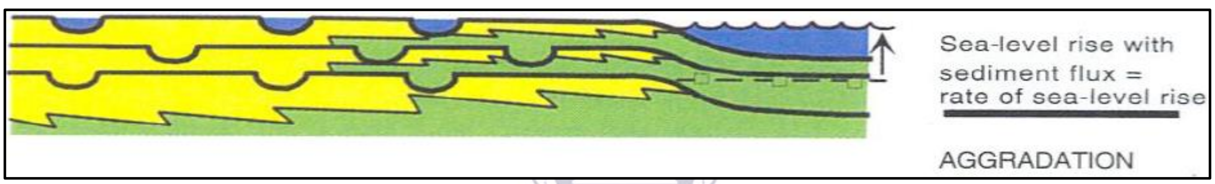


Figure 12: Aggradation (Posamentier and Allen, 1999)

Progradation – Lateral or sideward building out of sediments in a sea-ward direction. Younger sequences are deposited basinward due to the rate of deposition being higher than the rate at which accommodation space develops.

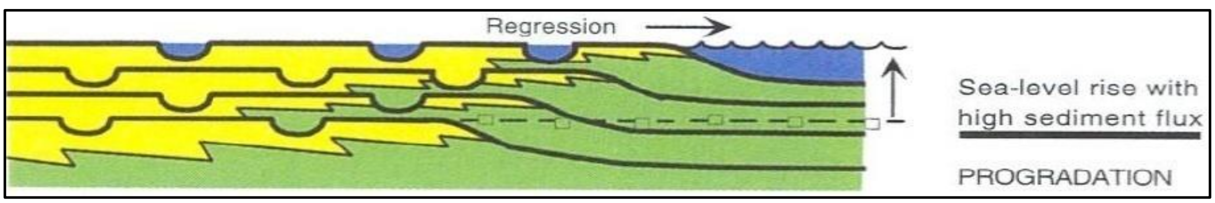


Figure 13: Progradation (Posamentier and Allen, 1999)

1.6. MAIN CONTROLS OF SEQUENCE STRATIGRAPHY

There are controls in sequences stratigraphy and they are subdivided into allogenic and autogenic processes. These processes ascertain the distribution of depositional elements in a depositional system including the larger scale stacking patterns of depositional systems in sedimentary basin fill.

Autogenic controls have induced themselves and they occur in fluvial and deep-water environments and are significantly specific at sub-depositional system scale and are commonly analysed and studied using the methods of conventional sedimentology and facies analysis. By contrast, allogenic controls supply a platform that controls and syncs trends in deposition documented anytime in all types of environments determined in a sedimentary basin fill and as a result, granting the development of sequence stratigraphic models. This means that allogenic controls are precisely applicable as the larger-scale basin fill architecture is controlled by them. Those standard allogenic controls on sedimentation are sea-level changes, climate, sediment supply, tectonics, accommodation space, depositional trends and their relationship with the environmental energy flux (Catuneanu, 2006).

1.7. SEISMIC DATA – SURFACES TO BE INTERPRETED

1.7.1. 13At1 – Aptian (Megasequence 13)

According to Muntingh*et al*., 1993, the early drift sequence is terminated by the Aptian (112-103My) 13At1 unconformity, marking the beginning of full drift, open oceanic conditions, (figure 14).The sequence between the 13At1 and the 14At1 marker is characterised by low accommodation rates and progradational stacking. Transgression and regional flooding of third order sequences occurred in areas where the 13At1 low stand system tract (LST) was not affected.

The manner in which the third order sequences sets are arranged, specifies that a rise in sea-level was produced by the combination of the effects of basinal tectonic subsidence and second-order tectono-eustatic sea-level rise under reasonable sediment supply rates. The rise in sea-level was recorded to have accelerated slowly and Broad et al., (2000) add that the 13At1 indicates low accommodation rates and marks the beginning of open-marine conditions. In an earlier study, Broad et al., (1996) states that the 13At1 marks the development of a shelf edge.

According to Muntingh and Brown, (1993), the development of a shelf edge and the deposition of prograding sequences and fully open marine conditions began after regional oil to gas-prone source rocks were deposited during the middle Aptian.

1.7.2. 14At1 – Late Albian (Megasequence 14)

Megasequence 14 dates 103-93Myr.The sequences were deposited with inter-changing progradation and aggradation between the 14At1 and 15At1; these were mostly deposited in the northern flank of the Orange Basin where high sediment supply rates resulted from the input from the Orange River. The 14At1 was deposited subsequent to the fall in sea-level, moderate erosion, uplift and transgression with regional flooding that took place during the deposition of the 13At1.

Contradictory to the 13At1, the arrangement or rather the geometry of the third order sequences here shows an accelerating rise in sea-level; which resulted from a combination of basinal tectonic subsidence and second order tectono-eustatic sea-level rise unlike with the 13At1 that had moderate sediment supply rates.

1.7.3. 15-16At1 – Early Turonian to Late Turonian

These sequences were deposited after an uplift, relative sea-level fall, minor erosion and regional flooding. The geometry of these sequencesshows high and sustained sediment supply rates that were thought to have balanced the rise in sea-level. This rise in sea-level was most likely generated by basinal tectonic subsidence and second order tectonoeustatic sea-level change, (Brown et al., 1995).

Widespread slumping, gravity faulting and normal faulting caused the deposition of sequences along an aggradational margin to be terminated between 80-85My. Gravity faults that have a north-northwestern incline have a complex zone of syn-sedimentary slumps, rollover anticlines and tilted fault blocks. Broad at al., (2000) also state that sequence stacking along the slope where deposition occurred terminated in widespread gravity faulting and folding in the Late Cretaceous and Muntingh., (1993) says that the termination was followed by intensive Type 1 erosion. This fault zone results in many structural closures that could act as possible stratigraphic traps in many postrift low stand system tracts that the fault zone intersects.

Above the Cenomanian-Turonian boundary, sequences are mainly aggradational, leading to shelf-edge collapse in the form of growth faults and large-scale slumping suggestive of other deltaic margins such as the Mississippi and Niger deltas, (Broad *et al*., 2000).

1.7.4. 22At1 – Maastrichtian

According to Muntingh., (1993), the decreased accommodation rates at the 22At1 unconformity were brought about by erosion at the end of the Cretaceous. This unconformity marks the end of the Cretaceous sedimentation with Cenozoicsediments represented by a well-developed wedge, thickening from a few hundred meters on the shelf to approximately 1500m basinward. The Tertiary succession is marked by episodic intrusives and common growth and gravity faults.

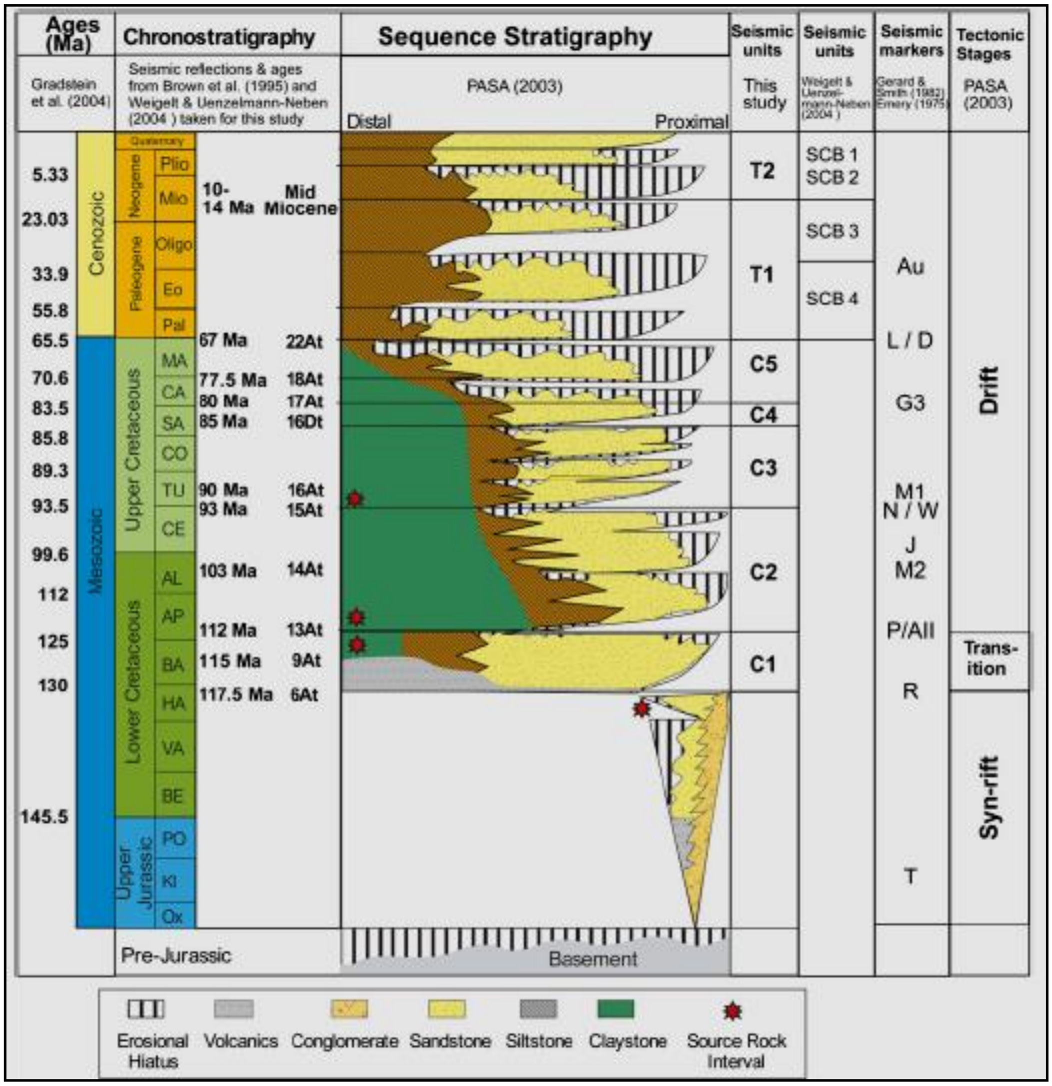


Figure 14: Chronostratigraphy and sequence stratigraphic chart for the Orange Basin, highlighting the drift section (Kuhlman *et al*., 2010).

1.8. DESCRIPTION OF BIOSTRATIGRAPHY

Basic biostratigraphy is concerned with the recognition of fossils and the relative position of their occurrences in space and time. Various fossil groups can be found in different sedimentary environments. The two main environments are land (terrestrial) and sea (marine) (Kleinpell, 1960).

In terrestrial sediments, spores and pollen are the fossil group to use. Other fossil groups, such as vertebrates or other larger fossils, can only be used if the sediments samples are sufficiently large. In practice, this limits their use to outcrop samples. The limitation on the use of spore/pollen is the amount of oxidation experienced by the sediments after deposition. Oxygen will remove organic material (spores/pollen) from the sediments. Spores can be used in Devonian (approx. 400 Mars) to recent sediments, pollen in Upper Cretaceous (approx. 80 Mars) to recent sediments. Both can be found blown into marine environments in considerable amounts.

In marine sediments, calcareous nannofossils are the most useful group for Jurassic (approx. 210 Mars) to recent sediments, since their preparation is cheap and the stratigraphic resolution which can be reached with them is high. Occasionally sediments can be leached of calcareous particles, however, the process also removes calcareous nannofossils (for instance in deep sea sediments). Their use as environmental indicators is limited, although some species are known to be associated with warm or cold water masses (Harvard University, 2004).

Palynomorphs (dinoflagellates, acritarchs and tasmanites) can be used in Permian (approx. 260 Mars) to recent sediments and in most sediment types (though they tend to be rare in chalky limestone). Since their preparation includes the dissolution of the surrounding sediments, their use is more expensive than nannofossils. The possible stratigraphic resolution can be high. Recently, the use of organic grain size and shape as environmental indicators has been developed and is apparently useful, especially in sub-recent sediments (Verhoeven and Louwye, 2013).

Foraminifera can be used in all marine sediments which have not been leached of calcareous material, i.e. from shallow marine to middle bathyal. Their stratigraphic resolution can be high and their association with certain depositional environments makes them good environmental (water depth) indicators. Foraminifera can be found in sediments of Carboniferous (approx. 360 Mars)to recent age. Their preparation cost is lower than that of palynomorphs, unless thin-sections have to be used (Frederiksen et al., 1996).

In silica enriched sediments, siliceous microfossils such as diatoms and radiolarians can be of use. The stratigraphic resolution can be high, especially in the Tertiary (approx. 65 Mars), but schemes are still under development for other time frames. Their preparation cost is similar to that of foraminifera.

It is good practice to always analyse at least two of these fossil groups per sample to provide a cross check. This reduces the chance of unexpected sedimentary circumstances leading to erroneous age and environmental estimates.The age estimates can be numeric if the fossils encountered in a sample can be related to the global zonation schemes which exist today (University of Maryland).

The most frequently used fossil groups in biostratigraphy are listed below, together with their use as stratigraphic and environmental indicators.

Table 17: Most frequently used fossil groups in biostratigraphy

Fossil Group Indicator	Environment Resolution	Stratigraphic Use	Time Range	Time ($x10^6$ yr)
Spore/Pollen	Poor-Medium	Medium	Devonian-recent	400-0
Nannofossil	Poor	Medium-High	Jurassic-recent	210-0
Foraminifera	Good	Medium-High	Carboniferous-recent	360-0
Dinoflagellates	Medium	Medium-High	Permian-recent	260-0
Diatoms/Radiolaria	Medium	Medium-High	Mostly Tertiary	65-0

1.8.1. Developments in biostratigraphy

The use of biostratigraphy as a tool in petroleum exploration is well established. Relative age dating is one of the basic elements of the geologic data set available to the explorationists. In addition to this, estimates of the depositional environment of sediments can usually be given.

The most important development in the stratigraphic field is the integration of biostratigraphic dating with observable seismic and geomagnetic cycles, known as sequence stratigraphy. This means that stratigraphers can now provide numeric age estimates for seismic sequences where traditionally only relative ages could be given. This direct link between seismic data and numeric ages can be a powerful aid in regional correlation (Powell et al., 2005).

Biostratigraphic data is also integrated with other disciplines, e.g. sedimentology. Besides being the basic tool in regional correlation of sedimentological units, it allows the position of a sediment unit in a seismic cycle to be pinpointed and also allows more accurate estimates. The sedimentological sequences can be placed in a regional and global framework, see figure 15.

Other stratigraphic tools, e.g. chemostratigraphy (stable isotope techniques: Oxygen, Strontium) Graphic Correlation or Cyclicity Analysis (duration estimates from electric logs), are now being integrated with biostratigraphic data. These can provide an additional cross-check besides giving useful paleoenvironmental information (Jones and Simmons., 1999).

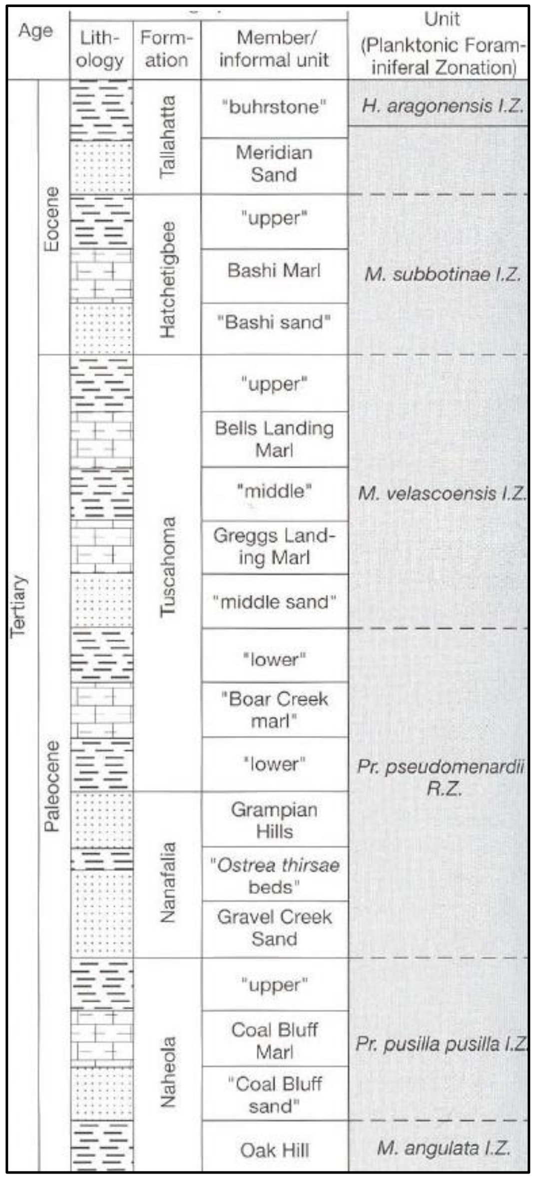


Figure 15: Illustration of the relationship between biostratigraphic units and lithostratigraphic units; Tertiary sedimentary rocks of eastern Gulf Coastal Plain, U.S.A (Mancini and Tew, 1995)

<u>CHAPTER 2</u> REGIONAL GEOLOGY OF THE ORANGE BASIN

The coastline of South Africa has a continental margin that is approximately 400 000km² in extent and has a continental shelf of 165 000 km² (Broad *et al*., 2000). Large parts of the Orange Basin are included by South Africa's western continental margin, see figure 16. This continental margin covers an area of 145 000 km² (Broad *et al*., 2000) and is described by Jungslager (1999) as a volcanic passive margin. The Orange Basin is located in the southernmost West African Basin and was fed by a delta system which is similar to the systems that are found further north of the African coast(PetroSA, 2014). The minor drainage of the Olifants system in the south contributed sediments along the Agulhas Columbine Arch; particularly between 117.5 Ma and 103 Ma (Brown *et al*., 1995)

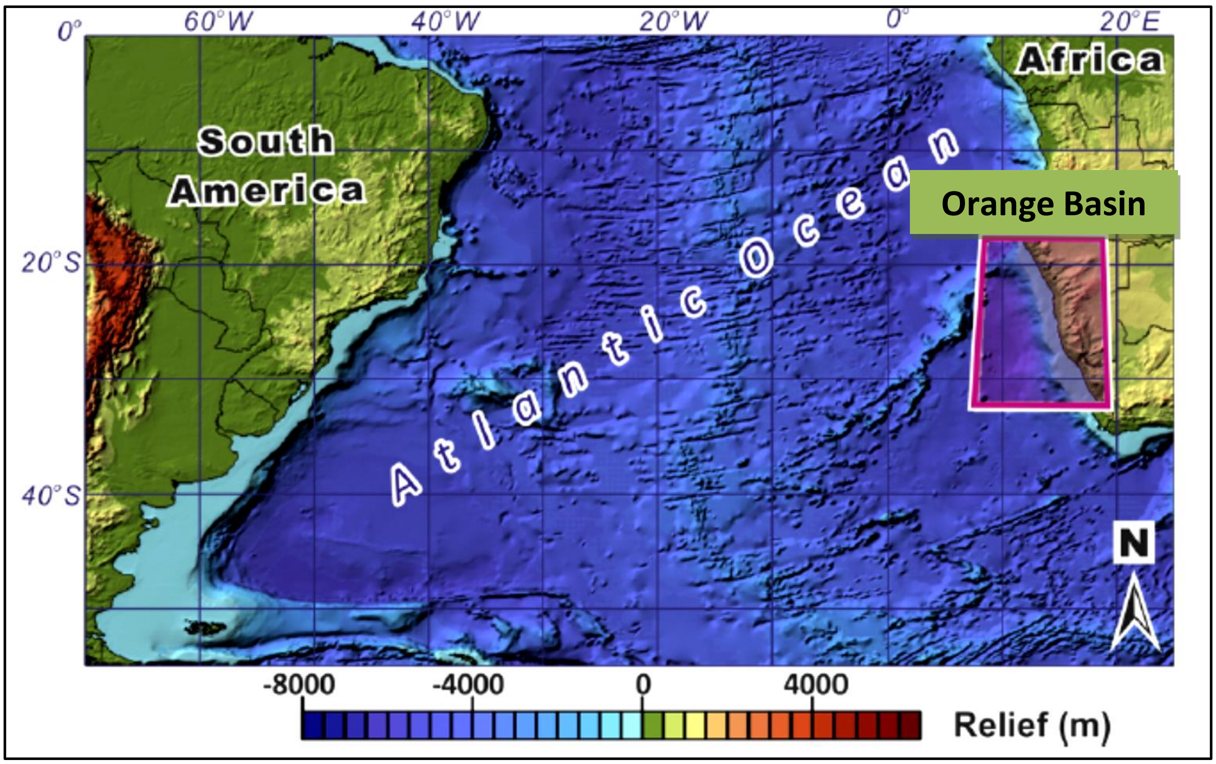


Figure 16: Location of the Orange Basin (Maystrenko*et al*., 2013)

The Orange Basin overlaps the South African/Namibian boundary; however, the largest fraction is in South African waters and is one of the under-explored basins in the world. So far, the most important discoveries have been the Kudu and Ibhubesi gas fields, see figure 17; even though quite a few gas and oil discoveries have been made in South Africa, which are not commercial (Oates and Pickford, 2001).

Figure 17: Location of the Kudu and Ibhubesi fields (PASA, 2012)

The breaking up of Gondwana resulted in a divergent margin which is believed to be part of the asymmetric or simple shear type (Etheridge *et al*., 1989) and is subdivided into crustal fragments constrained by transverse fracture zones, see figure 18. The breakup of Gondwana started in the Late Triassic or Early Jurassic. Drifting started as soon as rifting ended which gave rise to the formation of a mid-oceanic spreading ridge and newly formed oceanic crust at 121 Ma in the Cape Basin in the south (Martin and Hartnady, 1986) and at 117.5 Ma, latest Hauterivian in the north. The remnants of the half grabens to the east of the medial hinge were truncated by the rift/drift unconformity underlying Synrift succession, as illustrated in figure 16. The sedimentary infill that came thereafter could be as old as Jurassic but the oldest that was dated is Hauterivian(PASA, 2012). No Karoo sediments were found and the basement rocks that were encountered consist of granite, acid lavas, gneisses and phyllites (Broad *et al*., 2000).

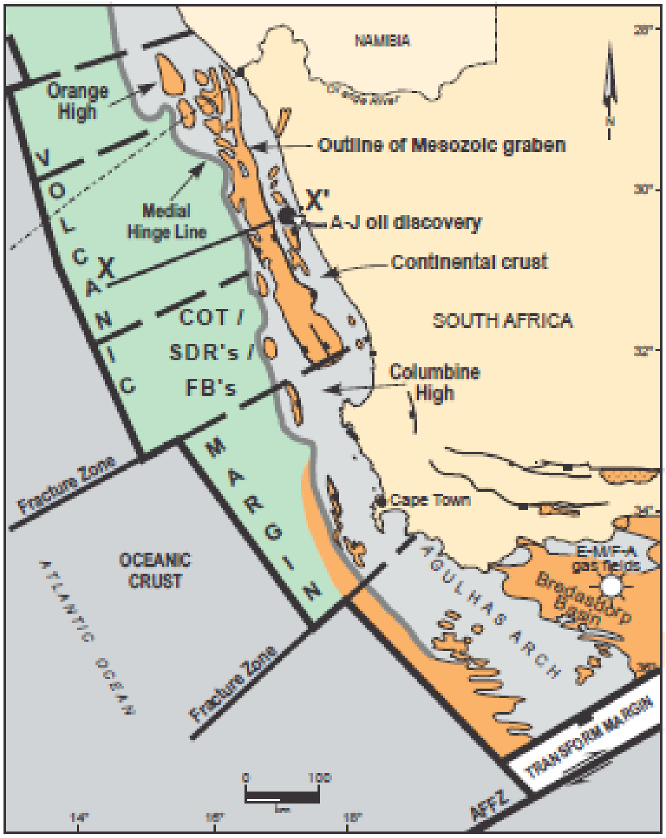


Figure 18: Major tectonic elements of western margin of South Africa (Jungslager, 1999)

2.1. PLATE TECTONIC SETTING AND DEPOSITIONAL HISTORY

The South African / Namibian border constrains the South African portion of the Orange Basin to the north, and in the south, it is bounded by the Aghulhas-Columbine Arch,(figure 19). The western margin of southern Africa is characterised by a divergent plate margin. This margin is underlain by syn-rift grabens that run parallel to the coastline and are overlain by siliciclastic sediments of the passive margin basin (Kuhlmann et al., 2010).

The Orange Basin is situated offshore of the south western coast of Africa facing volcanic rifted passive margin of southern Africa which was brought about by the rifting and drifting of the African and South American Plates which took place from Late Jurassic to Tertiary (Nürnberg and Müller, 1991; Light *et al.*, 1992, 1993; Clemson *et al*., 1997; Davidson, 2005). The Orange Basin is filled with approximately 7km of Late Jurassic to present day continental to siliciclastic sediments and covers an area of approximately 130 000 km^2 (Séranne and Anka, 2005; Hirch*et al*, 2007; Paton *et al*, 2007; 2008).

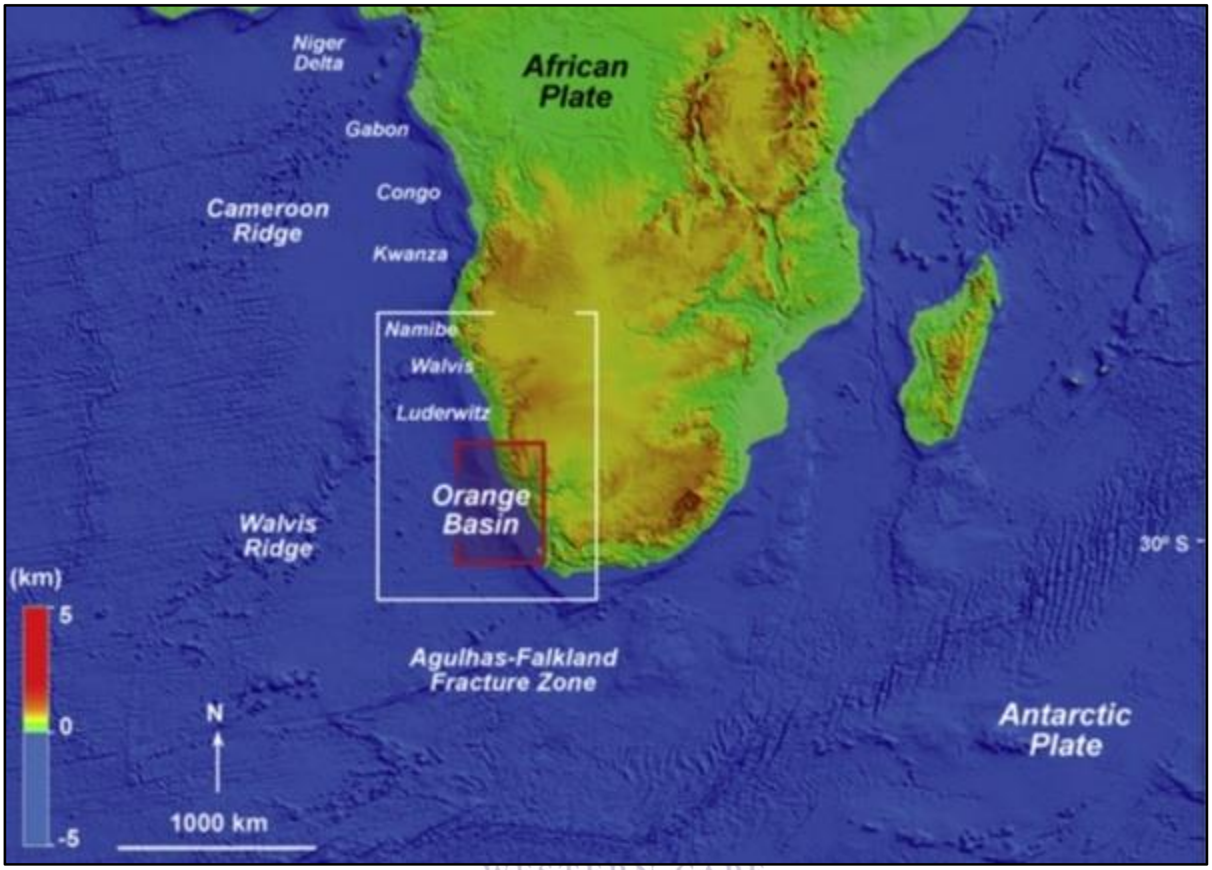


Figure 19: Plate tectonic setting of the Orange Basin (de Vera *et al*., 2010)

South western Africa has a continental passive margin which is constrained by two discontinuities in the north and the south that are NE-SW trending. These discontinuities are the Walvis Volcanic Ridge and the Aghulhas-Falkland fracture zone (Light *et al*., 1993; Clemson *et al*., 1997; Corner *et al*., 2002). The south-western most part of the west coast margin lies next to the Columbine-Aghulhas Arch and has a sediment wedge that is elongated and rather thin. Half-grabens, a central rift complex and listric faults that were brought about by gravity are some of the structural elements that are coupled with the rifting (refer to figure 21).

The formation of the basin was part of the rifting between the African and South American Plates that resulted in the breakup of the South Atlantic during Late Jurassic to Early Cretaceous, see figure 20. The breakup was coupled with some massive transient volcanic activity. Today, the volcanic rocks are able to provide age constrains on the age of the beginning of the rift stage as these rocks were formed due to magmatism when extension initially occurred (Hirsch *et al.*, 2010).

When rifting and the opening of the Orange Basin began, extension and possible inversion of the basement had already commenced (Clemson *et al*., 1999) and occurred at the same time as the extrusion of flood basalts at approximately 132Ma in the Etendeka-Parana Igneous province (Menzies *et al*., 2002). Basin flooding and deposition of deep marine sediments and later, the progradation of delta occurred during the stage of post rift subsidence, after rifting had ended (Light *et al*., 1993)

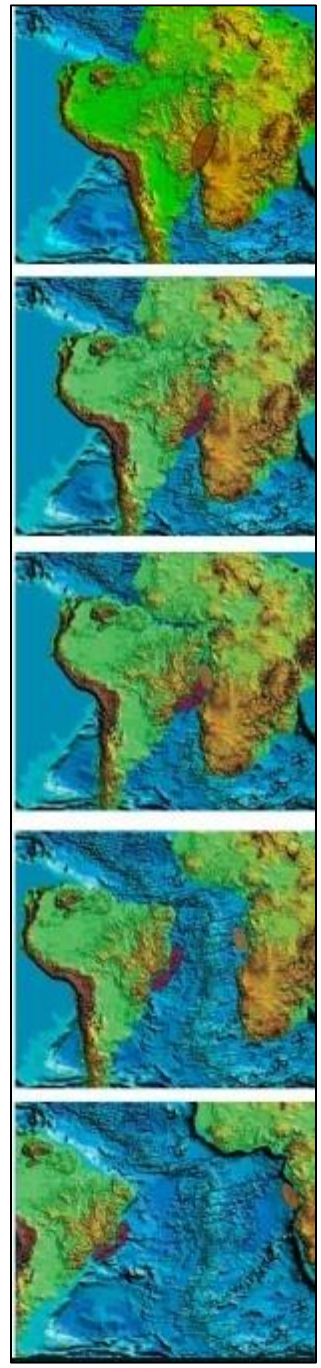


Figure 20: Continental reconstruction of several different stages of rifting between Africa and South America (http://www.geoexpro.com/articles/2008/04/the-dawning-of-two-continents).

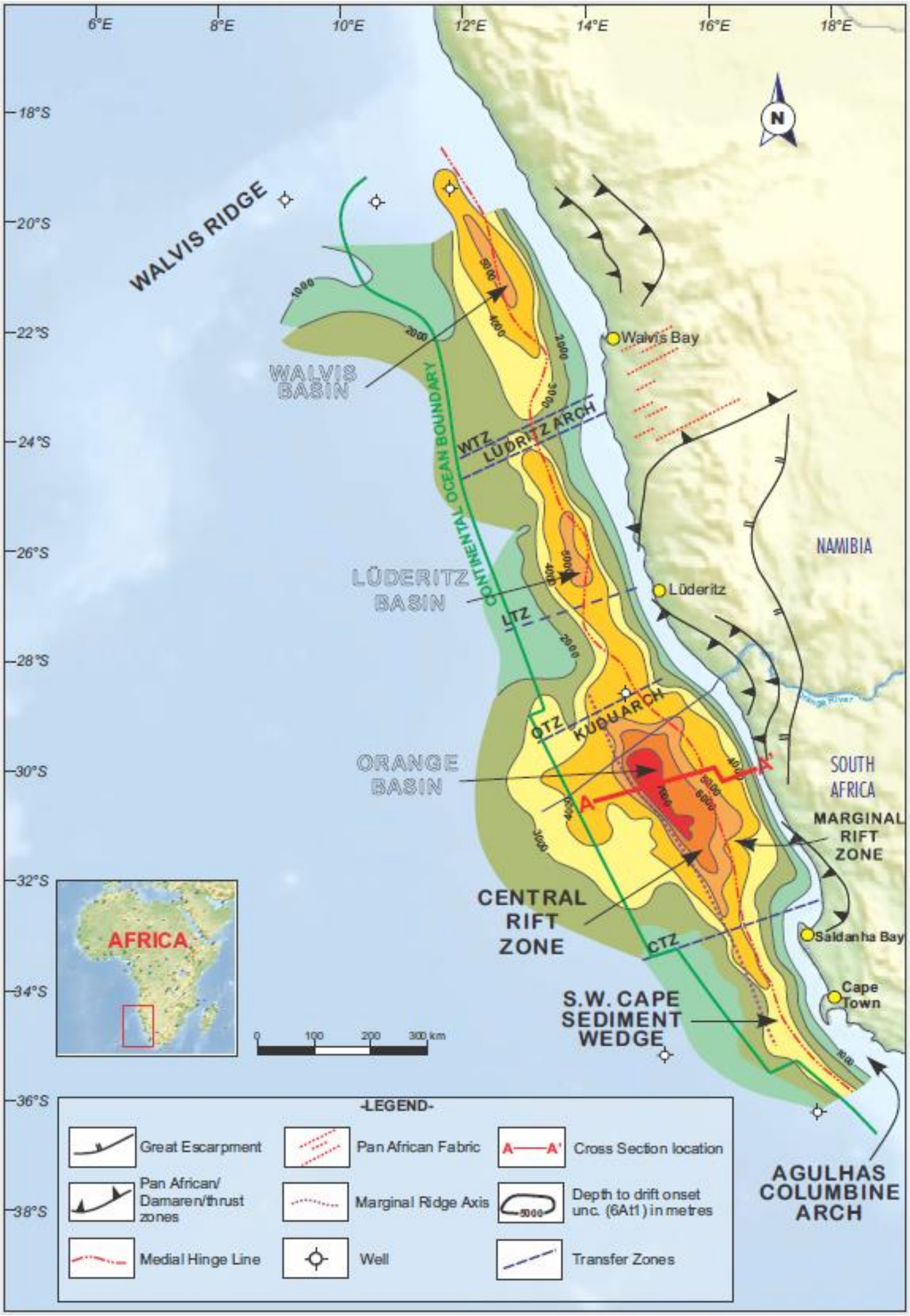


Figure 21: Major structural elements of the west coast margin (PASA, 2012)

Cambrian granites and metasediments were intersected in offshore basement. On the other hand, onshore outcrops show that pre-rift Karoo deposits may have been well preserved. The beginning of rifting and formation of grabens and half-grabens happened in the middle to Late Jurassic. Sediments found in grabenin-fill date from theHauterivian and are underlain by lavas of an uncertain age (SOEKOR, 1994).

Sediments that fill the Orange Basin are mainly of Lower Cretaceous-Early Tertiary age and overlie Synrift-grabens that contain lowermost Cretaceous-upper Jurassic fill.

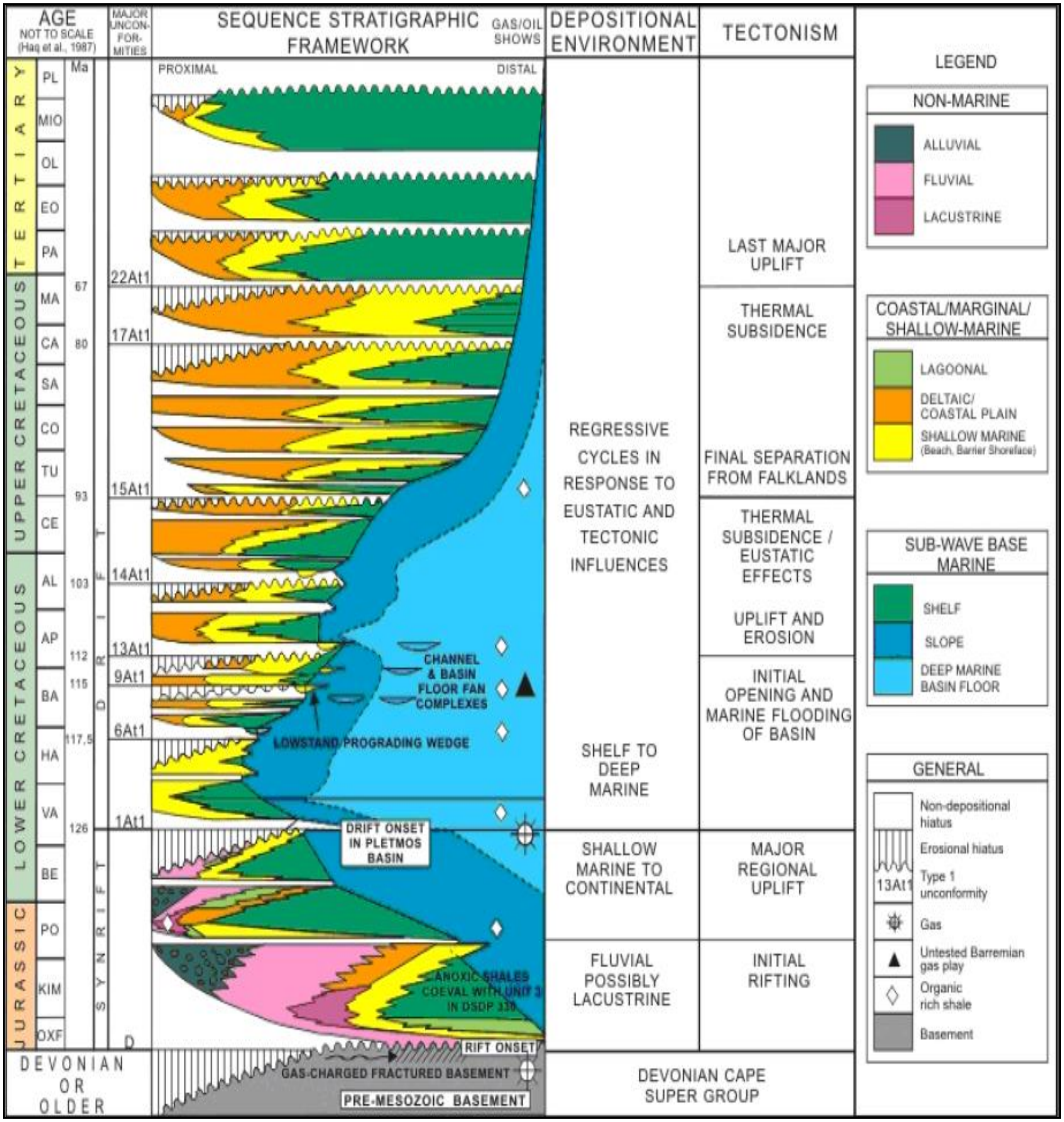


Figure 22: Generalised Chronostratigraphy for the Orange Basin (Source: Petroleum Agency SA Expl. Brochure, 2009; Brown *et al*., 1995)

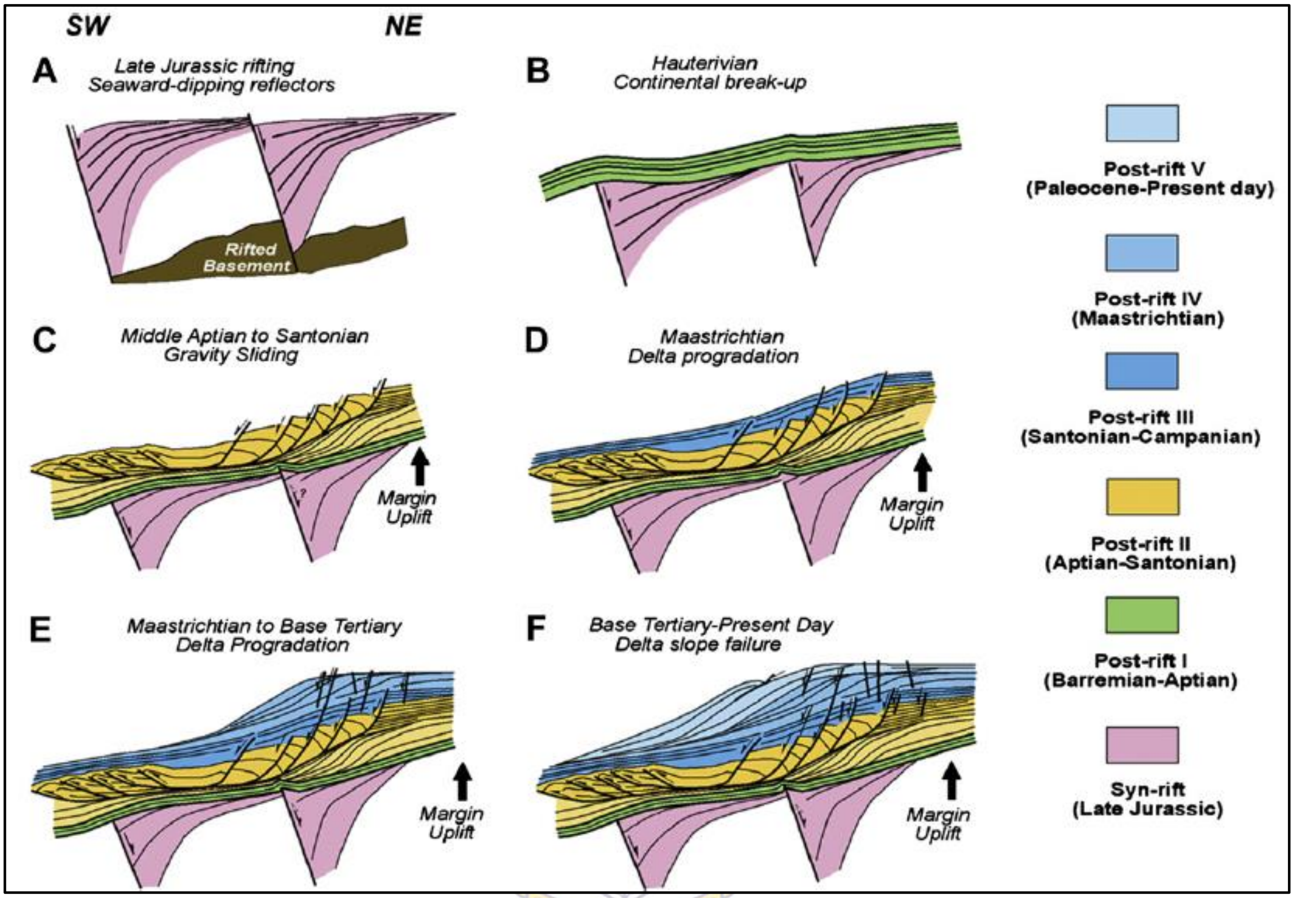


Figure 23: Synoptic basin evolutionary model for the gravity-driven system of the Orange Basin. A. Late Jurassic rifting (160-130Ma). B. Hauterivian-Aptian (133-120Ma). C. Middle Aptian-Campanian (120-75Ma). D. Campanian-Maastrichtian (75-70Ma). E. Base Tertiary-present day (65.5-0Ma) (de Vera *et al*., 2010)

2.1.1. Synrift Phase

The Synrift succession between horizons T and 6At1 was recognised in a central rift complex and in marginal half grabens. The rift complex is known to have developed approximately 50 to 150km basin-ward from the present coast. The succession in the central rift complex contains mostly lavas which are principally basic but locally acidic on its easternmost edge,(SOEKOR, 1994).

The marginal half-grabens that are explored are filled with coarse grained fluvial/lacustrine sediments and volcanics.

A regional hinge line separates the marginal graben system and an undifferentiated central rift wedge. The thickness of this central wedge is not known; however, that of the Synrift fill is 3km thick(?).

Upper Jurassic and Lower Cretaceous sediments fill the inner graben complex. These sediments are coarse continental clastics, fluvial/lacustrine sediments and volcanicswhich are laid down in an area of active synsedimentary faulting and jagged palaeotopography(Muntingh, 1993).

Only three marginal half grabens have been drilled and were found to contain volcanics, volcaniclastics and continental sediments. Organic-rich shales with oil-prone source rock potential were found to be the oldest datable sediments, they date Late Hauterivian.One well yielded 190 barrels per day of medium, waxy oil from lacustrine sandstones interbedded with the source shales. This synrift lacustrine oil play is still largely untested (Broad *et al*., 2006).

The central wedge displays progradational packages on seismic section but has only been sampled on its easternmost edge near the hinge line where thick basaltic lavas were encountered.

There is likely a pre-rift unit that is deduced from onshore deposits and may contain possible Permo-Carboniferous and Jurassic Karoo sediments and lavas preserved at the base of other half grabens. Overlying the grabens is an early drift sub-unit, from horizon 6At1 to 13At1,(figure 22). This horizon dates Hauterivian to mid Aptian and is representative of a proto-oceanic succession that is known to have been deposited during the change between fully rifting, continental conditions and that of fully drifting, open marine conditions, Muntingh, 1993.

2.1.2. Post-rift Phase

In the south-west African continental margin, Cretaceous post-rift thermal subsidence resulted in the deposition of clastic sediments; this subsidence was followed by two major periods of marginal uplift during the mid-Cretaceous (Brown *et al*., 2000) and also during the latest Cretaceous in mid Campanian (Kuhlmann*et al*., 2010; McMillan, 2003).

Parting of the South American and African continental placement of oceanic crustal rocks motioned the Early Cretaceous onset of the South Atlantic drifting phase, consisting of a roughly 10Myr long subsidence episode, see figure 22.

2.1.3. Drift

Drifting started occurring approximately at 117Ma along the southwestern margin of the African Plate. There is evidence that partially restricted marine environments were present in the Orange Basin before the main drifting phase began; this evidence occurs in the form of evaporates that are contained in the early drift siliciclastic sequences in the southern proto-Atlantic ocean (Brown *et al*., 1995).

More than 30 third-order post-drift sequences were deposited which resulted in very large amounts of depositional loading. This resulted in the subsidence (as mentioned before) of the Orange Basin in addition to thermal decay subsidence (PetroSA, 2014).

The drift phase occurs in the form of a thick sedimentary package that is interrupted by a number of unconformities, (figure 23). Seismic stratigraphic sequences and their system tracts have been defined in this interval and they give an understanding of the features of the basin fill. (Broad *et al*, 2006).

The mid Aptian 13At1 unconformity is evidently seen terminating the early drift sequence; this demonstrates the beginning of full drift, open oceanic conditions. The drift succession is a thick sedimentary wedge which is truncated by a number of unconformities. This succession has been split into seismic stratigraphic sequences and component system tracts. The shelf slope break is best described by a zone of Late Cretaceous faults with contingent maximum displacement (Muntingh, 1993).

Dominant deltaic complexes were prograding towards the west and deposited fluvial channel sandstones of reservoir quality between second order unconformities, 14At1

(103Ma) and 15At1 (93Ma). The main drainage system shifted about 300km towards the north during the time that the third order super sequence began (PetroSA, 2014).

The super sequence 13 shows progradational stacking patterns which are predominantly indicating very low accommodation rates. Super sequence 14 is categorised by stacking of aggradational and progradational patterns. Increased accommodation rates are evidenced and seen in sequences 15 and 16 where aggradational deposition took place.

The Albian fluvial channels form the reservoir of the Albian stratigraphic-structural play were deposited on the lower to middle shoreface of a delta front. This forms a very important play in the Orange Basin. The Ibhubesi gas field has very thin sandstone reservoirs; however, its porosity-permeability qualities are very good, so are the flow rates (PetroSA, 2014).

Progradational stacking patterns are shown in sequences 17 to 21 as a result of lesser accommodation rates. A well-developed sedimentary wedge signifies Cenozoic sediments; this wedge increases in thickness towards the basin. Growth faults are very common in the Tertiary succession whereas intrusives are less common (Broad *et al.*, 2006).

At the beginning of the Tertiary age, subsidence had already stopped on the West Coast, resulting in the stability of Cretaceous rocks underlying the Tertiary.. The 22At1 marks the base of the Tertiary succession.

The 22At1 has different levels of erosion and is more inclined towards the north of the block; truncation took place during the low stand of sea-level that marked the end of the Cretaceous period in South Africa (Dingle, 1973).

A thin layer of sediment covers the Cretaceous shelf with up to 1500m of sediment accumulated in the Tertiary depocentres. Unlike the Cretaceous that has the thickest accumulation towards the north, the Tertiary's thickest sediment accumulation occurs towards the south. This is due to the extra accommodation space that resulted from gravity faulting at the shelf edge. This faulting took place when the Tertiary sediments weighed on the steeply dipping Cretaceous rocks.

Studies have shown the Tertiary sediments as being more finer grained than the earlier Cretaceous sediments; thus, becoming chemically and biochemically more dominant (Dingle, 1973, Dingle *et. al*. 1983). These characteristics are related to low sediment supply which can be attributed to the change in climate (more arid conditions) which resulted in lower sedimentation rates.

2.2. PETROLEUM ELEMENTS

According to Magoon and Dow (1994), a petroleum system is a natural system that involves source rocks and all associated oil and gas which is inclusive of all the geological elements and processes important for the existence of a hydrocarbon accumulation. It is made up of 5 elements, which are source rocks, migration pathway, seals, reservoir and timing / maturation.

2.2.1. Reservoirs

A study that was conducted by Fugro Data Services looked at a few wells from the Orange Basin that showed coarsening upward sequence of sandstones with thicknesses between 5 to10m. Thicker sandstones were obtained from core from wells near the shelf break.

The earlier mentioned A-J1 discovery is in sandstones from upper Hauterivian which are fluvio-deltaic to lacustrine. The sandstones are at a depth of 3250m, with a porosity of 10% and a thickness of 9m. The gas discovery well, A-K1 in the Ibhubesi field is at a depth of 3275m, with a porosity of up to 20%. This well is in deltaic-fluvial sandstones of Albian age.

Other gas bearing Albian age reservoirs were encountered in deltaic sandtones in wells A-G1 and A-F1. The sandstones in A-F1 are at a depth of 2500m with porosities of up to 26% reported and a thickness of 17m. In A-G1, the sandstones were encountered at a depth of 3400m with porosities between 15-18% and moderate water saturations of 40-60% (Fugrodata services, 2010).

Cretaceous sandstones in wells K-E1 and K-A2 displayed porosities that ranged between 10-16% and permeabilities of more than 100mD. These sands also displayed significant amounts of quartz, which is due to the fact that the Orange drainage system provided most of the sediment input during the Cretaceous.

Orange Basin sediments show repeated trends / patterns of diagenesis which resulted in lower porosities in the sandstones due to cementation. In other cases, the porosities and permeabilities were preserved due to grain-coating clays as the pores do not completely become blocked, in medium to coarse grained sandstones. However, the opposite can be said for fine grained sandstones. The grain coating clays completely clog and block the pore throats resulting in the sandstones being completely impermeable.

Some wells that were intersected appear to have traces of intrusives including some of possible volcanic origin.

Some of the wells in the Orange Basin encountered sandstones with very good porosities and permeabilities, that is; the A-J1 oil and the Ibhubesi gas discoveries have reservoirs that date Lower Cretaceous and are derived from deltaic-fluvial sandstones. The sandstones appear to have undergone diagenesis which has preserved the porosities and permeabilities in medium to coarse sandstones and has decreased the porosities and permeabilities in finer grained sandstones due to pores being clogged by the grain-coating clays.

2.2.2. Source rocks

In the syn-rift Lower Cretaceous interval of South Africa, oil-prone source rocks have been identified; the potential of hydrocarbon generation varies from 9-11 kgHC / tonne and goes beyond 40 kgHC/tonne locally. The thickness of the source rocks can reach 60m (Broad and Mills, 1993). There have been gas plumes that were identified on seismic data over the wedge-out of the syn-rift section. These gas plumes may be seen as an indicator of source rocks (Bray *et al*., 1998).

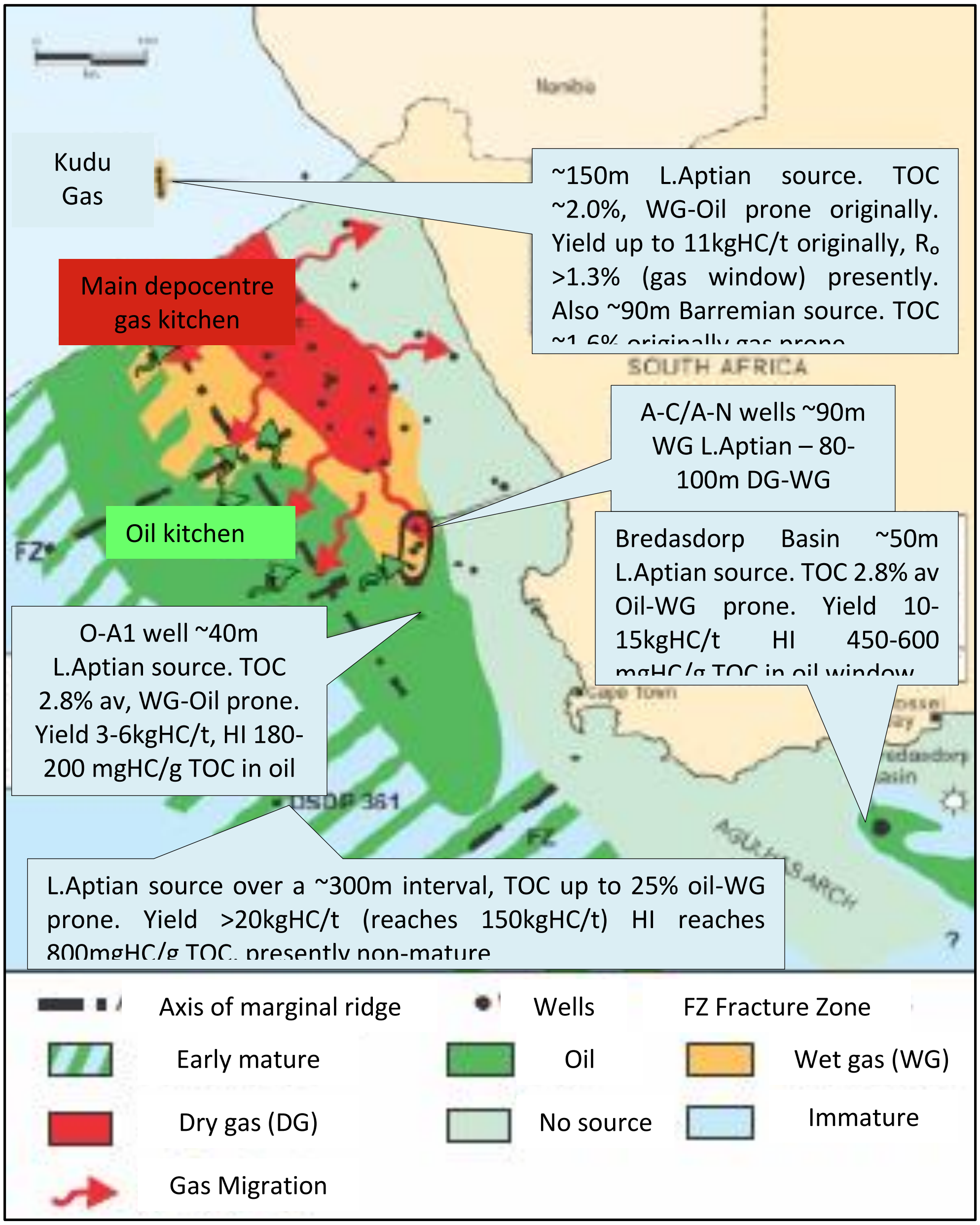


Figure 24: The active marine source rock kitchen at the lower Aptian level (Jungslager, 1999)

Another source rock was deposited on top of the Lower Aptian unconformity; this source rock is up to 90m thick and deposited regionally, refer to figure 24. According to Bray et al., the source rock is gas-prone on the shelf and is oil-prone to the west of that. In the Kudu Field wells, the average total organic content (TOC) of the source rocks is roughly 2%, with a thickness of 150m. However, a TOC of 8% was calculated with a Type II

Kerogen which characterises a source with the potential of both oil and gas (Bray *et al*., 1998).

The source rock of the Upper Cretaceous; Cenomanian-Turonian age is gas-prone and they have an average thickness of 30m. Their potential seems to increase towards the basin. However, this source rock interval is absent in the Kudu Field.

2.2.3. Migration paths and traps

The unconformity that formed during the break-up of Gondwana comprises marine mudstones and seems to regulate the up-dip migration of hydrocarbons that leave the source kitchen. There are several possible traps that are associated with the syn-rift section; from rotated fault blocks, pinchouts against faults and closures over fault blocks to normal faults.

Due to slight movements or compactional drape over, the Orange Basin has not so obvious structural closures in deep fault blocks. The Ibhubesi Gas Field may contain partly this type of structural trapping. The drift phase sequence has a lot of mud around all the margins of South Africa. If there are sandstone sections in the muddy sequence; chances are that they have some possible structural setting.

CHAPTER 3 DATA AVAILABILITY AND METHODOLOGY

This chapter gives a description of all the different types of data that were used for this study; it also will give the approach of how to go about achieving the aims and objectives of this study. The data that was available for this study is summarized in the table below. This dataset (wireline logs, biostratigraphy reports, seismic data and well completion reports) were obtained from PetroSA and from the Petroleum Agency of South Africa (PASA). The combined use of this data will help determine the palaeoenvironment and depositional facies of the drift section in Block 3A/4A using four wells.

3.1. DATA AVAILABILITY

Table 18: Dataset available for the four wells

Well Name	Wireline Logs	Biostratigraphy Data	Seismic Data (through well)	Well Completion Report
X-Z1	✓	✓	✓	✓
X-Z2	✓	✓	✓	✓
X-X1	✓	✓	✓	✓
BX-X1	✓	✓	✓	✓

3.1.1. Seismic Data

Seismic data is of great importance in this study as it will help with the regional picture of the basin and the block.

It helps understand facies distributions, faults, stratigraphy, and other structures and can also serve as a lithology indicator or direct hydrocarbon indicator. The wells in the block are not enough to give a clear regional understanding and overview, hence seismic data is useful.

The seismic data quality in the Block was reviewed to identify the degree of noise contamination of the data for interpretation purposes. This involved highlighting noise and processing artefacts within the data.

There are different vintages within 2D SEGY lines. Some of the 2D SEGY lines were reprocessed by WesternGeco forSasol. Between September 2000 and February 2001, some of the 2D lines were reprocessed.

One of the main objectives for the corrections was to bring the data to a consistent datum for interpretation. Several vintage types had different polarities, phases as well as misties that needed to be corrected.

Vintage Types

For this project, seven different vintages were used. The lines cover a distance of approximately 740 line km 2D seismic data reprocessed in the block. The lines were obtained between 1976 and 1992, (figure 25).

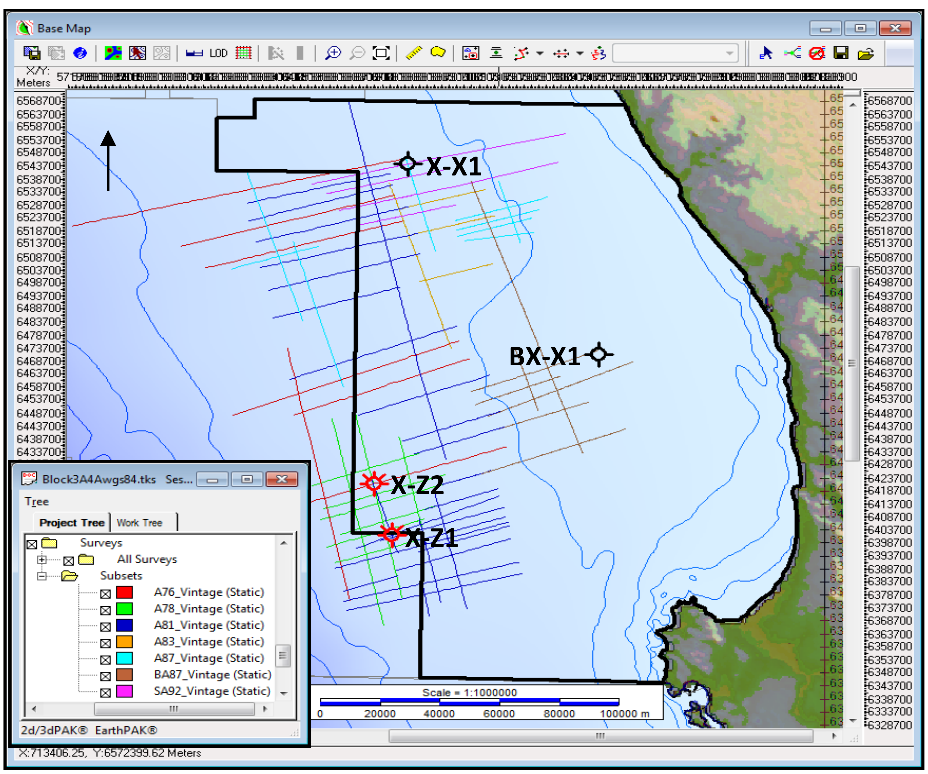


Figure 25: Basemap with vintage types in Block 3A/4A

Data Quality

The 2D seismic data in Block 3A/4A is filled with multiples, has short cable lengths, dipping noise, ringing noise, tiff images (scanned hardcopy seismic lines) and also has discontinuous fault problems. Table 6 gives an overall summary of the data quality of the 2D lines; the overall 2D data quality in the block is poor. Figure 26 shows an example of the bad quality 2D seismic data in block 3A/4A.

Table 19: Types of vintages and their quality of data

Vintage Type	Data Quality
A76	Poor
A78	Medium
A81	Medium
A83	Poor
A87	Poor-Medium
BA87	Poor
SA92	Poor

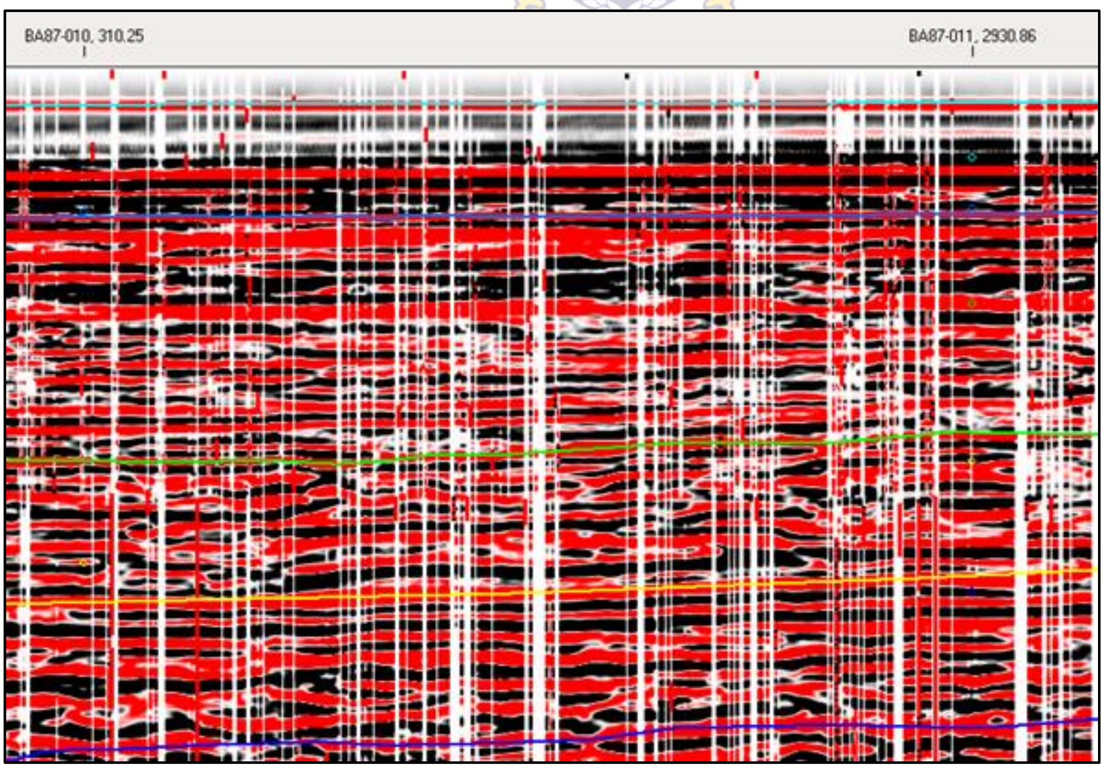


Figure 26: An example of the poor data quality

3.1.2. Wells

As stated in chapter one, this study only focuses on four wells that are inside block 3A/4A and they are X-Z1, X-Z2, X-X1 and BX-X1, see figure 25.The reason why these wells were chosen is because they all sampled the drift sequence andtheir data quality is better. The distance between the two X-Z wells is 21.14km, 125.73km between X-Z2 and X-X1, 90.80km between X-Z2 and BX-X1 and the distance from X-X1to BX-X1 is 97.80km. Table 7 gives a brief summary of the four wells of interest.

Table 20: Details of the wells of interest in Block 3A/4A under investigation

Well Name	Water Depth (m)	Total Depth (m)	Spud Date
X-X1	235.3	3805	2-May-76
X-Z1	324.9	4139.2	13-Jan-80
X-Z2	319.7	3613.4	30-Mar-80
BX-X1	141.7	1699	1-Apr-76

3.1.3. Wireline Logs

Electrical well logging has advanced immensely since it was introduced over a century ago. The thorough analysis of carefully chosen wireline services offers a method of deducing accurate indication of lithology, hydrocarbons, water saturation and permeability index. However, for the purposes of this study, only the gamma ray log will be looked at as it is the lithology indicator.

All four wells were logged, from the sea floor to their respective total depths.

3.1.4. Biostratigraphy Data

Biostratigraphy analyses were done by Ian McMillan from SOEKOR. The reports were useful in determining the validity and legitimacy of the seismic well top depths. However, not all the analyses were used as some did not focus on the depthsthat are used for this study.

For the X-Z2 well in which the SOEKOR analysis was not used, a study carried out by PetroStrat Applied Stratigraphy was used instead. This PetroStrat study was aimed at analyzing the biostratigraphy of selected wells in the Orange Basin using nannopaleontology, micropaleontology and palynology.

Table 21: Base and top markers of the Drift Sequence

	X-X1	X-Z1	X-Z2	BX-X1

Top of Drift Sequence		670m	345– 593.9m	
Base of Drift Sequence		3030-4139.2m	3020-3180m	1280-1286m

3.2. METHODOLOGY

3.2.1. Desktop Study

The first step was collecting all the available data of the Orange Basin and the wells to be used for this study. A desktop study was done on the regional geology of the basin and understanding the overall stratigraphy, plate tectonics, looking at the history of hydrocarbon exploration in the basin, the study area, petroleum elements in the basin and briefly looking at the regional setting of other basins in southern Africa.

3.2.2. Seismic Data

Seismic data was interpreted using the IHS Kingdom software and is in depth and not time (depth conversion was done on the data prior to the commencement of the study). Different lines were interpreted from seven different vintages ranging from 1976 to 1992.The first step in interpreting seismic data was to create a project by properly loading all the available data (well locations, well markers) into the software as per the desktop studies. After this process, all the horizons and their depths (sea floor, 22At1, 16At1, 15At1, 14At1, and 13At1) were loaded and interpreted in all the 2D seismic lines from the different vintages. After this interpretation, the sequences in between the interpreted horizons will then be analysed in detail and the events that took place thereof interpreted.

3.2.3. Core Data

The second step was analyzing the core and determining whether the logged depths are compatible with what the study is focusing on. Unfortunately, all the depths were logged deeper than where the drift section is, thus core data was not used.

3.2.4. Wireline Logs

The wireline logs were also interpreted using the IHS Kingdom software. The gamma ray log was interpreted and the stacking patterns of the sequences analysed as well.

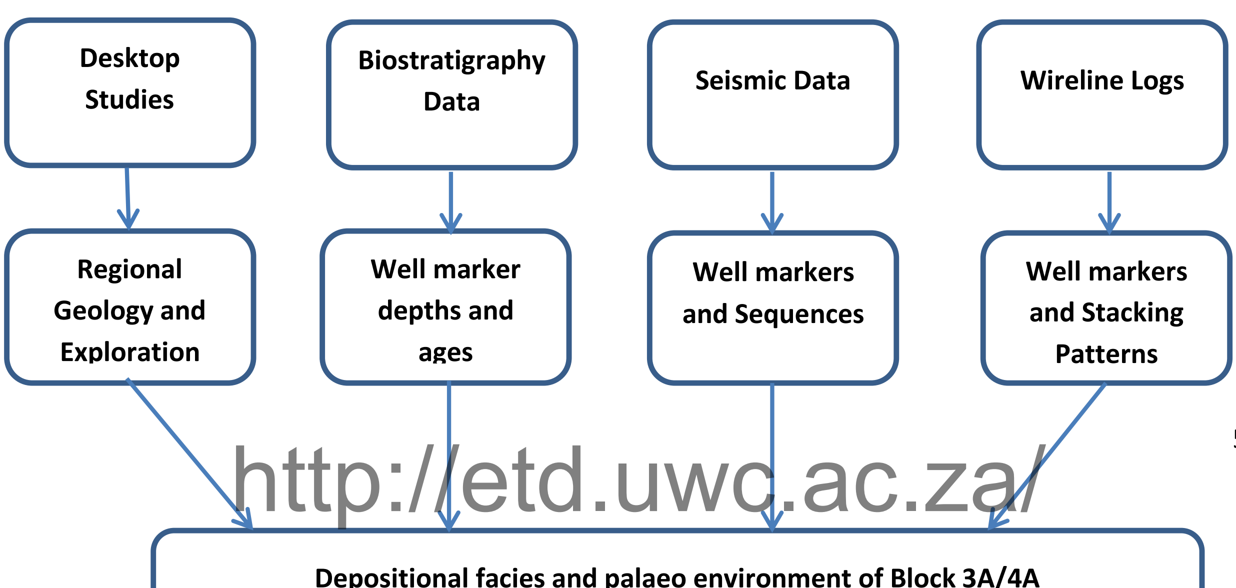
Before the interpretation, the data was loaded as it was in the previous section of seismic interpretation. The unconformity markers were then compared to what it seen on the logs, re-adjusted where possible.

Sandstone net to gross of each log was determined as well as the patterns respectively.

3.2.5. Biostratigraphy Data

After the core stage, the available biostratigraphy data of the wells was be looked at. The data providesinformation or rather direction of where the well markersare, through the analysis of organisms that were found in the samples in their respectable depths.

Previous articles from SOEKOR and other studies from different companies that were done on the biostratigraphy of the Orange Basin were closely studied and compared.



CHAPTER 4 RESULTS AND INTERPRETATION

4.1. DESCRIPTION OF SEQUENCES

The following are descriptions of the sequences between the unconformities on lines taken from Block 3A/4A.

4.1.1. Line A76-020 (figure 28)

13At1 – 14At1 (13A Sequence)

The slope goes down towards the west and a basinal feature can be observed to the west (with minor faults); it could have developed due to subsidence. A shelf edge feature can be observed towards the west of the line.

There is a major fault cutting through sequences to the east of the line and goes beyond the 16At1.

14At1 – 15At1 (14A Sequence)

The sequence thickens to the west with reflectors onlapping on the 14At1. There is a fault that is terminated in this section / interval, with a strip of bright reflectors between the dim ones. Some reflectors can be seen truncating on others.

15At1 – 16At1 (15A Sequence)

The sequence is cut by faults, none of which are major faults. The fault on the far west seems to have displaced the sequence downward.

The 15At1 has dark amplitude.

16At1 – 22At1 (16A Sequence)

The sequence appears to have had more accommodation space, validating what is written in literature. It thickens towards the west and thins to the east. The amplitudes darken towards the west of the sequence.

22At1 – Sea Floor

The sequence is characterized by weak amplitudes; it thins in the west and thickens to the west.

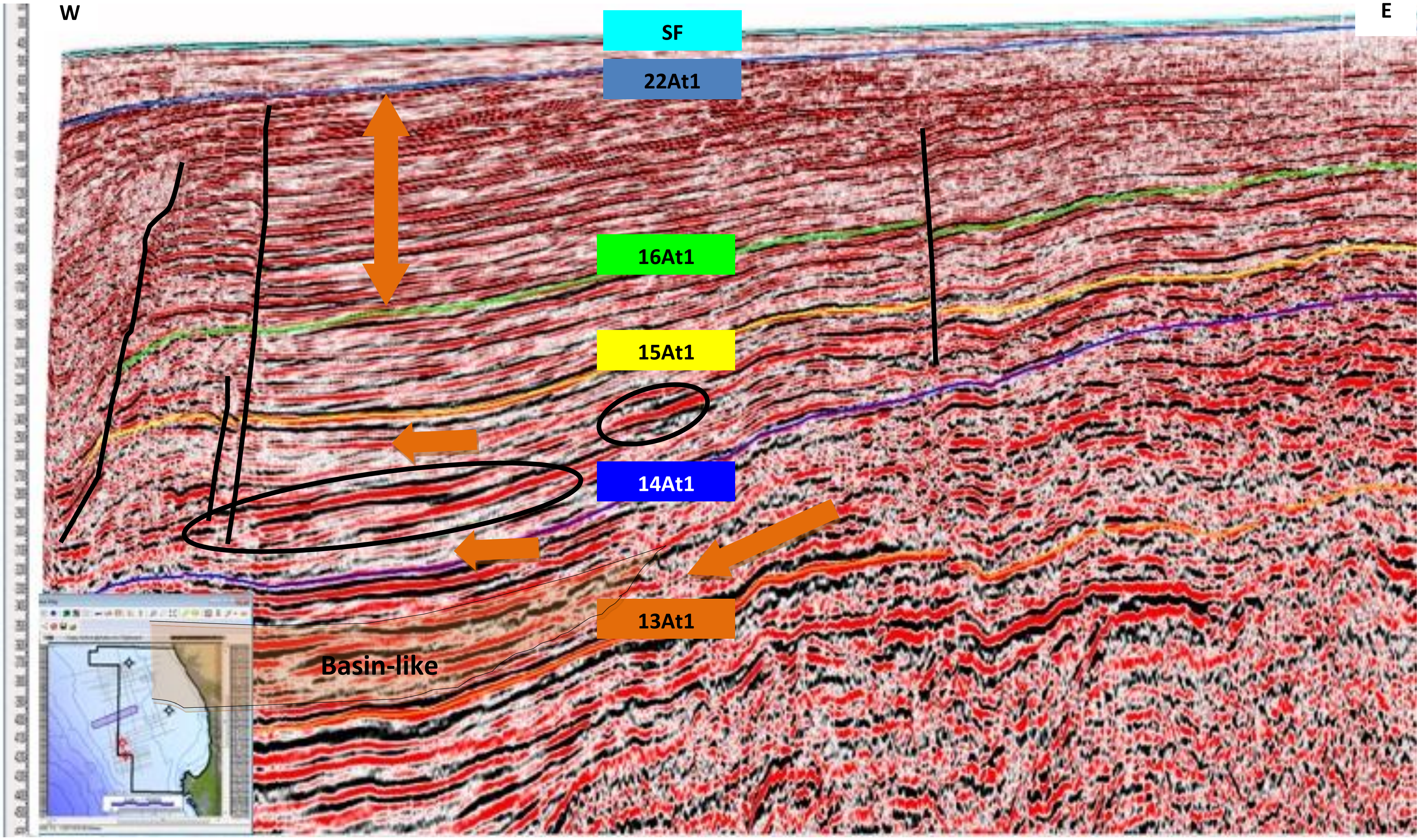


Figure 28: Line A-76-020

4.1.2. Line A76 – 026 (figure 29)

13At1 – 14At1 (13A Sequence)

The slope steepens from the west to the east; bright reflectors are onlapping on to others. There are two normal faults to the west of the line, basinal and slumping features.

There are reflectors that are truncating on others and a pinchout feature that can be observed to the west of the line.

14At1 – 15At1 (14A Sequence)

There are weak amplitudes and faults to the west.

15At1 – 16At1 (15A Sequence)

This sequence thickens towards the west and has faults to the west of the line. There appears to be a mixture of dark and weak amplitude on reflectors. Also, this sequence dips to the south west of the line.

16At1 – 22At1 (16A Sequence)

There is onlapping which supports the findings that the sequence was deposited after an event. The accommodation space has increased a lot from the previous sequences.

There is a mixture of dark and weak reflectors and there are faults that extend from underlying sequences and terminate just before the 22At1.

22At1 – Sea Floor

The sequence is thin in both the east and the west; however, it is thicker in the middle. It is also characterized by weak amplitudes as in the previous line.

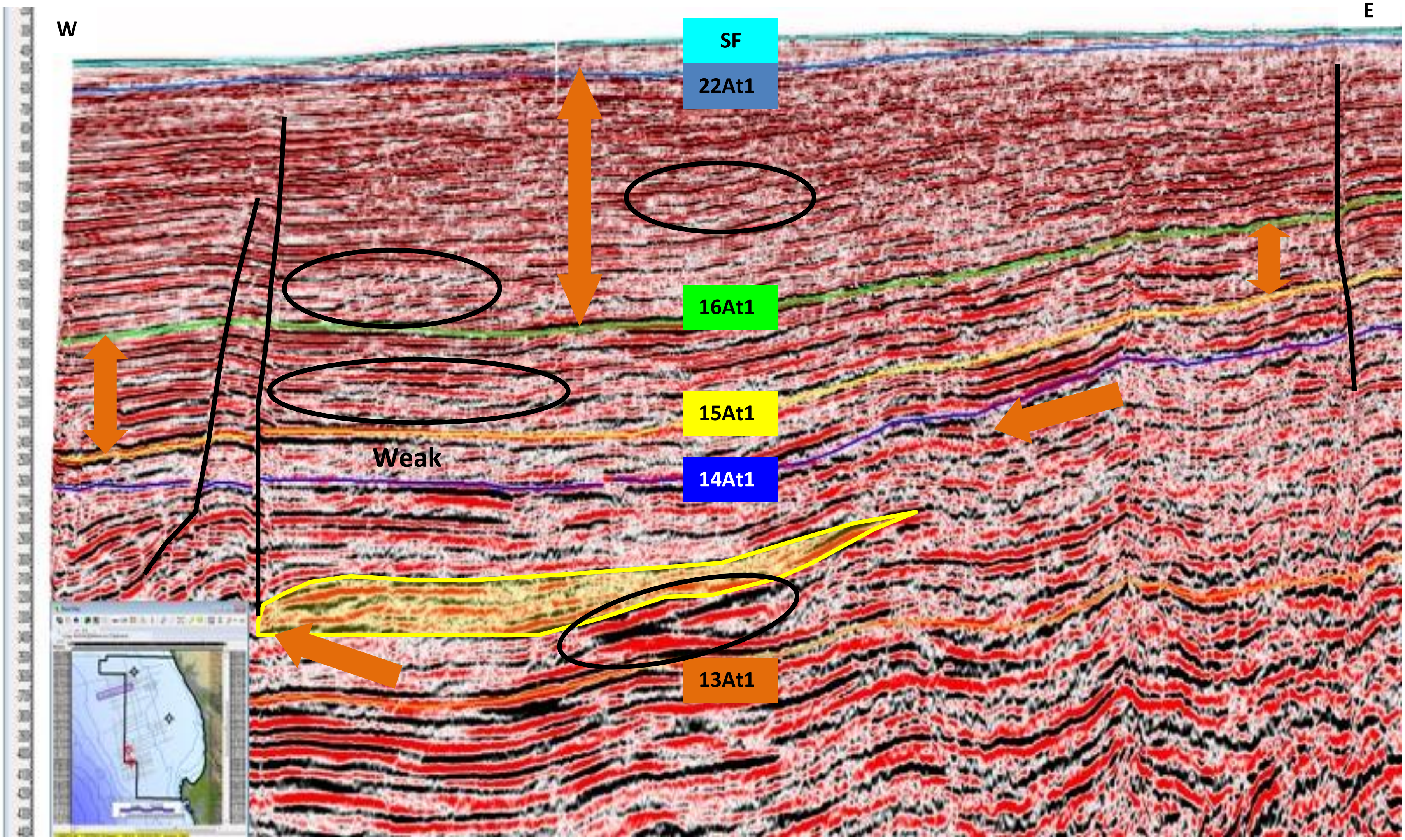


Figure 29: Line A76-026

4.1.3. Line A76 – 010 (figure 30)

13At1 – 14At1 (13A Sequence)

Truncation of reflectors on the 13At1 and on other reflectors. There are faults and a domal feature to the west of the line, as well as a subsidence feature in the middle of the line. Onlapping of the reflectors can also be seen.

14At1 - 15At1 (14A Sequence)

There is a high towards the east, thus the thickness in the east thinning from the west. There are reflectors truncating on the 14At1, with a subsidence feature observed together with a fault passing through.

15At1 – 16At1 (15A Sequence)

There are faults to the west of the sequence towards the shelf break which resulted in the steeply dipping reflectors to the south west; creating a folding impression. There appears to be truncation of these dipping reflectors.

The middle of the line has a channel feature throughout the sequences.

16At1 – 22At1 (16A Sequence)

Just like the previous lines, this sequence is thicker than the rest; from the increased accommodation space that was created and high sediment rate. This sequence also thickens towards the west to the shelf break and also has faults to the west of the line.

There is a reflector that evidently truncates on the eastern side of the line. This reflector could be interpreted as the 17At1 (indicated with dotted lines). There is also a channel feature on this sequence, in the middle of the line.

22At1 – Sea Floor

The sequence is a little thicker in the middle than it is in the east and the west.

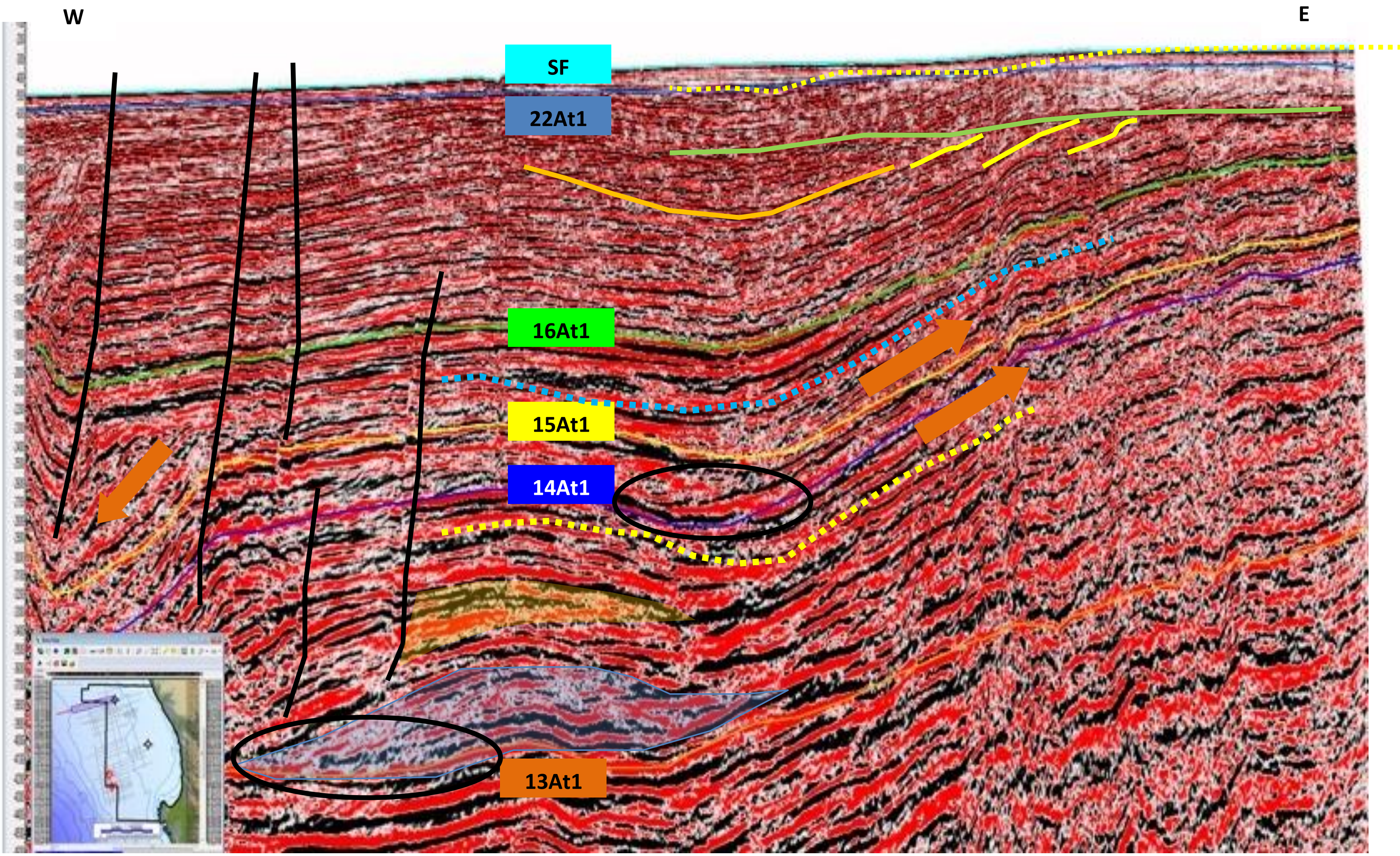


Figure 30: Line A76-010

4.1.4. Line A76 – 006 (figure 31)

13At1 – 14At1 (13A Sequence)

The sequence thickens to the west towards the shelf break. Reflectors truncate on the 13At1 and on other reflectors, there is a combination of dim and bright reflectors and onlapping of reflectors on the 13At1.

There is a pinchout feature that can be observed to the east of the line and a steepening slope from the west to the east.

14At1 – 15At1 (14A Sequence)

There is a subsidence feature, a high towards the east that can be observed and faults passing through. This sequence is thinner towards the east and truncation of reflectors on the 14At1.

15At1 – 16At1 (15A Sequence)

To the south of the block, the 15A sequence is deeply steeping to the south west, more so that is truncated by what is believed to be the 17At1 towards the east of the line.

There is onlapping of reflectors.

16At1 – 22At1 (16A Sequence)

This sequence, just like the other lines thickens towards the west. The amplitude of the reflectors is darker towards the west of the well and they dip to the south on the far west. The eastern part of the line shows to have undergone an uplift; implying that there is a high towards the BX-X1 well.

There is a mixture of dark and weak reflectors and there are faults that extend from underlying sequences and terminate just before the 22At1.

22At1 – Sea Floor

Reflectors are seen truncating on others. The sequence is thick in the west and thins towards the east.

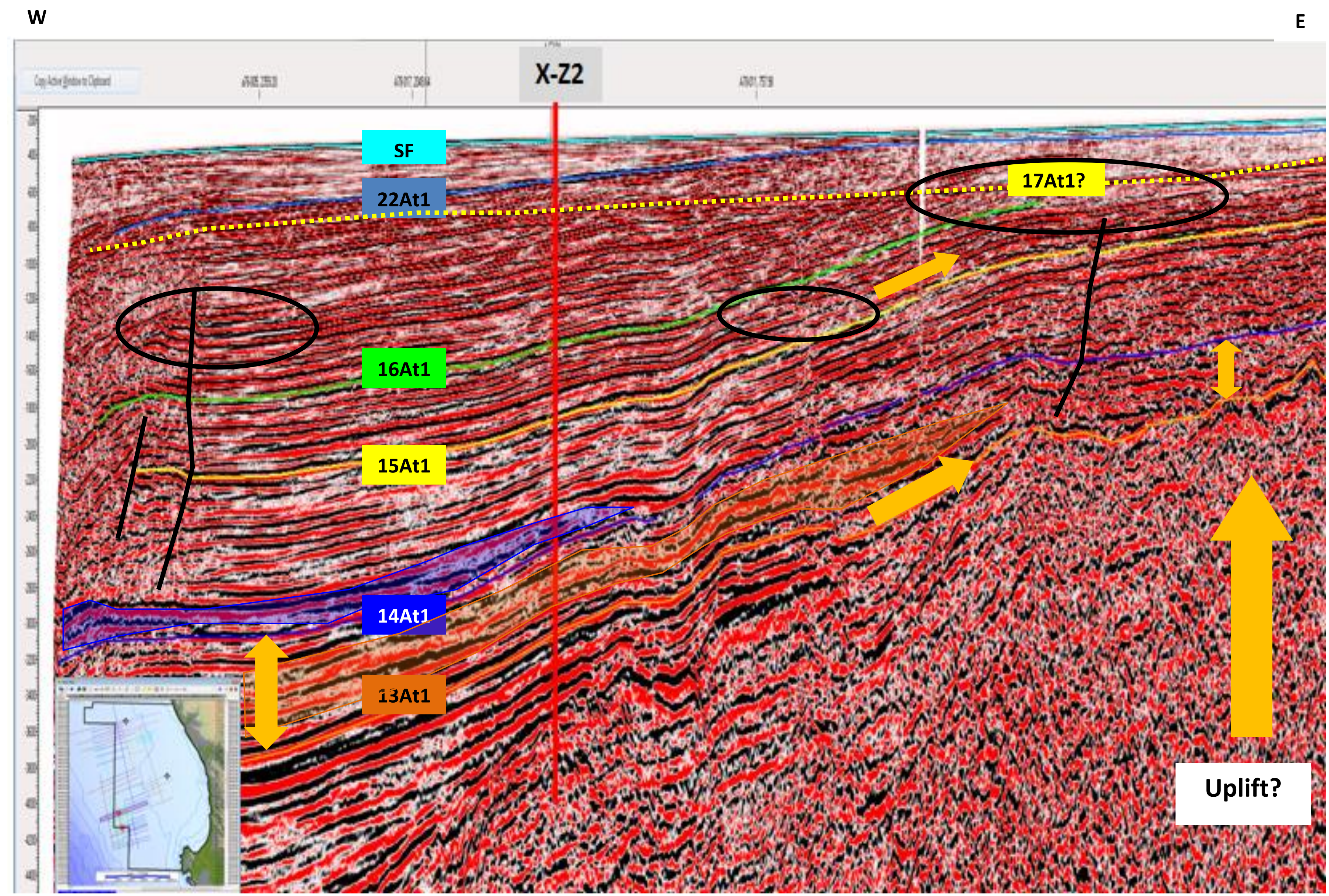


Figure 31: Line A76-006

4.1.5. Line A78 – 015 (figure 32)

13At1 – 14At1 (13A Sequence)

There is a major fault that is running through the sequences and is terminated just before the 22At1, on the eastern side of the well (X-Z1). The reflectors have a fading effect.

West and east of the major fault, the reflectors show to have been folded.

14At1 – 15At1 (14A Sequence)

In this sequence, the reflectors are relatively uniform. Similar to the sequence below, there is a major fault running through in the west and dim reflectors.

15At1 – 16At1 (15A Sequence)

The 15At1 has dark amplitude. The SSE of the line has a major fault running through the sequences and terminating just before the 22At1 (towards the shelf-break). Studies have stated that this sequence experienced a collapse of the shelf-edge in the form of growth faults which are observed on this particular line.

16At1 – 22At1 (16A Sequence)

This sequence has minor faults to the NNW. There seems to be uniformity in this sequence and thickening towards the SSE. The major fault created a folding impression on the sequences.

22At1 – Sea Floor

The sequence has very weak amplitudes and is a little thicker to the west.

NNW SSE

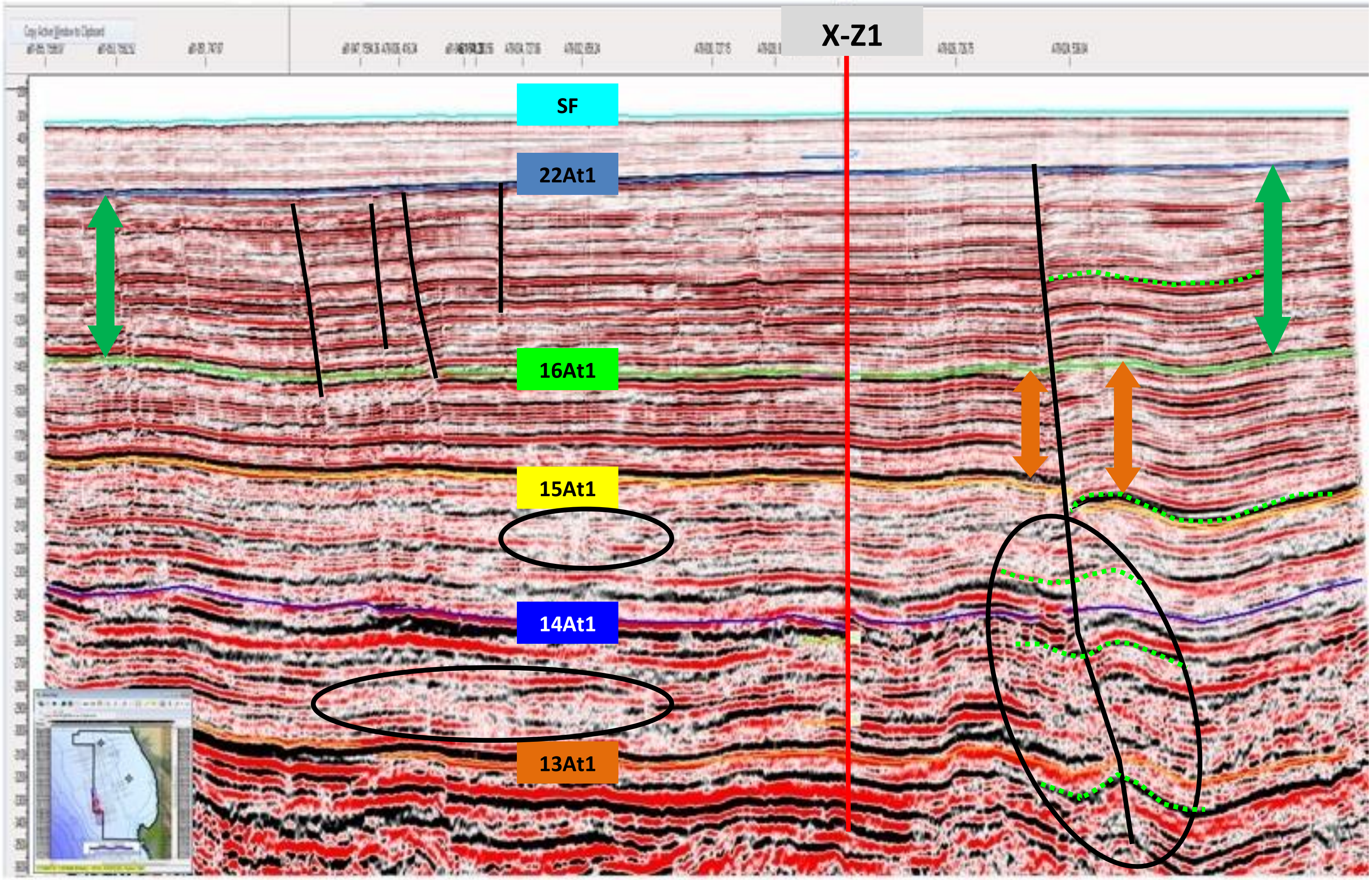


Figure 32: Line A78-015

4.1.6. Line A81 – 067A_A (figure 33)

13At1 – 14At1 (13A Sequence)

Reflectors are dipping towards the north and are dim in the south east.

14At – 15At1 (14A Sequence)

Downlapping and onlapping of reflectors can be observed. There are no faults seen in this sequence.

15At1 – 16At1 (15A Sequence)

The 15At1 has a dark amplitude that gently dips to the south. Amplitudes in this sequence are generally dark with patches of weak amplitudes. This sequence thickens towards the NNW of the line.

16At1 – 22At1 (16A Sequence)

This sequence is noticeably thin on the SSE and thickening towards the NNW and is truncated by the 22At1. Weak amplitude can be observed right through the sequence.

22At1 – Sea Floor

Sequence is very thin.

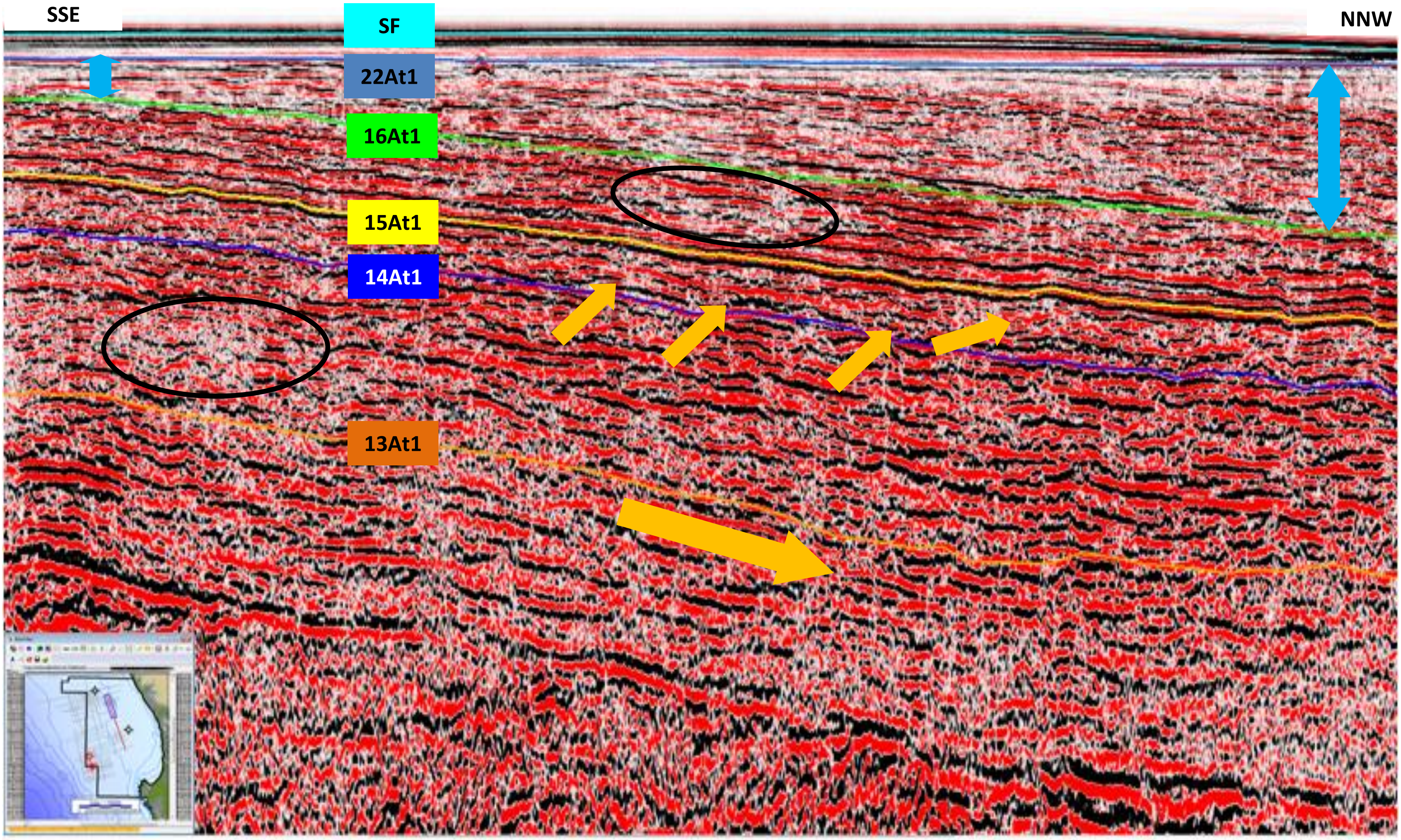


Figure 33: Line A81-067A_A

Table 22: Simplified well markers as per seismic lines

	X-X1	X-Z1	X-Z2	BX-X1	Ages
13At1	3157m	3122m	3100m	1200m	Aptian
14At1	-	2533m	2625m	960m	Albian
15At1	1244m	1800m	1900m	-	Upper Cenomanian - Early Turonian
16At1	790m	1478m	1467m	756m	Upper Turonian - Early Coniacian
22At1	399.33m	600m	580m	549m	Maastrichtian

4.2. FACIES MAPS

Constructing facies maps for each of the markers was amajorattribute for this studywhich has helped in understanding sediment disbursal pattern after seismic interpretation of Block 3A/4A was done. The maps were generated on IHS Kingdomto determine distribution patterns of each sequence around the block.

The principle behind generating a facies map is to restructure palaeogeography. Facies maps are generated at an isochronous surface or within a coeval interval, (AAPG Wiki, date accessed: 26 April 2016).

Facies maps that are based on numerical stratigraphic data (thicknesses, percentages and ratios of lithogic components) are recent in literature.

Interpretation of facies maps depend on the interval to be interpreted, the scale of the map and the rate of change of the facies in the map area. Generally, two types of maps are identified: regional maps that show extensive trends over big areas and local maps which show more detail in smaller areas, (Krumbein, 2006).

13At1

This deeper surface has a structural high in the south eastern portion of the block, going to a low in a westerly direction. The BX-X1 sits roughly at a depth of 1350m, with X-X1 at 2900m and wells X-Z1 and X-Z2 approximately at 3200m. What is shown by the facies maps (figure 34) is that the 13At1 surface is not even, it moves from a high in the east to a low towards the shelf in the west.

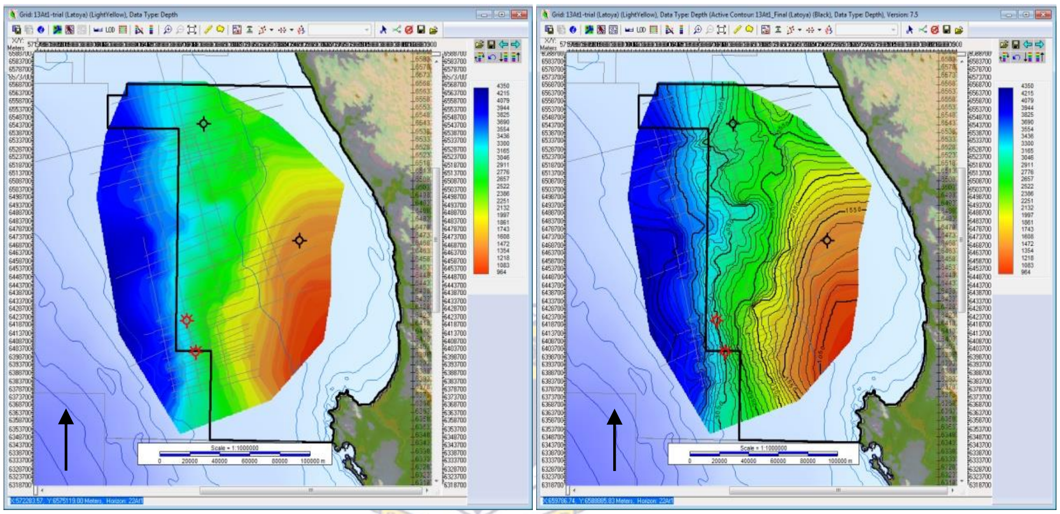


Figure 34: 13At1 facies maps

14At1

The large surface area on the facies maps (figure 35) in the east is a high extending extensively to the north towards the X-X1 well and then moving on to the west towards the shelf to a structural low. When looking closely at the facies maps, it could be said there are two structural highs on this surface; towards wells X-X1 and BX-X1.

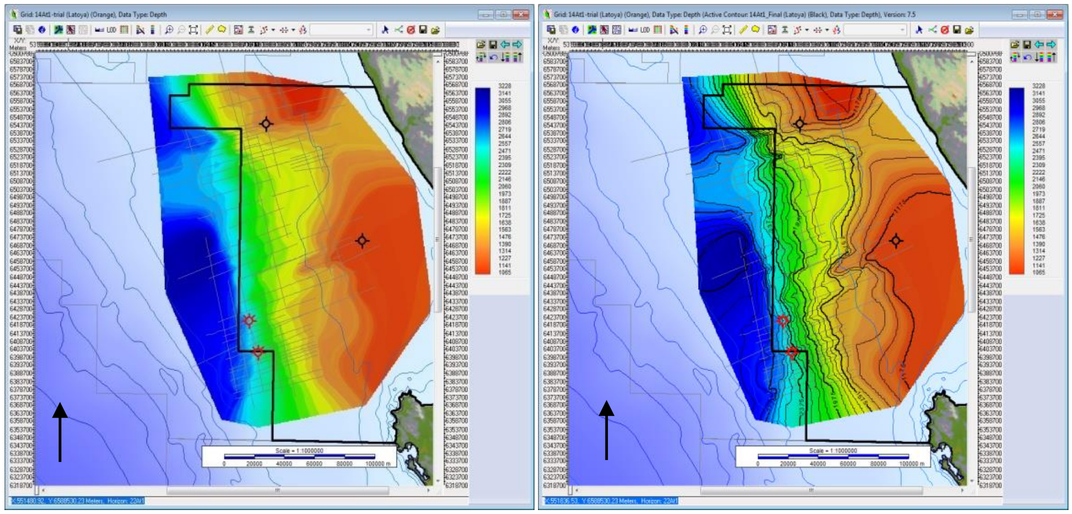


Figure 35: 14At1 facies maps

15At1

The 15At1 is not that far off from the 14At1, however, the structural high towards well X-X1 is not obvious, as can be seen infigure 36. There is a large surface area that has a high in the east of the block (towards well BX-X1), then going to a low in the west. Wells X-Z1 and X-Z2 are sitting at depths of approximately 1800m.

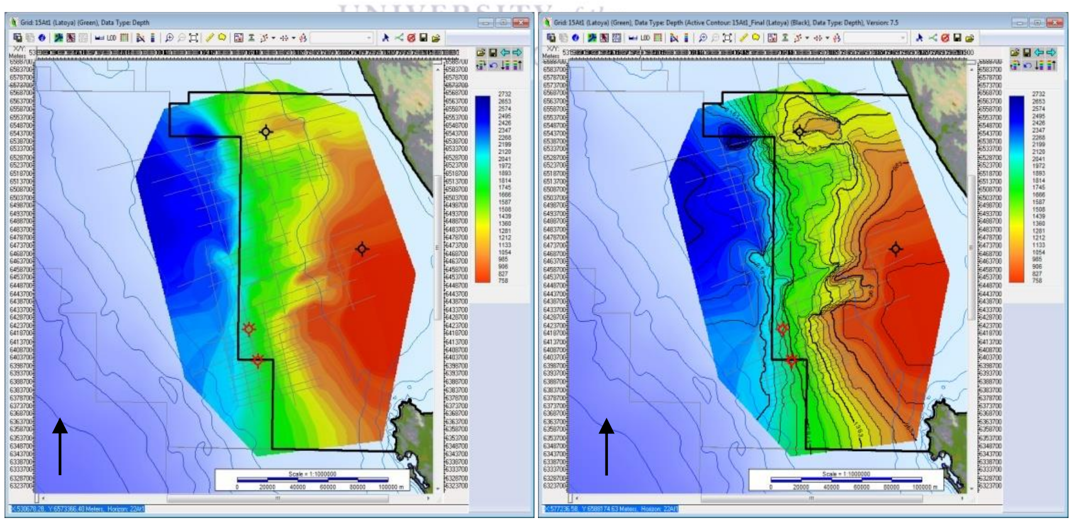


Figure 36: 15At1 facies maps

16At1

Also on this surface, is a structural high around well BX-X1. The slope decreases from east to west. Wells X-Z1 and X-Z2 are at a depth of approximately 1500m, BX-X1 at 500m and X-X1 at 800m. These 16At1 maps, compared to the previous surfaces, show that the higher you go structurally, the more the structural high that was observed in the east disappears, see figure 37.

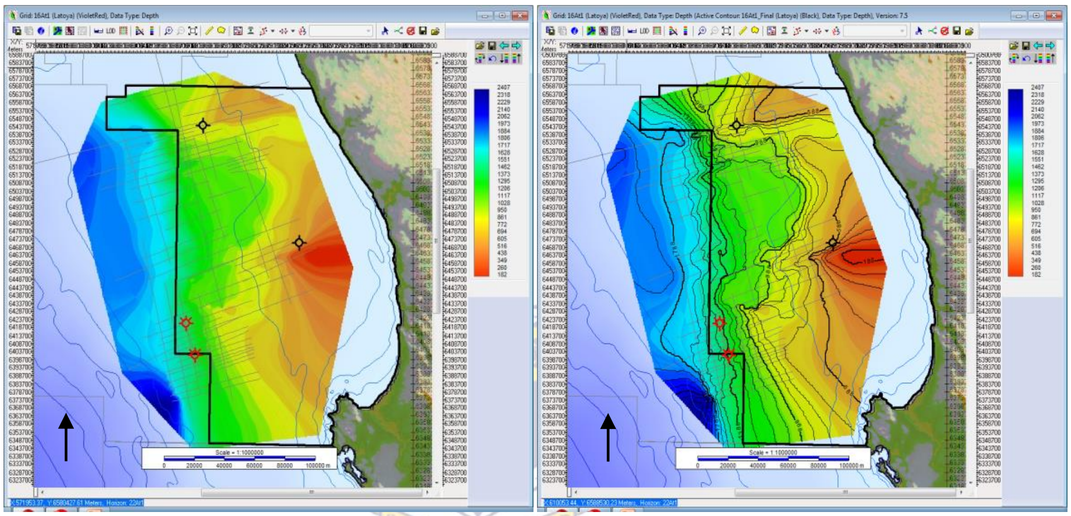


Figure 37: 16At1 facies maps

22At1

The slope steepens from west to east, with a high around the BX-X1 at roughly 400m, X-Z1 and X-Z2 at 1400 and X-X1 at 700m. This upper surface, compared to the deeper surfaces is smoother, see figure 38. This could be because of the absence of recent tectonic activities.

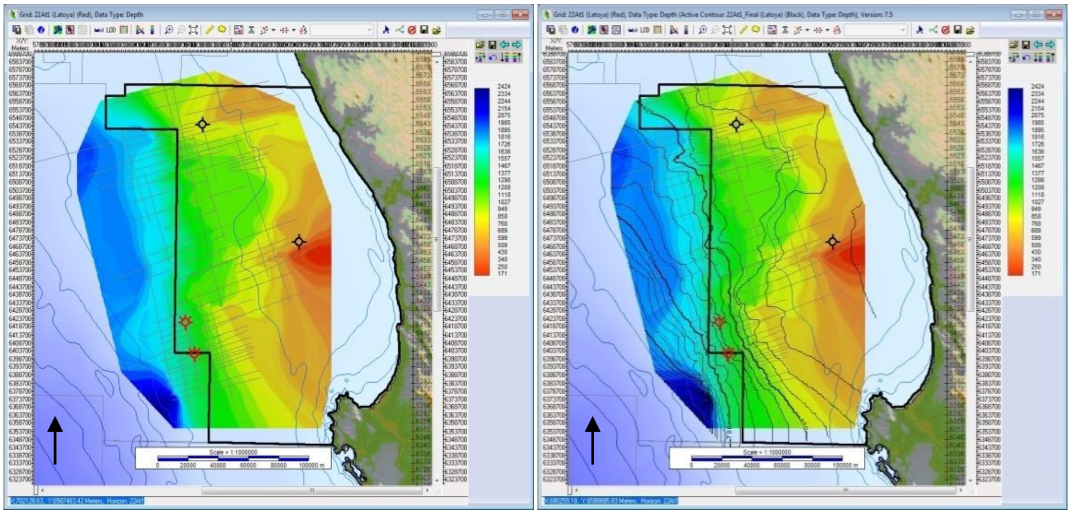


Figure 38: 22At1 facies map

4.3. WIRELINE LOGS

4.3.1. Description of wireline logs

As stated above, electrical well logging has advanced a lot since it was introduced over a century ago. The detailed analysis of carefully chosen wireline services provides a method of deriving / inferring accurate lithology, hydrocarbon, water saturation and permeability index. Since natural Gamma ray log is a good indicator of broad lithology, it is used in the current study as a lithology indicator.

All four wells (X-X1, X-Z1, X-Z2 and BX-X1) have gamma ray logs; from the sea-floor to their final drilled depths.

The gamma ray log is defined as a measurement of the natural radioactivity of rock formations. The gamma ray generally reflects the clay/siltcontent of rock formations in sedimentary rocks; the reason for this is that the radioactive elements are inclined to concentrate on siltand clays. Low levels of radioactivity are usually observed in clean formations except if there is radioactive material such as volcanic ash, granite wash or if the formation water contains dissolved radioactive salts.

Gamma rays are an explosion of electromagnetic waves with very high energy that are released impulsively by some radioactive elements. Almost all the gamma radiation experienced in the earth is released by the radioactive potassium isotope of atomic weight 40 and by the radioactive elements of the uranium and thorium series.

When gamma rays scatter through matter; the rays encounter successive Compton-Scattering collisions with atoms from the rock formation material losing energy with each collision. The photoelectric effect of formation atoms then absorbs the gamma rays after sufficient energy loss. As a result, natural gamma rays are slowly absorbed and their energies decreased as they pass through the rock formation. The rate of absorption differs with formation density (Schlumberger, 1989).

Table 23: Summary and comparison of seismic and wireline log well marker depths

	Time		X-X1 (m)	X-Z1 (m)	X-Z2 (m)	BX-X1 (m)
13At1	Aptian	Seismic	3157	3122	3100	1200
		Wireline logs	3193	3053	2991	1200
14At1	Albian	Seismic	-	2533	2625	960
		Wireline logs	-	2543	2630	960
15At1	Upper Cenomanian – Turonian	Seismic	1244	1800	1900	-
		Wireline logs	1292	1802	1853	-
16At1	Upper Turonian – Coniacian	Seismic	790	1478	1467	756
		Wireline logs	880	1491	1470	756
22At1	Maastrichtian	Seismic	399.33	600	580	549
		Wireline logs	400	600	511.85	549.12

Seismic

Wireline logs

Calibration of markers

The markers on wireline logs were calibrated by using the gamma ray log for each well and determining where each marker could be sitting; correlating that to what the biostratigraphy says as well, thus, placing the marker appropriately by collaborating evidence drawn from both sources. Taking into consideration the results from biostratigraphy as well as looking at the marker on seismic lines to see whether that area could be representative of an unconformity.

The depths of some of the well markers were adjusted, by a few metres. The reason for the adjustments is that the original markers were not sitting correctly on the wells; some would not correlate with the top of the sand unit.

Net-to-gross (Sandstone)

The sand net-to-gross of an interval is the total sand package over the entire package of sand, silt, clays and shales. The goal of determining the net sand is to eliminate non-sand rock intervals. Crain's petrophysical handbook describes the net pay as the thickness of rock that contributes to economically viable production with today's technology. Table 11 shows the net sandstone of the four wells.

Table 24: Estimation of the sand net-to-gross percentages between markers

Interval	X-X1 (%)	X-Z1 (%)	X-Z2 (%)	BX-X1 (%)
SF - 22At1	50-65	70-80	70-80	50-60
22At1 - 16At1	60-70	65-75	60-70	30-40
16At1 - 15At1	40-60	30-40	20-30	-
15At1 - 14At1	-	10-20	10-20	10-20
14At1 - 13At1	<10	10-20	<10	<10

Log Signatures

The recognition of logpatterns plays a significant role in the correlation of lithologies. Subsurface, intervals and facies can change vertically and across. However, correlating units across large areas is achievable because the signatures / patterns are normally the same and are relatable in space and time.

There are two classes of patterns, symmetric and asymmetric patterns and six types of patterns within the two classes; irregular, flat, funnel, bell, cylindrical and bow. Symmetric patterns are styles that have a horizontal line of symmetry (flat, cylindrical and bow); while asymmetric patterns are those that do not have horizontal symmetry (irregular, bell and funnel), (Evernick, 2008).

The log characters of the four wells studied mostly indicate an irregular pattern which falls under the asymmetric patterns. However, when zooming in on the logs, upward fining and upward coarsening log patterns can be defined.

According to Evernick 2008, log patterns with irregular signatures indicate aggradation or fluctuating depositional environment. This type of log signature can be observed from the 13A sequence of all four wells.

In the 13A sequence, wells X-Z1 and X-Z2 begin their log signatures with a funnel-shaped log signature (from the 13At1) and then become irregular in shape like the other 2 wells before reaching the 14At1. Funnel-shaped log signatures indicate clastic marine settings. Thus, the 13A sequence in wells X-Z1 and X-Z2 could be indicative of clastic marine settings; moving on to a fluctuating depositional environment (aggradation) which is indicated by irregular log patterns. Wells X-X1 and BX-X1 are only indicative of aggradational / fluctuating depositional environment.

Wells X-Z1 and X-Z2 display a cylindrical type of log signature from the 14At1 to just above the 2400m marker; moving on to an irregular pattern which is also observed in well BX-X1. A cylindrical pattern in log signatures indicates deep-sea settings in a steady state environment and as stated before; an irregular pattern indicates aggradation / fluctuating depositional environment. This could be supported by the fact that well BX-X1 is located on a structural high while wells X-Z1 and X-Z2 are located in the far west towards the shelf.

In the 15A sequence, well X-X1 shows upward fining patterns indicated by a bell shaped signature. This type of log signature is characterised by deltaic-fluvial depositional environments. In wells X-Z1 and X-Z2, the log patterns are funnel-shaped which as mentioned before, is indicative of clastic-marine settings. Well BX-X1 does not have the 15A sequence.

All four wells in the 16A sequence indicate similar log signatures. However, wells X-Z1 and X-Z2 have a cylindrical log signature just above the 16At1 to just below the 1200m marker. This type of signature indicates deep-sea settings.

After the cylindrical log signature, upward coarsening can be seen; as wells as in the other two wells, BX-X1 and X-X1. This upward coarsening pattern is characterised by a funnel shape, which indicates clastic marine settings.

Wells X-Z1, X-Z2 and BX-X1 display upward coarsening patterns in the 22A sequence. This type of pattern is indicative of clastic-marine settings.

4.3.2. Description of log signatures(refer to figures 39 and 40)

13A Sequence

All wells do not seem to have distinct sand packages, especially well X-X1.

Well X-Z2 has the most sand with shale interbedded in between. Well BX-X1 also has sand with shale in it.

14A Sequence

Well X-X1 does not have the 14A sequence, let alone the 14At1. The 14A sequence in wells X-Z1 and X-Z2 have very small sand intervals, with shale interbeds. Well BX-X1 has a very small 14A sequence, with sand and shale.

15A Sequence

WellBX-X1 does not have the 15A sequence. The X-X1 15A sequence shows sands with shale interbeds; the sand is not necessarily clean. However, wells X-Z1 and X-Z2 do not have sand units in the 15A sequence; this is a very poor interval.

16A Sequence

The X-Z1 and X-Z2 wells seem to have the thickest 16A sequence sands and well BX-X1 the thinnest. Well X-Z1, unlike in the 22A sequence has a thick sand package right above the 16At1 marker. Both the X-Z1 and X-Z2 do not seem to have distinct shale interbeds, like in the 22A sequence.

22A Sequence

The 22At1 is shallow in all four wells, at depths of less than 1000m. This interval is mostly composed of sand. However, in the BX-X1 well, shale interbeds can be observed. X-Z1 and X-Z2 display more or less a similar signature; very clean sands with no sign of shale interbeds.

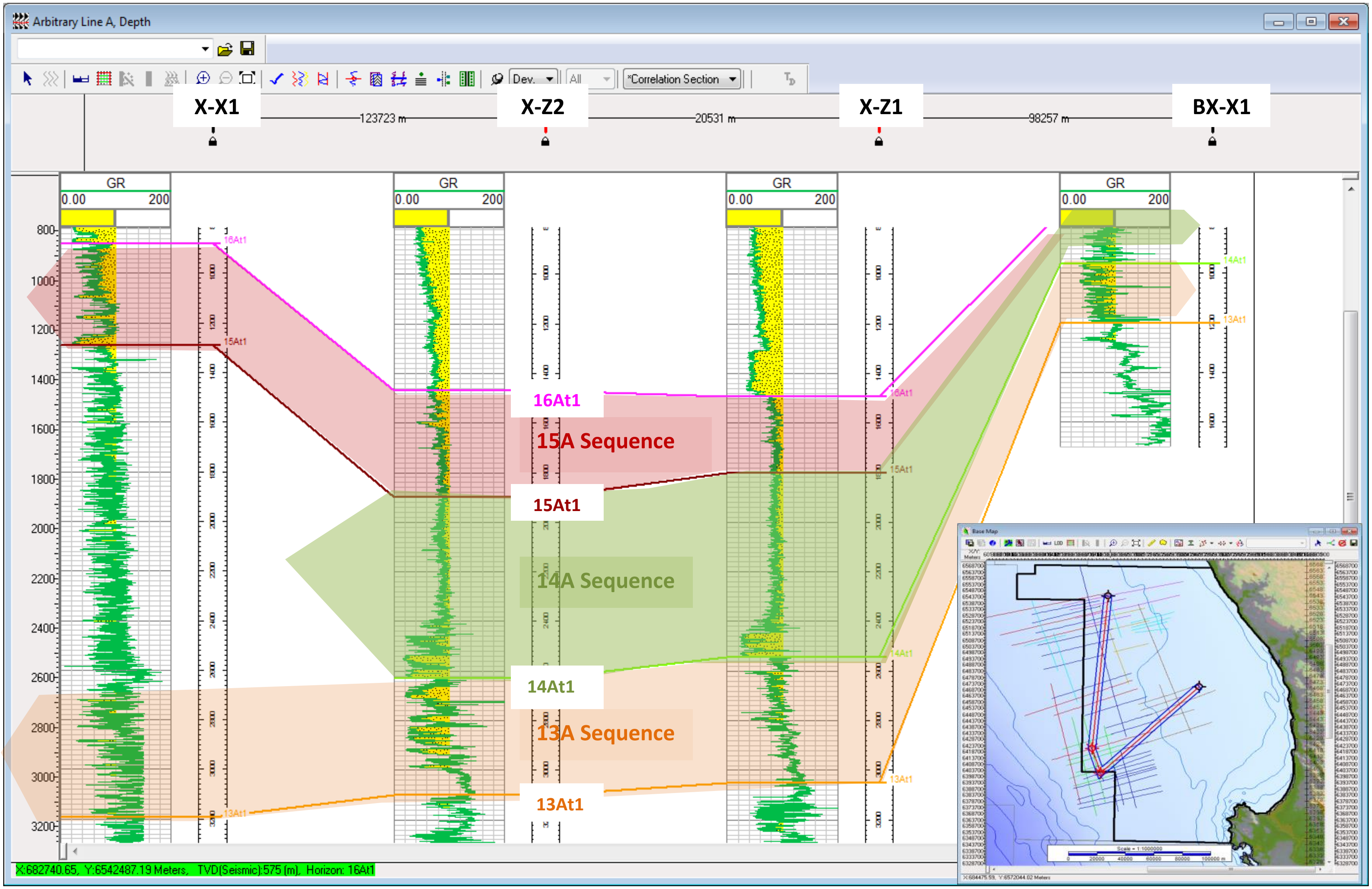


Figure 39: Gamma ray log sequence correlation for wells X-X1, XZ1, X-Z2 and BX-X1; for the 13A, 14A and 15A sequences

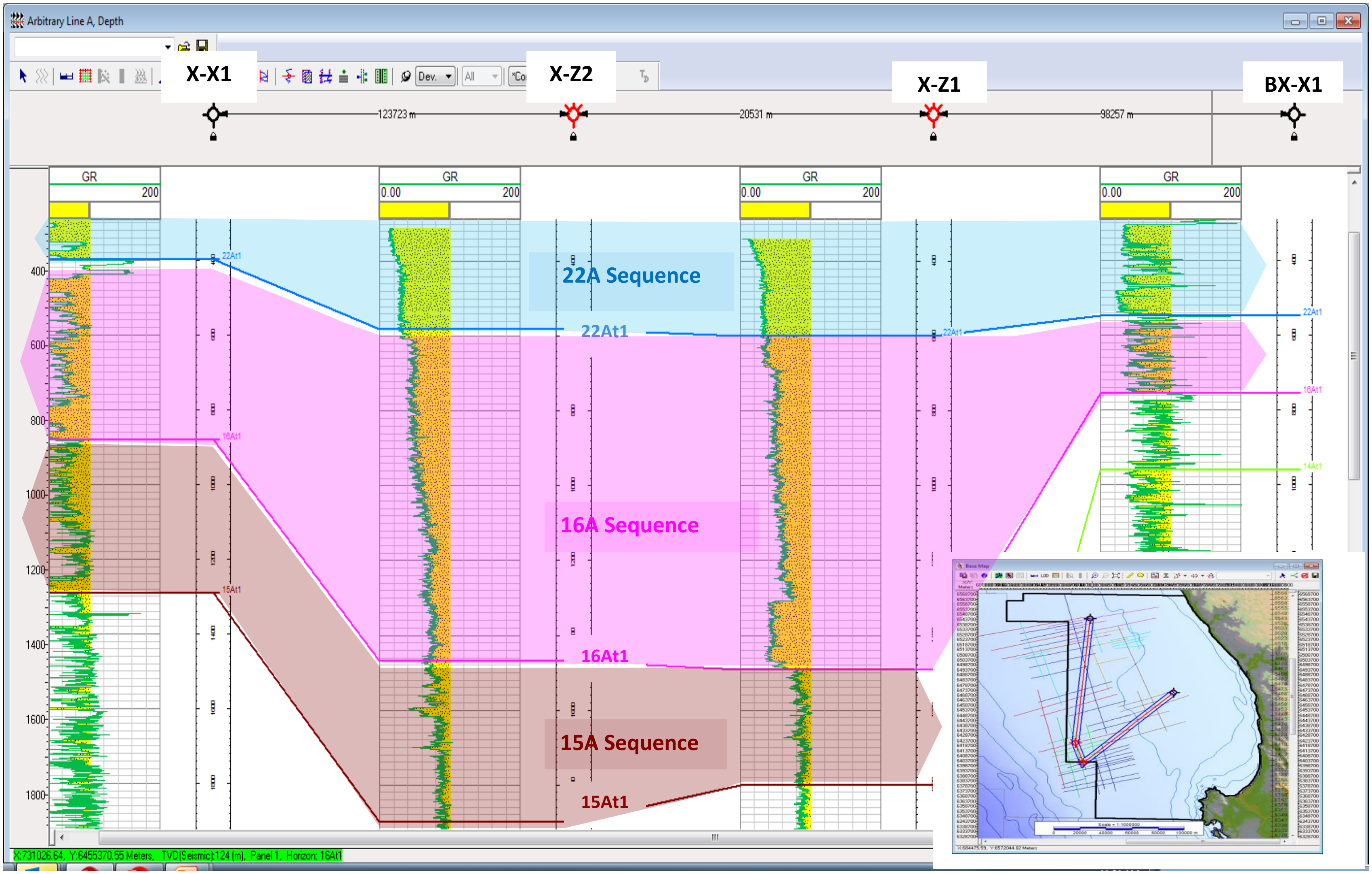


Figure 40: Gamma ray log sequence correlation for wells X-X1, XZ1, X-Z2 and BX-X1; for the 15A, 16A and 22A sequences

4.3.3. Seismic line and Gamma Ray log correlation

Seismic lines in this section were used to confirm the correlation on a bigger scale. Even though some seismic markers do not correlate with the markers that are positioned on logs, the difference is not that great.

Figures 41, 42 and 43 show seismic lines with wells and log characters on them; displaying the position of the markers where they were interpreted on the software.

Unfortunately, there is no seismic line that passes through well BX-X1 in the east of the block; only tiff images of the seismic profiles are available.

The majority of the markers sit at the bottom / base of sand packages and intervals, like the wireline correlation done earlier in this section. Not only do both the seismic and wireline log markers matchat the base of sand packages but most of them are correlatable where there is a strong log pattern change, that is; from a sand to a visible shale.

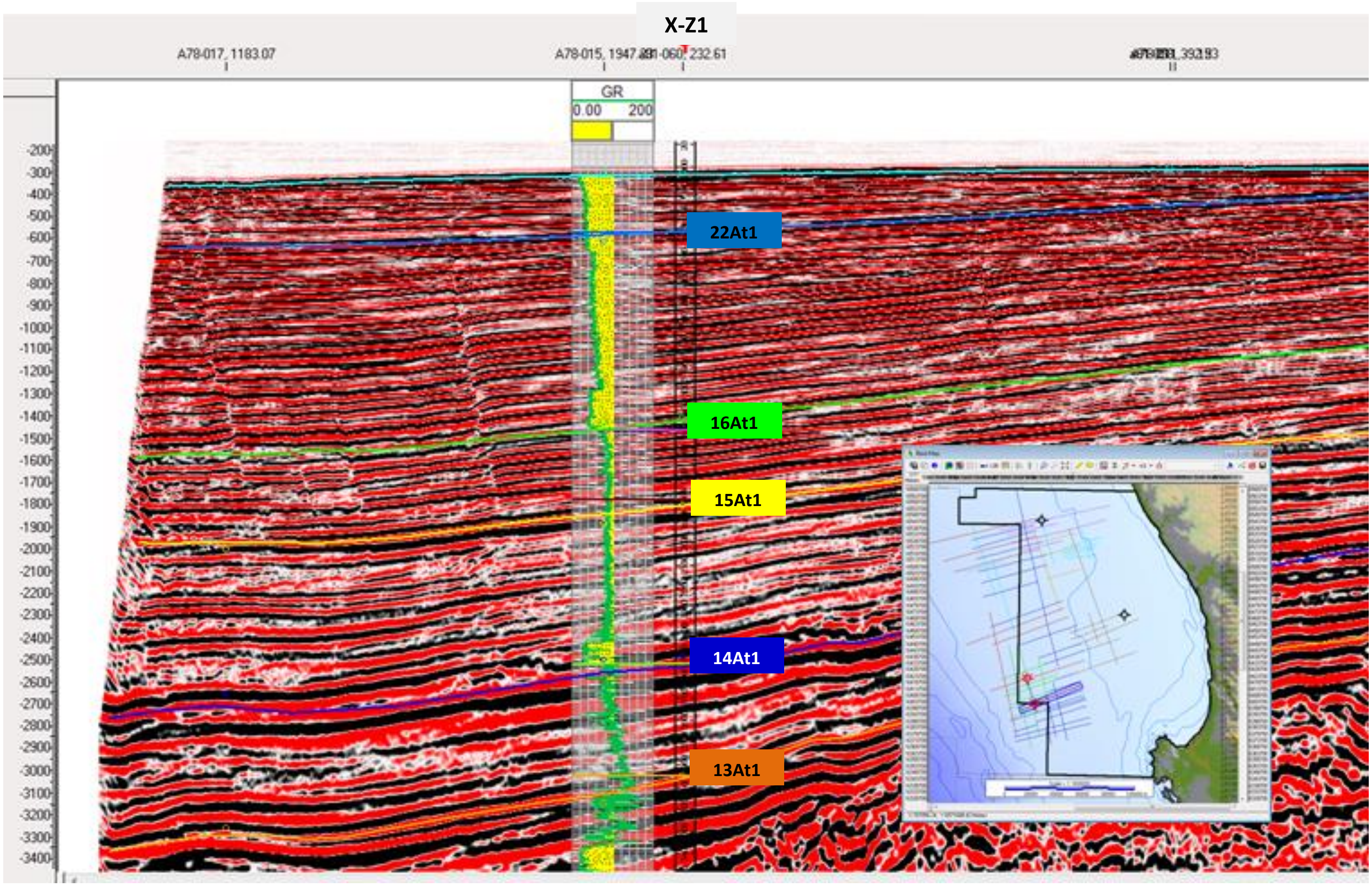


Figure 41: Seismic and Gamma Ray correlation of markers in the well X-Z1

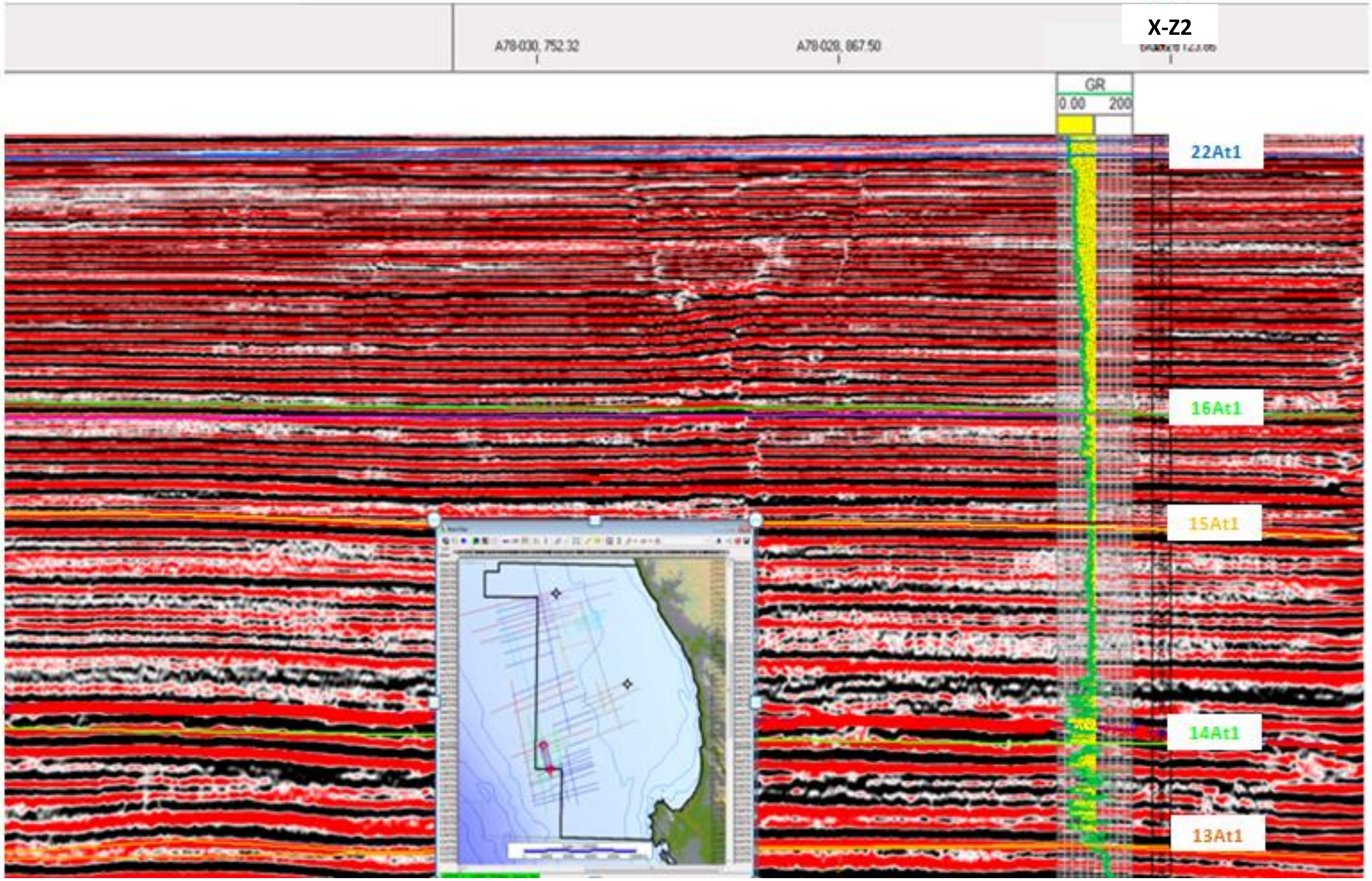


Figure 42: Seismic and Gamma Ray correlation of markers in the well X-Z2

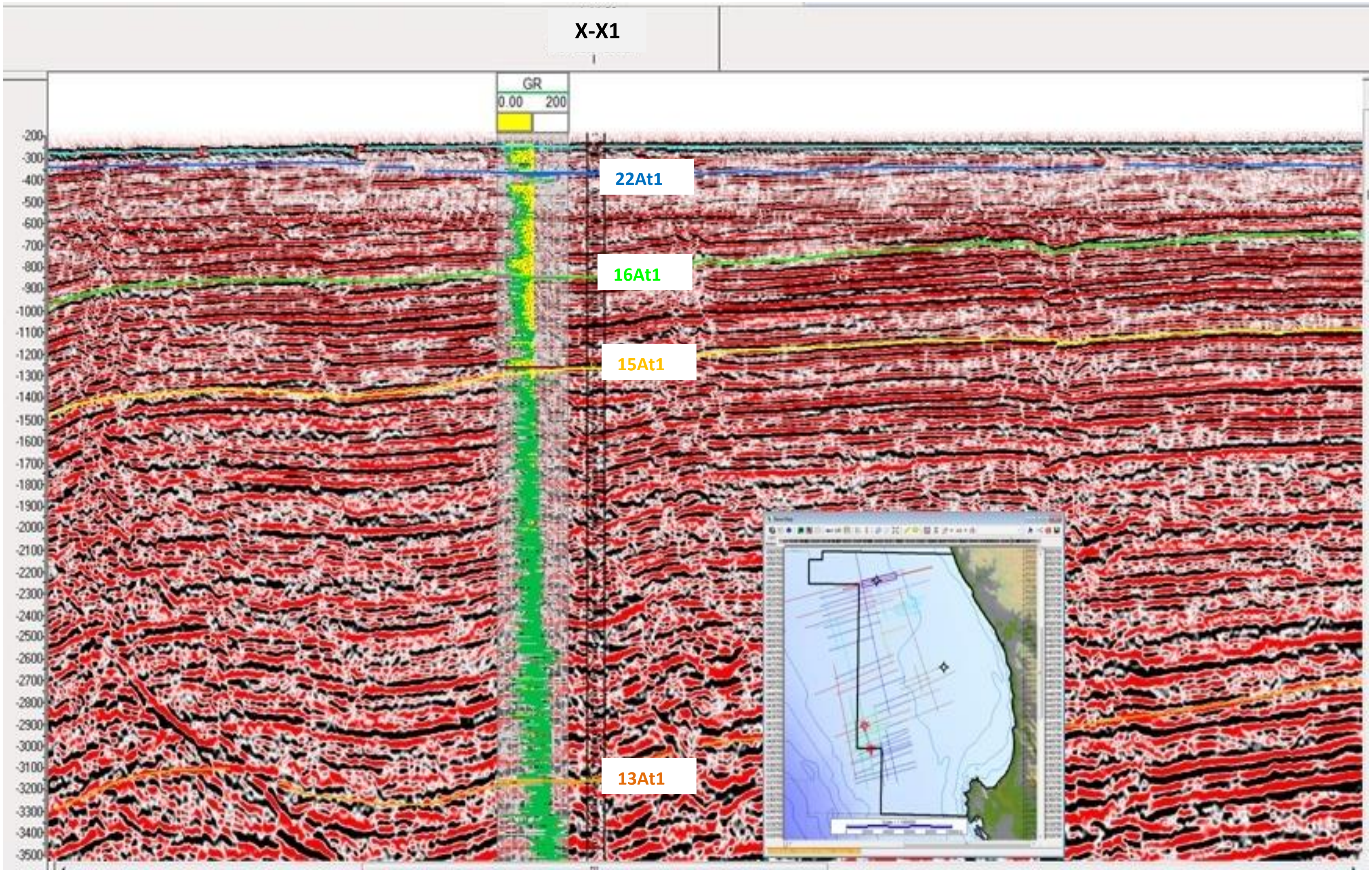


Figure 43: Seismic and Gamma Ray correlation of markers in the well X-X1

4.3.4. Stacking Patterns

Stacking patterns are defined as the geometric arrangement of sedimentary successions, essentially the vertical succession of facies and their surfaces. Stacking patterns help establish the depositional setting of a sedimentary section and helps understand the sequences in which the sedimentary succession was deposited.

The decisive factor in defining strata stacking patterns comprise geometries and facies relationships that came about from the interaction or relationship of available accommodation and sediment supply during deposition, Catuneanu et al., 2011.

Stacking patterns result from the difference in accommodation space between progradation, retrogradation and aggradation.

4.3.5. Description of stacking patterns

Well X-X1

13A Sequence – From the 13At1 going up, an upward coarsening pattern can be observed then rapidly moving to upward fining. A second similar set of pattern is observed again. From that point on, going to the 15At1, it is upward coarsening only, (refer to figure 44).

15A Sequence – In this sequence, only upward fining patterns can be seen. It is alterations of sand and shale, (refer to figure 44).

16A Sequence – Only upward coarsening patterns can be observed in this sequence, (refer to figure 45).

22A Sequence – Upward fining sequence only, (refer to figure 45).

Well X-Z2

13A Sequence –Upward coarsening sequences that change to upward fining before reaching the 14At1can be seen, (refer to figure 44).

14A Sequence – The 14At1 marker starts with an upward coarsening sequence to a depth of approximately 2400m, and then it changes to upward fining. This upward fining pattern is followed by upward coarsening and upward fining patterns (refer to figure 44).

15A Sequence – The base of the 15A sequence shows irregular patterns; not quite clear whether it is upward fining or coarsening. These irregular pattern then moves to upward coarsening sequences until the 16At1 marker (refer to figure 44).

16A Sequence – This sequence is dominated by an upward coarsening pattern (refer to figure 45).

22A Sequence – Upward coarsening can also be observed in this sequence (refer to figure 45).

Well X-Z1

13A Sequence – From where the 13At1 marker sits, this sequence is characterised by upward coarsening patterns (refer to figure 44).

14A Sequence – Upward fining is seen right throughthe sequence (refer to figure 44).

15A Sequence –Just like in the previous well X-Z2, the 15A sequence also starts with irregular patterns moving on to upward fining and upward coarsening towards the end ofthe sequence (refer to figure 44).

16A Sequence – This sequence starts off with a sand package from the 16At1 marker, which displays upward fining sequence and then changes to upward coarsening throughoutthe sequence (refer to figure 45).

22A Sequence – Similar to the previous well, this sequence is characterised by upward coarsening (refer to figure 45).

Well BX-X1

13A Sequence– This sequence is characterised by upward coarsening patterns (refer to figure 44).

14A Sequence – Sequence displays upward coarsening patterns (refer to figure 44).

16A Sequence – This sequence also displays upward coarsening patterns (refer to figure 45).

22A Sequence – Just like the sequences below the 22A sequence, this sequence is also characterised by upward coarsening patterns (refer to figure 45).

When carefully studying the stacking pattern of the 13A sequence throughout the wells, it appears that there was aggradation of sequences where the sediment rate was enough to maintain the depositional surface. Sequences 14A and 15A are indicative of the retrogradational pattern. In well BX-X1, this retogradational pattern is carried through to the 16A sequence while other wells display progradation (sequences deposited farther basinward when the rate of deposition was greater than the rate of accommodation) on the 16A sequence right through to the 22A sequence.

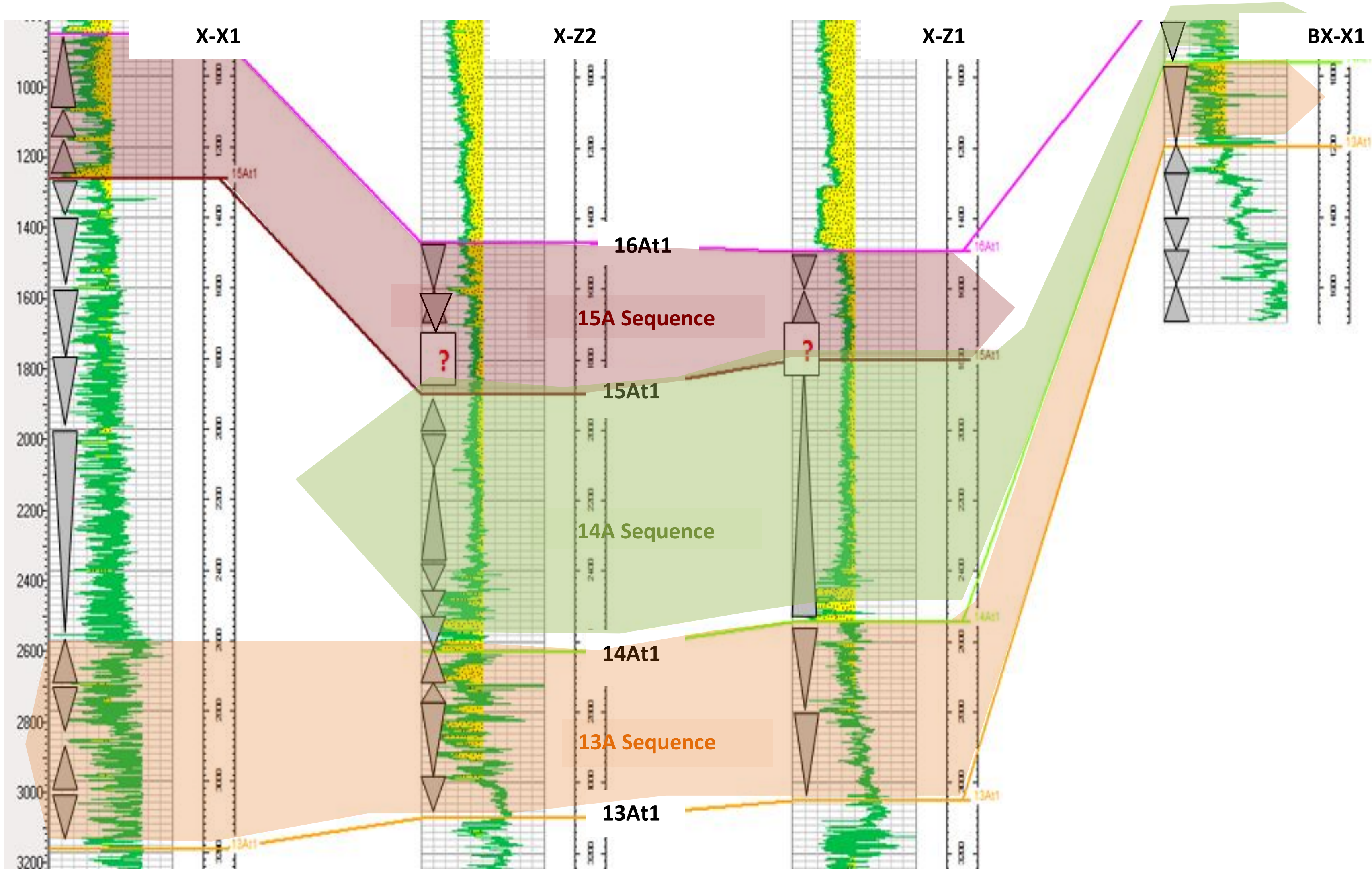


Figure 44: Stacking patterns across the 13A, 14A and 15A Sequences in wells X-X1, X-Z1, X-Z2 and BX-X1

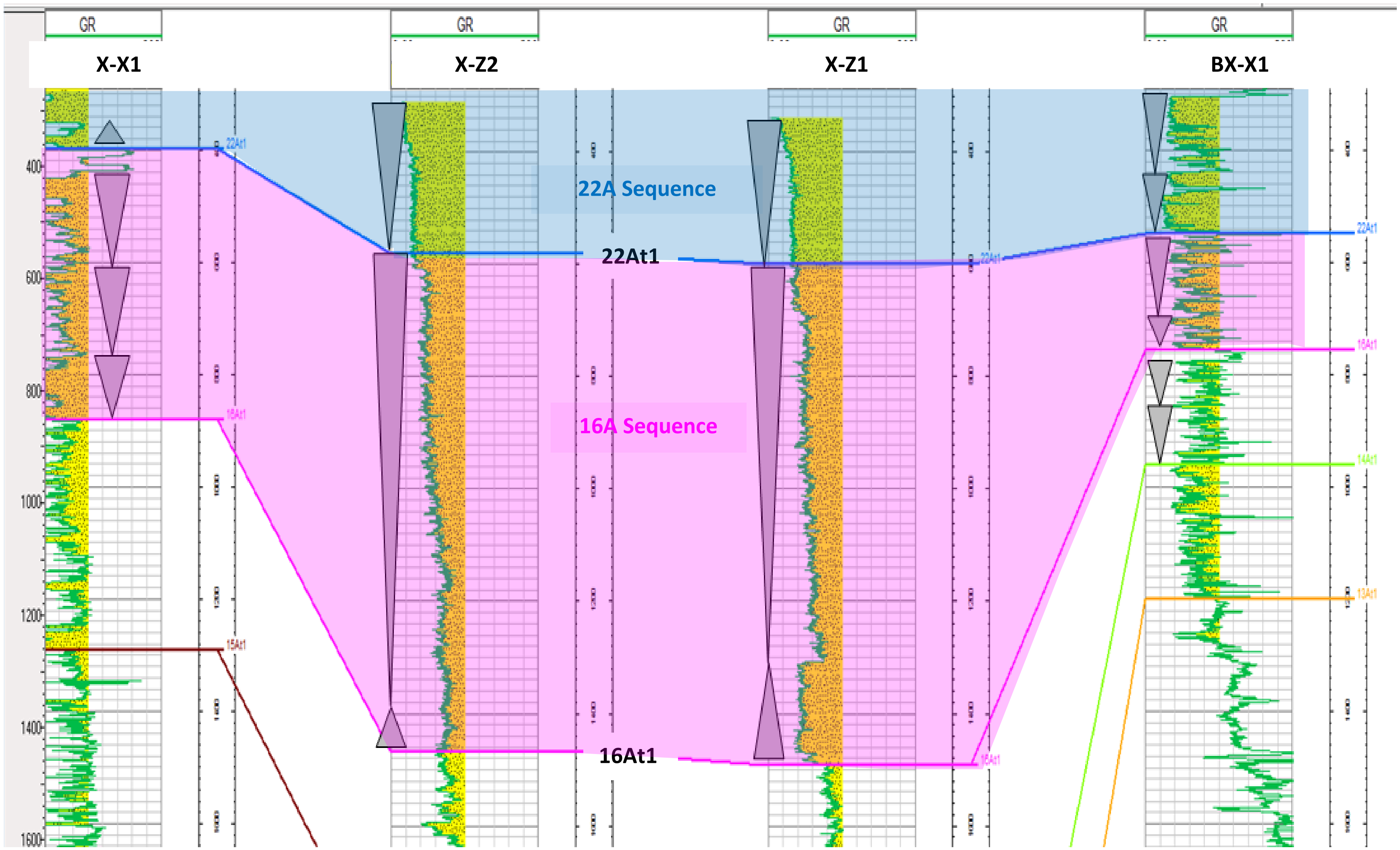


Figure 45: Stacking patterns across the 16A and 22A Sequences in wells X-X1, X-Z1, X-Z2 and BX-X1

4.4. BIOSTRATIGRAPHY

4.4.1. Biostratigraphic zonation

Plotting a range of fossils in a section and/or a stratigraphic distribution is very crucial when one wants to determine time by fossil analysis. Correct and precise data should be collected together with each specimen at the same time. Zonation divides the time into three parts that are not the same; these different times are: before the appearance of the fossil, the time of its existence and the time since its disappearance. All the sedimentological units in which fossils occur are said to be into zone; these different zones are called biozones.

The following are all four wells divided into different zones and some in years with respect to their depths; showing what was intersected when biostratigraphic analyses were conducted for the depths thus indicating time intervals (University of Maryland).

As no new biostratigraphy data was available for interpretation, various sources that contained general data and data of a few wells in Block 3A/4A were used.

Well X-X1

The biostratigraphy results for well X-X1 were modified after McMillan, 1976.

In the X-X1 well, which is in Block 3A/4A; the age restrictions of the sequences are very uncertain due to very restricted microfauna that was recovered from a section that was recovered from the well.

The foraminifera are mainly clustered forms, although rarely calcareous and even rare planktonic foraminifera are also present. As a result, speciation of the clustered species is considered to be of little importance because of challenges in accurate species identification in the groups. The ostracodes are common in the upper part of the sequence.

Even though true Biozones have not been projected; the following zones can be recognised:

Zone I (3380-Basement)

There are red beds and single chaopyteoogonum (which is indicative of freshwater). No microfossils could be observed; thus a continental depositional environment was inferred.

Zone H (3330-3380m)

This zone has diverse microfauna, mostly ammobaculites and haplophragnoides and also a significant number of calcareous benthonic species. Ostracodes occur in various numbers and all this is suggestive of a transitional inner shelf depositional environment.

Zone G (3038-3330m)

In this interval foraminifera consist of haplophragnoides, ostracodes are absent, lignite occurs throughout this zone and land-derived material is rare. The type of lithology found here are interbedded brown-red and grey shales. The depositional environment suggested for this zone is transitional.

A palaeontologysummary by McMillan and Valicenti for SOEKOR in a well completion report suggest that the 13At1 (Aptian) for well X-X1 is situated between depths of 2900 – 3802m.

Zone F (1310-3038m)

Foraminifera can be observed together with planktonic species. However, the foraminifera decline with an increase in depth. Ostracodes are absent in the lower parts of the zone. Land-derived material occurs throughout the zone and there are small traces of glaconite (1780-2048m). An inner shelf environment is proposed for this zone.

Zone E (1080-1310m)

Land-derived material continues to be present, with poor fossil occurrences and very small amounts of ostracodes.

Zone D (960-1080m)

There are no ostracodes observed in this zone and there is a decline in megaspores. Land-derived material and microfaunas seem to be more than they were in the above zone.

Zone C (860-960m)

There is a decline in microfauna. Microfossils are the same as in zones A and B and there are large amounts of ostracodes observed; this is suggestive of inner shelf depositional environment.

Zone B (680-860m)

There is a slight improvement of the marine environment as the foraminifera are more diverse, occasional ostracodes and less land-derived material. There is still a dilution of sea water, however; the fossils suggest deposition to be on the inner shelf.

Zone A (533-680m)

There is a large number of megaspores that can be observed in this section (hexagonal incertaesedis, lignite, foraminifera) and there are no ostracodes. The depositional environment is very poor marine due to a large number of land-derived material. The foraminifera suggest deposition being close to the shore with strong influence from of dilution of sea water.

Indications of age:

The microfauna of this well provides an unclear indication of age; however, a single specimen of orientalia species was found in zone B (750-760m) and this suggests a Cenomanian age (this again is unreliable as the type of orientalia species is based on one species from the USSR)

In zone F, the species hedbergella was found and it indicated Aptian-Albian-Turonian age. Earlier hedbergella species are rounder and smooth walled, Barremian – Hauterivian; however, the hedbegella species in well X-X1 have rough edges therefore date after Barremian – Hauterivian.

A number of ostracodes are comparable and suggest Aptian – Albian age.

The above mentioned findings suggest an uncertain Aptian-Cenomanian age for the marine sequence.

X-Z1

The biostratigraphy results for well X-Z1 were modified after McMillan, 1980.

Pre-Late Aptian (3030-4139.2m (TD))

The microfauna found in this interval do not provide an indication of the age of the sediments. Also, the shales obtained from other core do not have traces of fossils. Towards the TD, a large quantity of lava is observed.

According to seismic data, the 13At1 sits in this interval at a depth of 3053m (which is from the Aptian age).

Late Aptian (2778-3030m)

Shales having Aptian fauna were found interbedded in the lower parts of the sandy interval. The downward deposition of the environment is observed in Late Aptian, and species of hedbergella appear to be many in the lowest Late Aptian. The bottom part of this section seems to have been deposited in pro-deltaic conditions; thus explaining the absence of benthonic species. This could be because the conditions were unfavourable for them to live. The environment of deposition is suggested to be transitional inner shelf at the top of the interval, going deeper towards the outer shelf.

Albian (2120-2778m)

In sands that appear from 2350m, clumped up foraminifera are observed and are limited in the more shaly intervals (from 2520m). Rotalipora specimens don't appear as much as they should in this interval; this could be due to the large freshwater input into the basin, the water probably prevented the specimens to reach the shore.

The biostratigraphy ties in well with the seismic data with respect to the 14At1, which according to the reference chart is supposed to be of Albian age. On seismic data, the 14At1 sits at a depth of 2543m which speaks very well to the biostratigraphy.

Based on the above, it is concluded that the Albian interval has been deposited in an outer shelf environment; to inner shelf to transitional for Early Albian.

Cenomanian (1760-2120m)

Foraminifera and ostracods appear to be repetitive in this interval and generally; faunas are poorly diversified here and this could be due to a freshwater inflow. At the lower pats of this interval, ammonites occur in large numbers, further down; the sediments appear to be more sandy. Depositional environment deduced as outer shelf, possible upper slope.

On seismic data, the 15At1 is at 1802m, which according to the biostratigraphy by Ian McMillan should be Cenomanian. The West Coast reference chart of seismic reflectors also articulates that the 15At1 should be sitting at Late Cenomanian.

Coniacian (1370-1760m)

This interval appears to have been deposited in gradually deepening water with depths of 1600-1760m; fursenkoina species could be suggestive of a prodelta sequence. There is a small number of ostracods in the lower Coniacian and they suggest lower salinity waters. Thus the environment that is deduced from this interval is middle to outer shelf depositional environment.

The 16At1 lies in the Late Turonian to Early Coniacian, which coincides with the biostratigraphy report. On seismic, the 16At1 is sitting roughly at 1491m, see table 12.

Santonian (850-1370m)

An inner to middle shelf environment of deposition is inferred for this level. This is due to a gentle increase in planktonic foraminifera, benthonic species mainly from epistomina to haplophragomoides species and that globotruncana species were found to be rare.

Campanian (670-850m)

Sediments from this interval were found to have large amounts of episstomina specimens, however, with sporadic planktonic foraminifera. A shallow marine environment is interpreted for this interval. Globotruncanaventricosa was absent due to the fact that the deposition took place in shallow waters.

When looking at seismic data at the X-Z1 well, this Campanian level lies a few meters below the 22At1 (600m), which agrees with the reference chart of seismic reflector nomenclature of the West Coast Margin of South Africa.

Early Miocene (397.7m)

A group of microfauna was found in white clay of Early Miocece age. Large groups of foraminifera (globigerina and ocassionalgloboquadrina and globigernoides) and martinottiela were obtained too. The sediments that were obtained from samples collected in this section were interpreted to suggest a deep water deposition, perhaps upper slope environment.

Holocene (347.5m)

There were foraminifera, benthonic species and a variety of radiolarian species found to be present. The group of the foraminifera species and the type of sediments found there were the same as the Holocene sediments found off the west coast. A cold water environment of deposition is suggested by the presence of left-coiled entities of globorotalia. Occasional radiolarian and the great quantity of foraminifera that were found are suggestive of an open-sea location, possibly an outer shelf.

BX-X1

A sample acquired from the sea-floor had a variety of microfauna whose composition suggest a Quartenary age, however; the presence of the planktonic foraminifera globigerina patchyderma is suggestive of a Pliocene to recent age for the sample. Fairly deep water conditions are suggested by the presence of Planulinaariminensis, Eurovigerina peregrine and Globobuliminaturgida. Also, the benthonic foraminifera

Cassidulinalaevigata, Nonionella and Globobuliminaturgida also supports cold water conditions.

Between 1280-1286m, freshwater ostracodes were found. The composition of the fauna found was composed of species from the Aptian (McMillan and Brenner, 1976).

The biostratigraphy report for BX-X1 only covers one depth that is of interest, which is the 13At1. The rest of the depths are too shallow for the interests/focus of this study. The 13At1 is at a depth of 1200m on seismic and more or less agrees with the biostratigraphy. The 13At1 depth also speaks to what the reference chart of seismic reflector nomenclature of the West Coast says.

X-Z2

A well completion report that was written for X-Z2 by PetroSA, previously known as SOEKOR has a microfaunal-based breakdown of the ages of sediments of the well. The ages are shown in the table below.

Table 25: Well X-Z2 well markers derived from biostratigraphy data (Stallboom and Brown, 1991)

Age	Depth (m)
Late Aptian	3020-3108
Albian	2190-2861
Cenomanian	1797-2190
Coniacian	1420-1797
Santonian	900-1420
Campanian	593.9-900
Maastrichtian	345-593.9

The above ages and depths match the well markers marked on the seismic profile; thus correlating to what the microfaunal age breakdown shows.

Table 26: Summary and comparison of seismic and biostratigraphy well marker depths

	Time	X-X1	X-Z1	X-Z2	BX-X1
13At1	**Aptian**	3157	3122	3100	1200
		2900 - 3802	3030-4139	3020-3180	1280-1286
14At1	**Albian**	-	2533	2625	960
		-	2120-2778	2490-2861	
15At1	**Upper Cenomanian - Turonian**	1244	1800	1900	-
		1550-1555	1760-2120	1799-2190	-
16At1	**Upper Turonian - Coniacian**	790	1478	1467	756
		790-1210	1370-1760	1420-1799	
22At1	**Maastrichtian**	399.33	600	580	549
			670	345-593.9	

Seismic

Biostratigraphy

As stated before, the biostratigraphy report for BX-X1 only covers one depth that is of interest, which is the 13At1. The rest of the depths are too shallow for the interests/focus of this study.

CHAPTER 5

5. DISCUSSION AND CONCLUSION

4.1. Discussion

According to the well completion reports that were used, the structural high that is observed on seismic lines in the 13A sequence was formed as a result of the uplift event that took place after the deposition of the sequence. This uplift can be observed in the east of Block 3A/4A; see lines A76-010 and A76-006 (refer to figures 48 and 50).

Submarine and subaerial erosion also took place; this can be validated by the truncation episodes observed on seismic on lines A78-015 and A76-010 (refer to figures 46 and 48).

Again, domal and basin features as well as pinchoutsconfirm the uplift and subsidence episodes that took place between Aptian and Albian (13At1 and 14At1). The domal features and pinchouts could act as stratigraphic closure for hydrocarbon entrapment.

The 14A sequence (between 14At1 and 15At1) experienced higher sediment supply rates compared to the 13A sequence. The aggradation in this sequence could explain why there are uniform reflectors in line A78-015 (refer to figure 46). The aggradation was due to the tectonic subsidence and eustatic-tectono sea-level(?) which also resulted in an accelerating rise in sea-level(?). The subsidencein the west (towards the shelf) could have resulted from the shelf collapse.

Progradation is the reason why on some lines, onlapping, downlapping and truncation is observed.

No flooding was observed during the deposition of the 14A sequence as during aggradation, the rate of sediment supply equaled the rise in sea-level and because there was acceleration in the sea-level rise (?).

There was a shelf collapse event above the Cenomanian – Turonian boundary where sequences are mainly aggradational, resulting in growth faults and large scale slumping; this is according to Broad et al. 2000. This is confirmed by the faults that are observed on seismic in the 15 and 16A sequences towards the west of the study area where the shelf is; refer to lines A78-015, A76-010 and A76-020 (figures 46, 47 and 48). The faults could act as seals and structural closures in hydrocarbon accumulations.

The truncation seen on some seismic lines in the 15A sequence is due to the termination of sequence stacking that resulted in erosion(?). The structural high to the east resulted during an uplift of the lower sequences before the 15A sequence was deposited.

As mentioned above, the 16A sequence is characterized by faults to the west of the lines which could have resulted from the shelf collapse.Just like in the 15A sequence, faulting terminated sequence stacking and resulted in erosion; as can be explained by the erosional surface observed in the 16A sequence (refer to line A76 020, figure 47).

The 16A sequence thins in the east and thickens towards the west. This could be because of the shelf collapse in the west which meant more accommodation space in the west, thus a thicker sequence. Again, the faults could act as structural traps in a petroleum system.

The 22A sequence is the thinnest and youngest succession which is thinner in the east and thicker towards west. The thickness in the west is due to the extra accommodation space that resulted from gravity faulting at the shelf edge.

At stated before in previous sections, proven reservoirs in the Orange Basin date Albian. After interpreting and studying the seismic data carefully, lines A76-010, A76-026 and A76-006 have possible reservoirs (indicated in different colours) which according to interpretation date Aptian and Albian, see figures 48, 49 and 50. These possible reservoirs are stratigraphic in nature

The overall picture of block 3A/4A through the interpretation of facies maps is that there are structural highs towards the east of the block that is; around wells X-X 1 and BX-X 1. This validates Kuhlman et al., 2010 and Brown et al., 2000; that there were events of uplift in mid Cretaceous and late Cretaceous in mid Campanian.

The structural highs are more evident from the 13At1 to the 15At1 surfaces east of the block. Surfaces 16At1 and 22At1 only show structural highs around the BX-X1 well.

The structural high that resulted from the uplift event that took place could have likely destroyed hydrocarbon entrapments. However, It is possible that the Albian sequences that were studied and interpreted in this study could contain hydrocarbon accumulations in places that were not affected by the uplift, as has been proven before in the Orange Basin, in neighbouring blocks to be exact.

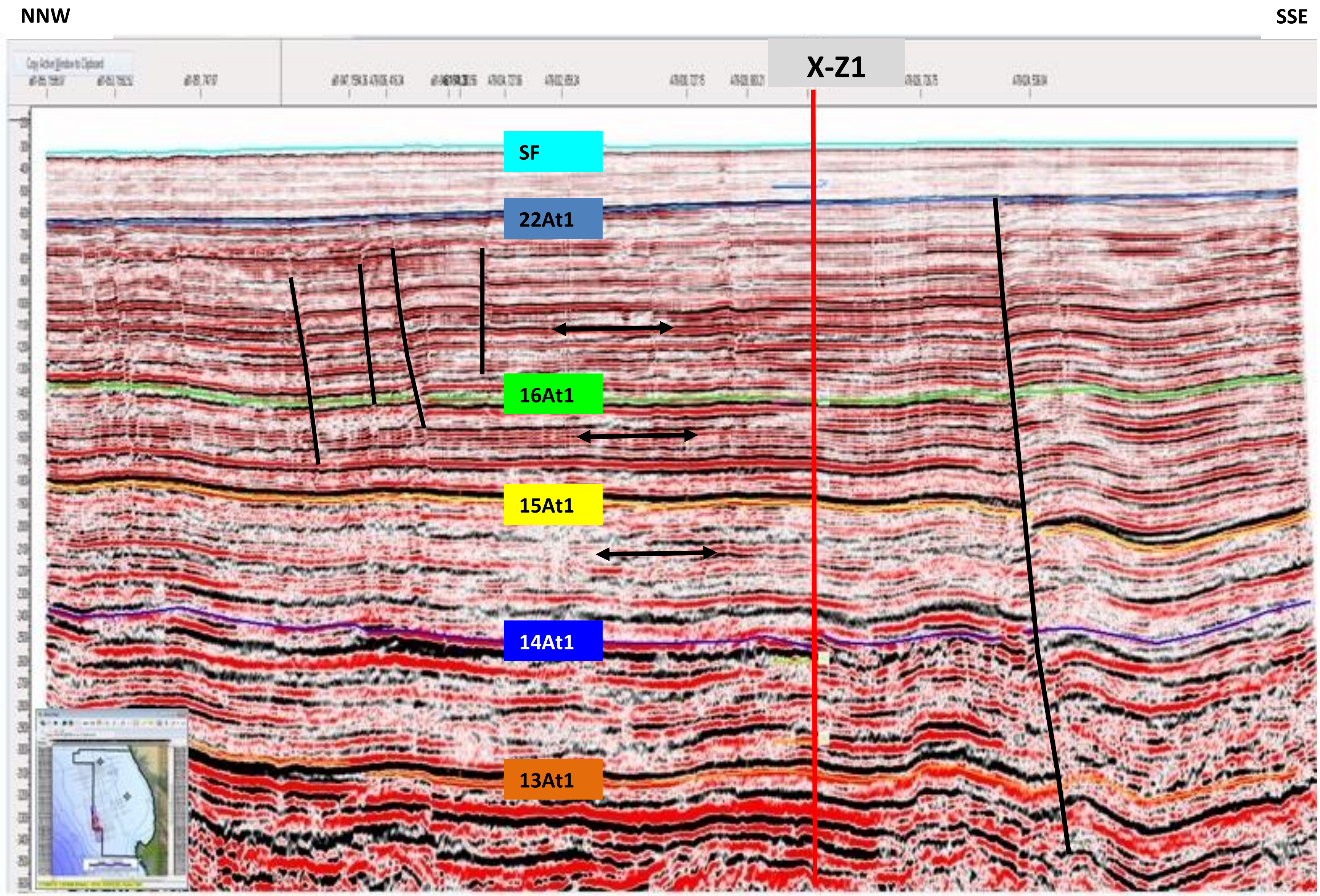


Figure 46: Line A78-015

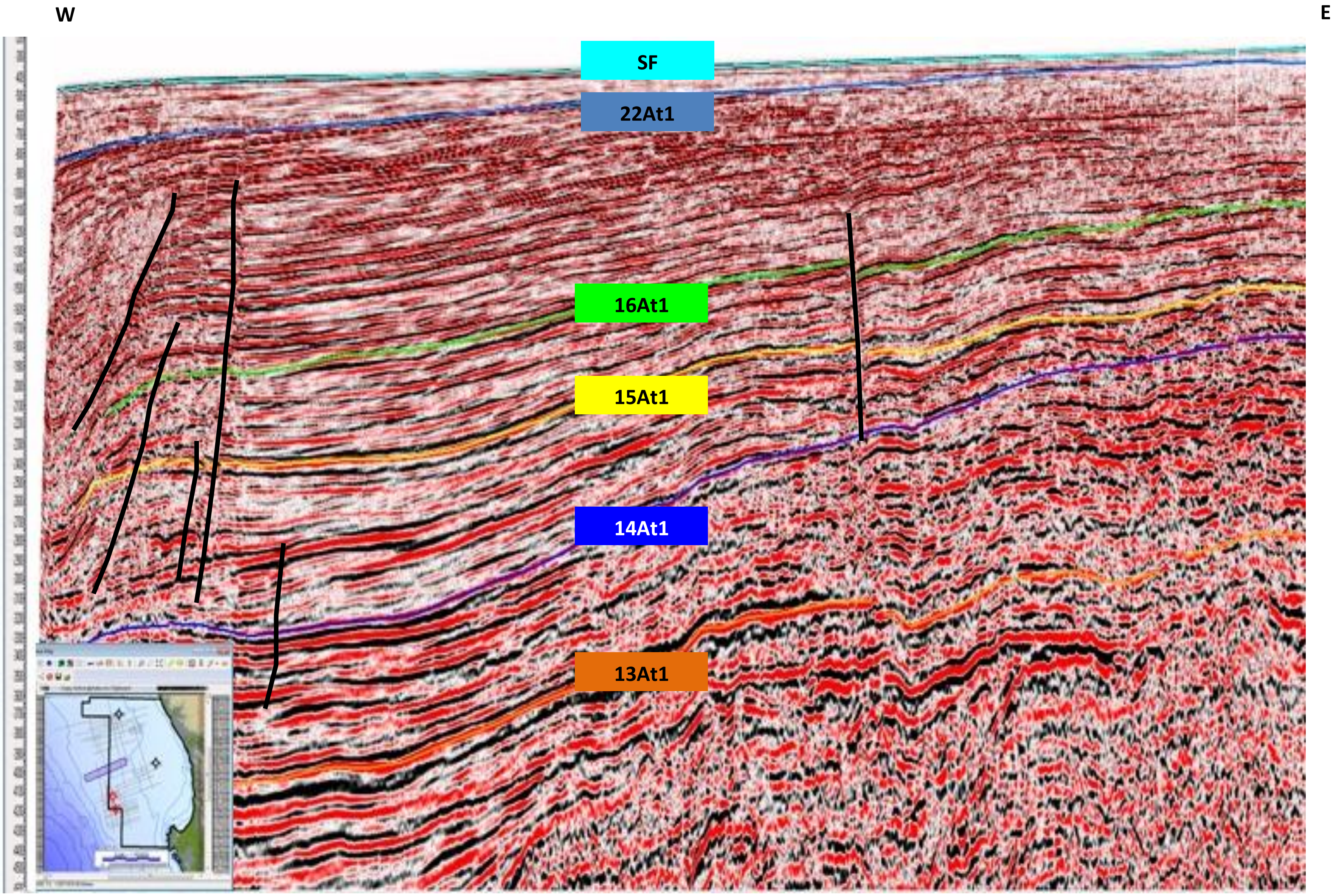


Figure 47: Line A76-020

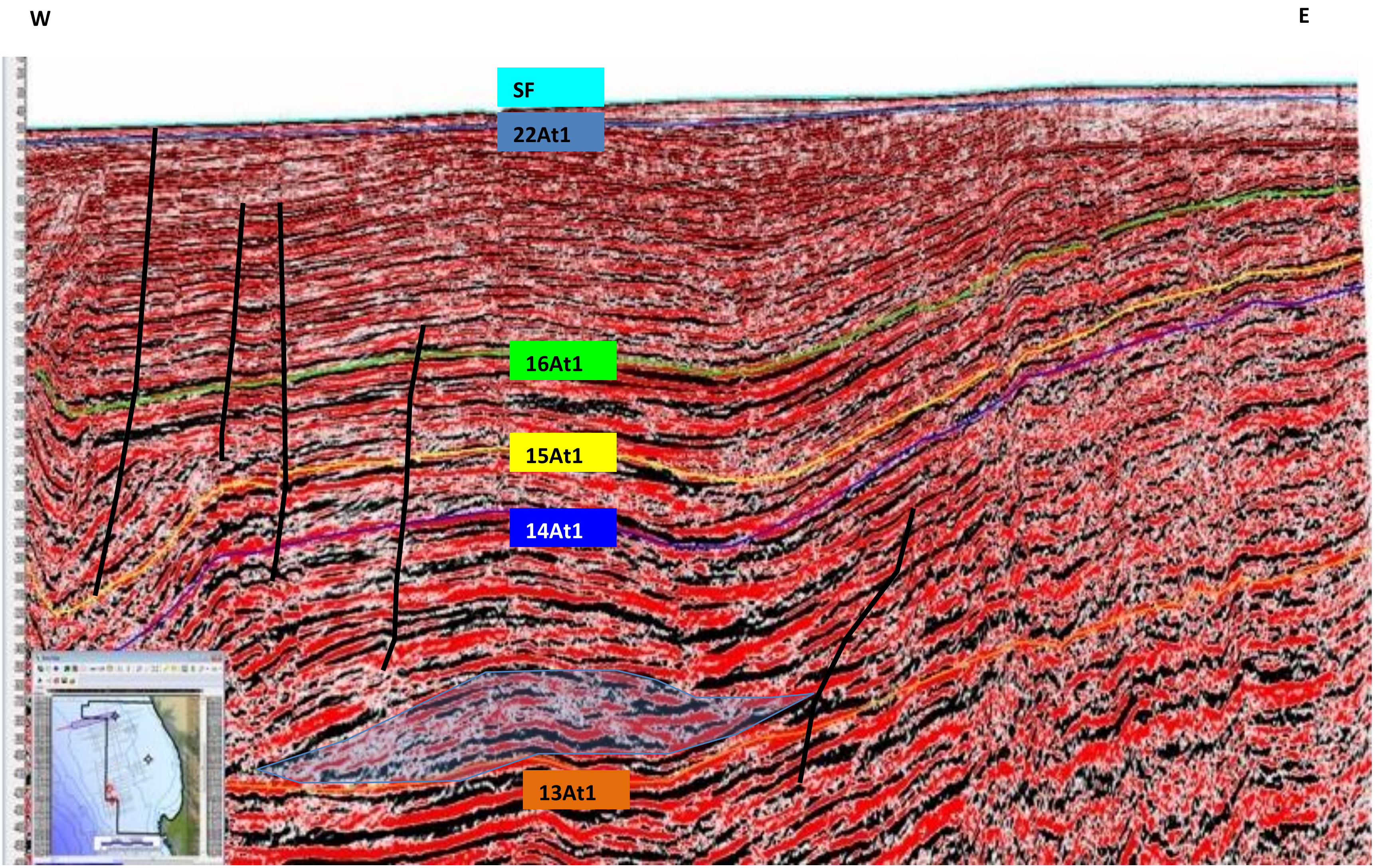


Figure 48: Line A76-010

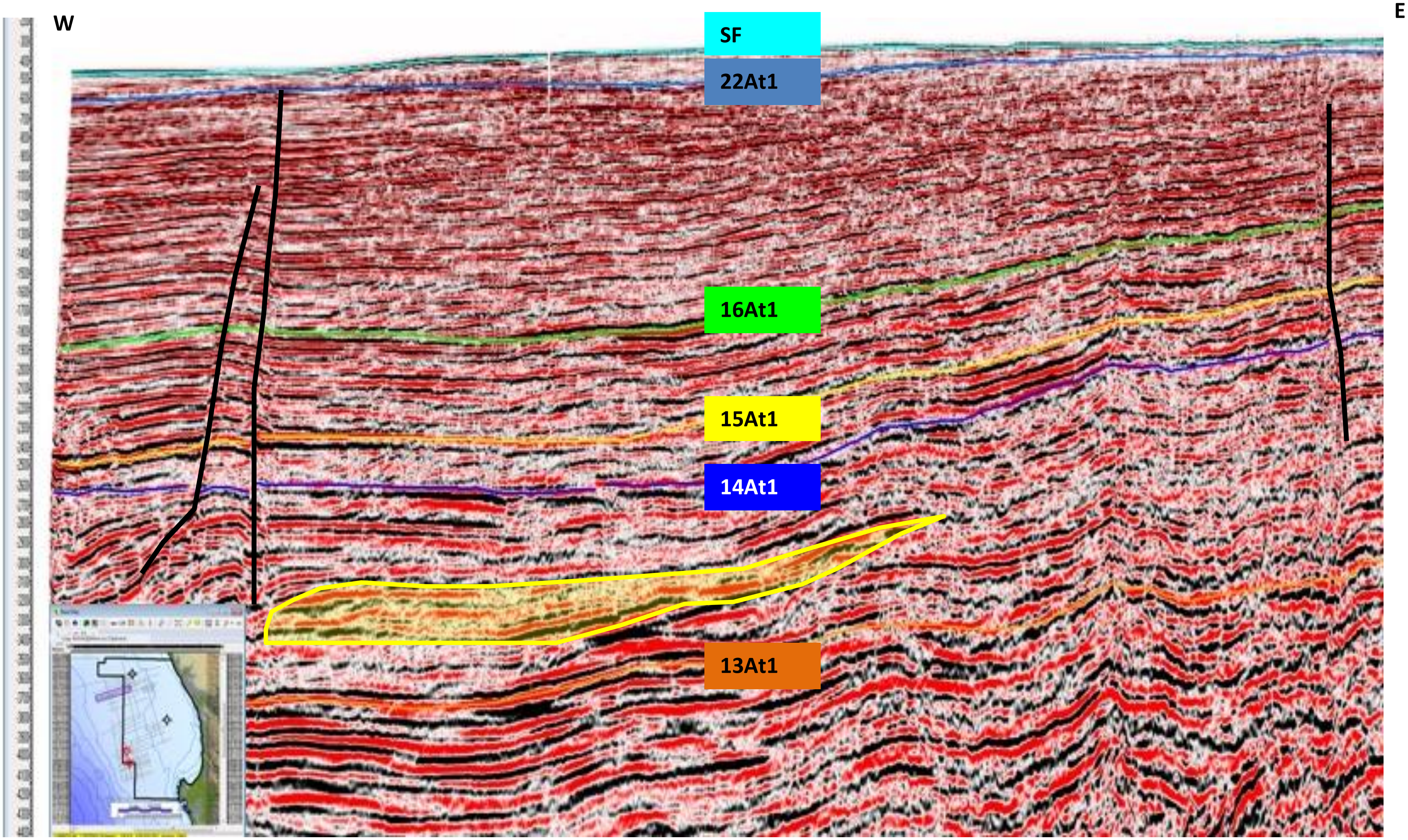


Figure 49: Line A76-026

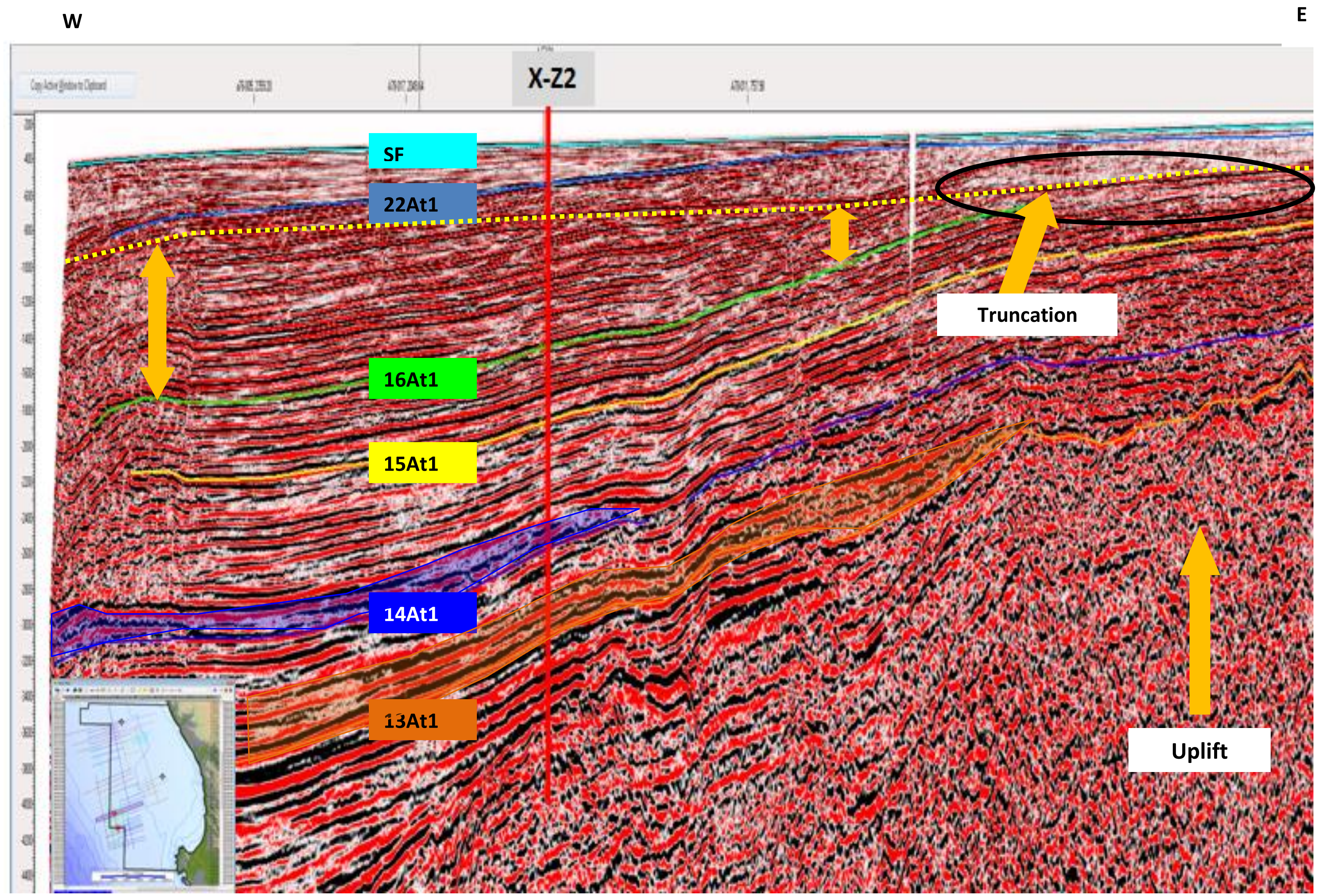


Figure 50: Line A76-006

In the wireline log section, the 13A sequence logs for the wells (BX-X1 and X-X1)do not display similar log signatures but wells X-Z1 and X-Z2 do; which could mean that the sequences were deposited at the same time. However, well X-Z1 shows very little sandstones in the 13A sequence, unlike well X-Z2. It is evident by looking at the 13A sequence in wells X-Z1 and X-Z2 that there was a transgression and possible flooding during this period. Well BX-X1 has little sandstones(see figure 51) in the 13A sequence; the sequence is thinner than it is in other wells. This could be due to the uplift event that was mostly concentrated on the eastern parts of Block 3A/4A where well BX-X1 is located. The 13A sequence in well X-X1 only contains shale and not sandstones. In the 13A sequence, wells X-Z1 and X-Z2 show some potential for hydrocarbons as they both contain sandstone packages with overlying silt.

Again, wells X-Z1 and X-Z2 have similar log signatures and sandstone packages in the 14A sequence. Above the sandstones are silt packages, in both wells. Well X-X1 does not have the 14A sequence. Well BX-X1 has interlaminated sandstone and silt packages and yet again, the 14A sequence is thinner(roughly 200m)compared to other wells; this points again to the uplift event.Well BX-X1 could have initially had hydrocarbon potential; had it not beenfor the uplift event which was described by Craven and Roberts, 1976 as volcanic. If there was a hydrocarbon accumulation around well BX-X1, then the uplift event has probably overcooked the hydrocarbons

In the 15A sequence; wells X-Z1 and X-Z2 containsandstones interlaminated with shalein both wells. In well X-X1 there is sandstone that is interbedded with shale; this 15A sequence could have some hydrocarbon potential. Well BX-X1 does not have the 15A sequence.

The 16A sequence in well X-Z1 has a distinctive, clean and thick sandstone package just above the 16At1. However, well X-Z2 does not have the sandstone package. It could be that it was eroded at some point.

Well X-X1 also has sandstone; however, it is interlaminated with shale. The different sandstone packages in this well and sequence could serve as different reservoirs and the shale, seals.

Well BX-X1 also contains sandstone with shalein it, especially in the 16A and 22A sequences. During the deposition of the 15 and 16At1, there was a lot of aggradation and progradation. This explains why the sequences have sandstones with silt in them; especially for wells X-X1 and BX-X1 (the proximal wells of the four).

In the biostratigraphy section, all four wells were subdivided into biozones and age; thus, indicating what was intersected in the different zones and age thereof.

In well X-X1, it was found that there are age restrictions and uncertainties in other zones due to very limited microfauna that was analysed from the well. The only zones that provide clear indications of the age breakdown in the well are zones F, which represents depths 1310 – 3038m and B which is representative of depths 750 – 760m.

Zone F is suggestive of Aptian – Albian – Turonian ages due to the presence of the Hedbergella species. The age suggested for zone B in well X-X1 is Cenomanian. This is because of the Orientalia species that was found in the sample.The rest of the zones did not give clear indications of ages.

The biostratigraphy data suggests that the 13At1 and 13A sequence are from the Aptian age. The ages of the other markers in well X-X1 were not determined from the biostratigraphy data; again, this is due to unclear and unreliable findings(?).

In well X-Z1, from the basement(approx. 4000m) to a depth of 3030m is where the 13At1 is found, which dates Aptian. The 13A sequence interval contains large amounts of volcanic material. A late Aptian interval from 2778 – 3030m is suggestive of the transitional inner shelf.

The Albian interval (2120 – 2778m) which is representative of the 14A sequence was deposited in an outer shelf environment and this is also where the 14At1 sits. From the depth of 1760 – 2120m it is the Cenomanian interval which is suggestive of an outer shelf environment, due to the freshwater inflow. More so, this is where the 15At1 is found. The outer shelf stretches towards the Coniacian – Turonian interval, at depths of 1370 – 1760m (the interval where the 16At1 is located).

In the Santonian interval, foraminifera and benthonic species are found in large numbers. Thus, an inner shelf environment is inferred.

Deposition seems to have occurred in shallow marine environments in the Campanian interval (670 – 850m). This level is where the 22A sequence is found in well X-Z1.

In well BX-X1, the only depth of interest that was sampled is from 1280 – 1286m where the 13At1 is located. Samples from this depth in this well suggest cold water conditions.

The 15Aand 16A sequences in well X-Z2 are suggested to have been deposited in slope / shelf conditions.

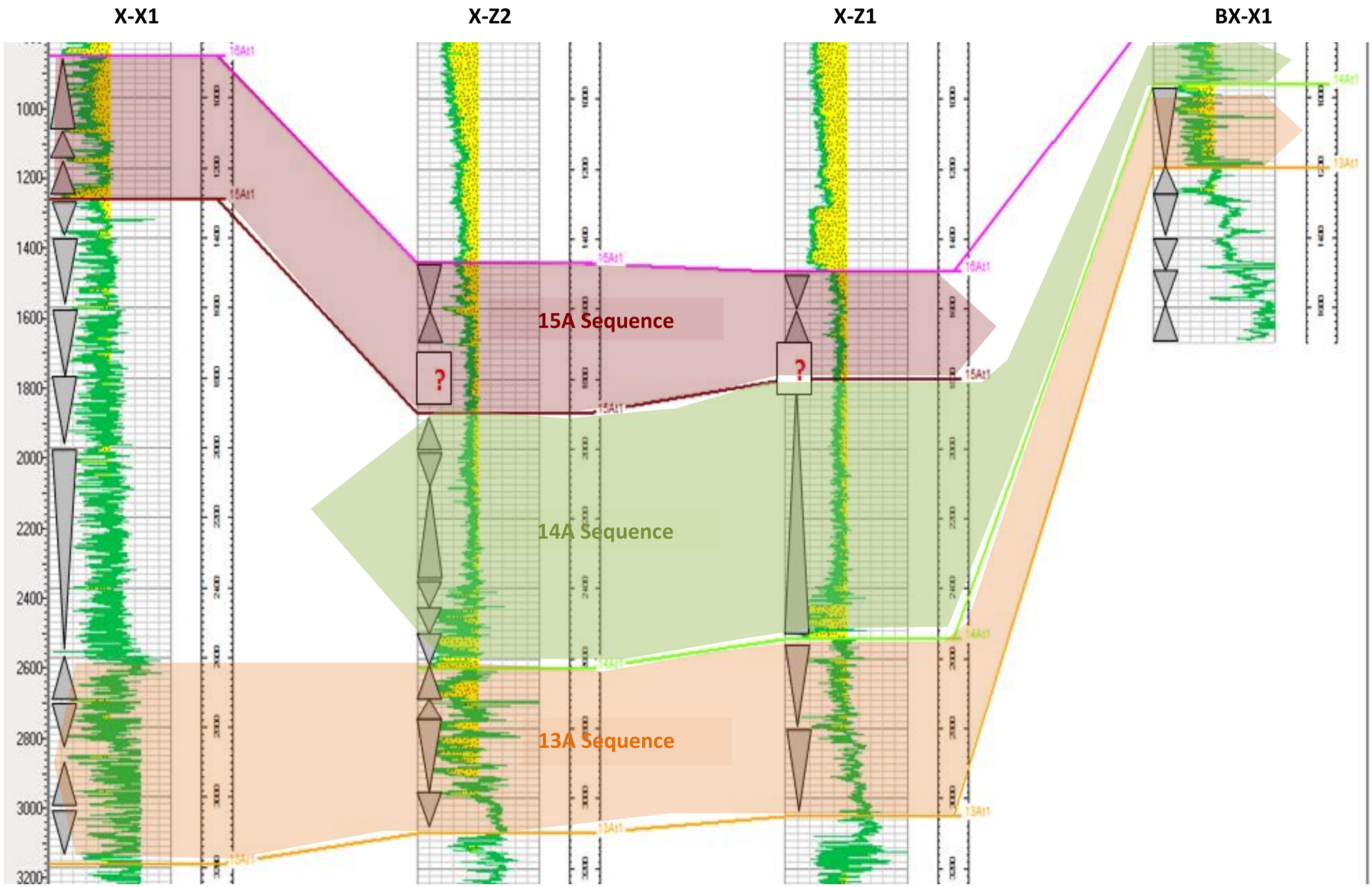


Figure 51:Gamma ray log sequence correlation for wells X-X1, XZ1, X-Z2 and BX-X1; for the 13A, 14A and 15A sequences

4.2. CONCLUSION

Biostratigraphic interpretation suggest that most of the sequences in the drift section of the study area were deposited in shelf conditions, the 13A sequence in freshwater conditions and the 22A sequence in shallow marine environments. The proximal part of the study area shows thinning of sequences, especially towards the BX-X1 well. This thinning is due to the uplift event that took place during the Late Cretaceous. Although well BX-X1 has got some sandstone in the 15A sequence, the volcanic uplift event could have possibly destroyed hydrocarbons due to the heat that came with the upliftGamma ray log analyses and interpretation have revealed sandstone packages in the wells, interlaminated with silt. These sandstone packages could serve as possible reservoirs in hydrocarbon entrapments and the silt as seals. It is worth noting that wells X-Z1 and X-Z2 in particular have sandstone packages in the 14A sequence which date Albian; these packages could be of good potential since proven hydrocarbons in the Orange Basin date Albian. Other sequences have shown to contain interesting stratigraphic and structural features associated with hydrocarbon entrapments.

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