Sequence stratigraphic characterisation of petroleum reservoirs in block 11b/12b of the Southern Outeniqua Basin

A thesis in Petroleum Geosciences
By

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KEYWORDS

Southern Outeniqua Basin
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Block 11b/12b
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Reservoir
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Sequence
Systems tract
Turbidites
Progradation
Seismics

ABSTRACT

The main purpose of this study was to identify and characterize the various sand prone depositional facies in the deepwater Southern Outeniqua Basin which generally tend to form during lowstand (marine regression) conditions producing progradational facies.

It made use of sequence stratigraphy and turbidite facies models to predict the probable location of deepwater reservoirs in the undrilled Southern Outeniqua Basin using data from basin margin Pletmos Basin and the deepwater Southern Outeniqua Basin.

Basin margin depositional packages were correlated in time and space with deepwater packages. It was an attempt at bridging the gap between process-related studies of sedimentary rocks and the more traditional economic geology of commercial deposits of petroleum using prevailing state-of-the-art in basin analysis. It enabled the most realistic reconstructions of genetic stratigraphy and offered the greatest application in exploration.

Sequence stratigraphic analysis and interpretation of seismics, well logs, cores and biostratigraphic data was carried out providing a chronostratigraphic framework of the study area within which seismic facies analysis done. Nine (9) seismic lines that span the shallow/basin margin Pletmos basin into the undrilled deepwater Southern Outeniqua basin were analysed and interpreted and the *relevant seismic geometries were captured*. Four (4) turbidite depositional elements were identified from the seismic lines: channel, overbank deposits, chaotic deposits and basin plain (basin floor fan) deposits. These were identified from the *relevant seismic geometries (*geometric attributes) observed on the 2D seismic lines. Thinning attributes, unconformity attributes and seismic facies attributes were observed from the seismic lines.

This was preceded by basic structural analyses and interpretation of the seismic lines. according to the structural analysis and interpretation, deposition trended NW-SE and NNW-SSE as we go deepwater into the Southern Outeniqua basin.

Well logs from six (6) of the interpreted wells indicated depositional channel fill as well as basin floor fans. This was identified in well Ga-V1 and Ga-S1 respectively. A bell and crescent shape gamma ray log signature was observed in well Ga-V1 indicating a fining up sequence as the channel was abandoned while an isolated massive mound-shape gamma ray log signature was observed in Ga-S1 indicating basin plain well-sorted sands.

Core analyses and interpretation from two southern-most wells revealed three (3) facies which were derived based on Walker's 1978, turbidite facies. The observed facies were: sandstone, sand/shale and shale facies.

Cores of well Ga-V1 displayed fine-grained alternations of thin sandstone beds and shales belonging to the thin-bedded turbidite facies. This is typical of levees of the upper fan channel but could easily be confused with similar facies on the basin plain. According to Walker, 1978 such facies form under conditions of active fan progradation. Ga-S1 cores displayed not only classic turbidite facies where there was alternating sand and shale sections but showed thick uninterrupted sections of clean sands. This is typical of basin plain deposits.

Only one well had biostratigraphic data though being very limited in content. This data revealed particular depth sections and stratigraphic sections as having medium to fast depositional rates. Such rates are characteristic of turbidite deposition from turbidity currents.

This study as well as a complementary study by Carvajal et al., 2009 revealed that the Southern Outeniqua basin is a sand-prone basin with many progradational sequences in which tectonics and sediment supply rate have been significant factors (amongst others such as sea level change) in the formation of these deepwater sequences.

In conclusion, the Southern Outeniqua basin was hereby seen as having a viable and unexplored petroleum system existing in this sand prone untested world class frontier basin of the Southern Outeniqua basin.

DECLARATION

I declare that *Sequence stratigraphic characterisation of petroleum reservoirs in block 11b/12b of the Southern Outeniqua Basin* is my own work, that it has not been submitted before for any degree or examination in any other University, and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references."

Nformi Emmanuel Nfor May 2011

Signature

DEDICATION

To God Almighty *“......in whom are hidden all the treasures of wisdom and knowledge”*.

Col 2:3

ACKNOWLEDGEMENT

The privilege is mine to have had someone of exceptional ingenuity, foresight and insight to have supervised me. Thanks very much Prof. Paul Carey for squeezing out time and energy to ensure that this work is well done despite the unlimited challenges that arose as you supervised me. Your criticisms, corrections and friendship bore immense fruit in making this research realized.

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In the footsteps of Issac Newton who said *“If I have been able to see further, it was only because I stood on the shoulders of giants*", I hold in esteem the pioneering works of Carlo Ippolito Migliorini (1891 to 1953), Philip Henry Kuenen, Arnold Bourma and others who pioneered deepwater turbidite research as well those who pioneered *sequence stratigraphy* which is considered as the 3rd revolution in sedimentary geology. These are the giants on whose shoulders we can stand.

Table of Contents

List of Figures

CHAPTER ONE: AN OVERVIEW

1.1 Preamble

The long history of interest in gravity-driven deep-water sedimentation is founded on early key works by Philip Henry Kuenen, Carlo Ippolito Migliorini, Francis Parker Shepard, Arnold Bouma and others. Research in this field of sedimentary geology has recently accelerated. This is largely driven by the interest of the oil industry as their exploration on continental margins around the world has extended into increasingly deep water (SEPM Sequence Stratigraphy Web, 2009).

While the Deepwater Horizon incident (20th April 2010 in the Gulf of Mexico)[1] introduced a new dimension of uncertainty to the offshore oil and gas sector, deepwater oil discoveries are increasingly important to the global and U.S. reserve base, according to research compiled by IHS CERA in 2010.

From this report, the volume of new oil reserves coming from deepwater has been on an upward trend since the 1990s, and has become particularly important in recent years. From 2006 to 2009, annual world deepwater discoveries in over 600 feet of water accounted for 42 percent to 54 percent of all discoveries onshore and offshore. In 2008 alone, deepwater discoveries added 13.7 billion BOE to global reserves.

The report further highlights that global deepwater production capacity in 2,000 feet (610 m) of water or greater has more than tripled since the year 2000, rising from 1.5 million b/d in 2000 to more than 5 million b/d in 2009.

Projections before the April 20 blowout in the Gulf of Mexico showed that deepwater production capacity had the potential to rise to 10 million b/d by 2015, a rate of expansion well above the expected average rate of global supply growth (IHS CERA, 2010).

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[1] At 9:45 P.M. CDT on 20 April 2010, during the final phases of drilling the exploratory well at Macondo, a geyser of seawater erupted from the marine riser onto the rig, shooting 240 ft (73 m) into the air. This was soon followed by the eruption of a slushy combination of mud, methane gas, and water. The gas component of the slushy material quickly transitioned into a fully gaseous state and then ignited into a series of explosions and then a firestorm. An attempt was made to activate the blowout preventer, but it failed. After burning for approximately 36 hours, *Deepwater Horizon* sank on 22 April 2010. The remains of the rig were located resting on the seafloor approximately 5,000 ft (1,500 m) deep at that location, and about 1,300 ft (400 m) (quarter of a mile) northwest of the well. Some estimates of the spill make this the largest oil spill ever in the Gulf of Mexico and US history (wikipedia).

1.1.1 Deepwater Offers Larger Discoveries

Deepwater discoveries are significantly larger on average than new onshore discoveries. The average size of a new deepwater (600 feet or more) discovery in 2009 was about 150 million BOE compared with the onshore average of only 25 million barrels. Global deepwater production also exceeds that of any country except Saudi Arabia, Russia and the USA. That is, if deepwater production was viewed as its own "country," it would exceed that of every other country except Saudi Arabia, Russia, and the United States (IHS CERA, 2010).

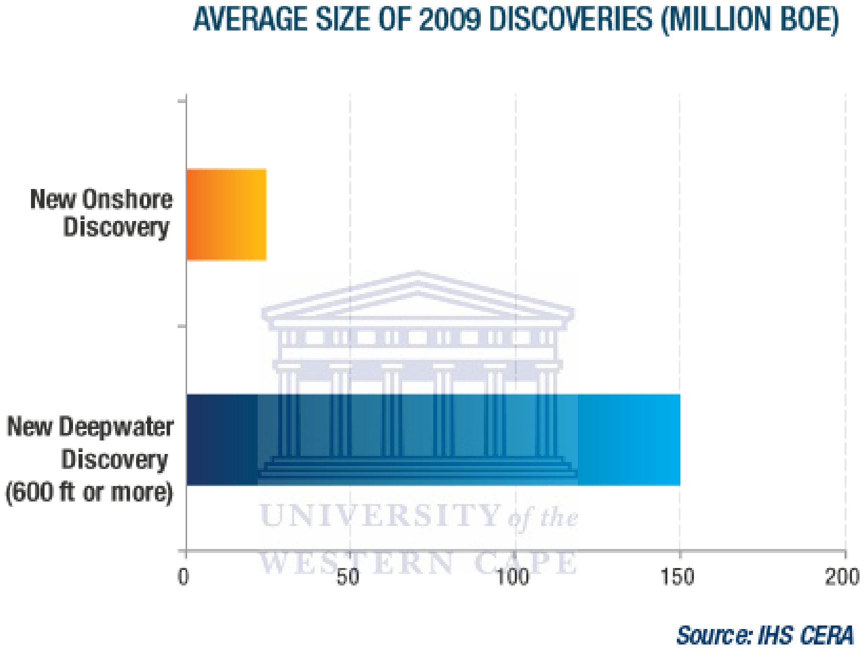


Figure 1.1: Average size of 2009 new onshore and new deepwater discoveries

As of yearend-2000, 900 wells had been drilled in 71 basins in greater than 400 m of water depth, with most wells being drilled in only six basins globally (Worrall et al., 2001).

Parallel developments in seismic and seafloor imaging have provided fundamental new insights into the character and three-dimensional structure of deepwater deposits. Increasingly sophisticated laboratory and numerical simulations can now be used to replicate natural processes. Seismic direct hydrocarbon indicators (DHIs), including amplitudes variation with offset (AVO), have been critical in our understanding of reservoir and charge risk (Society of Exploration Geophysicists, 2000).

Because of the associated risk, DHIs were a major driving force behind the initiation of significant deepwater drilling in the 1980s (Weimer and Slatt, 2004). Advances in seismic-reflection imaging have arguably been the most important element in allowing companies to explore deep water because seismic imaging often reduces geologic risk to acceptable levels (Rudolph, 2001).

1.2 Introduction

Recent increases in global demand for hydrocarbons, declining production from mature provinces and high oil prices are driving a new phase of international exploration for petroleum resources in frontier basins.

Until the recent advances in high frequency seismic acquisition and deepwater exploration, the methodology of sequence stratigraphy has more commonly been applied to sediments that accumulated in coastal, shelfal and other shallow water settings rather than deepwater (SEPM Sequence Stratigraphy Web).

The primary energy resource in South Africa is coal. She imports approximately 62.5% of its crude oil requirements with current domestic consumption approximately 550,000 bbl/d (PASA, 2008). Much of petroleum exploration and production has been concentrated in shelf and shallow waters of South Africa. New seismic data indicates deepwater drilling might be the answer to South Africa's unquenchable thirst for oil (Roux et al, 2004),

The Southern Outeniqua Basin, a frontier basin situated off the South coast of South Africa remains very much under-explored. It is an untested world-class frontier area with hydrocarbon potential (Roux, 2004).

For operational reasons (deep water and strong ocean currents) this basin has been left virtually unexplored. No wells have been drilled and until recently, the only control was provided by a wide grid of old seismic lines. New 2D seismic data acquired by Canadian Natural Resources (formerly Ranger Oil) in 2001 and 2005 confirmed the presence of major structures in this deep water frontier area (Petroleum Agency SA Brochure, 2008). Latest seismic interpretation of this new data indicates the possibility of a gigantic basin floor fan complex (named “paddavissie”) with an upside potential of billion of barrels of oil also confirmed by the latest infill seismic data. According to PASA Brochure 2008, the Southern Outeniqua Basin is highly rated for oil in the central and southern extent of the basin, and more gas-prone towards the northern periphery with its thicker overburden. Regional studies suggest the presence of multiple source rocks, shallow marine and turbidite sandstones and large structural and stratigraphic traps.

The first offshore petroleum exploration well in South Africa was drilled by Superior Oil Company in 1969 and resulted in the discovery of the Ga-A gas field in the Pletmos sub-basin about 60 km southeast of Plettenberg Bay. The gas was reservoired in shallow-marine sandstones of Valanginian age underlying the 1At1 unconformity and in fractured basement rocks (Broad et al., 2006).

South Africa's first commercial discovery of oil or gas was made by Soekor in 1980 in the Bredasdorp sub-basin (West of our study area), where porous and permeable shallow-marine sandstones of Valanginian age flowed gas and condensate at commercial rates. Production began in 1992 with daily average production being approximately 195 million standard cubic feet of gas and 5,190 barrels of condensate in 2002/2003 (Broad et al., 2006).

In 1987, the first of several small oil fields was discovered in the central Bredasdorp sub-basin where oil was reservoired in porous sandstones within submarine fan complexes of Aptian and Albian age (Wood, 1995).

The first of these, the Oribi oil field, began production in 1997 at an initial rate of 25 000 barrels of oil per day (bbl/d) but by the end of the 2003 was in decline, with combined production from the Oribi and Oryx fields being about 14 000 bbl/d. The Sable oil field began oil production in 2003 and when in full production was expected to produce some 30 000bbl/d which was expected to replace approximately 7% of South Africa's import requirements for crude oil (PetroSA, 2003).

Exploration and drilling in South Africa's offshore basins has demonstrated the presence of active petroleum systems with thermally mature petroleum source rocks, porous and permeable reservoir sandstones and effective traps. It has resulted in commercial production of oil and gas. Current exploration indicates good potential for further discoveries (Broad et al., 2006). A detailed account of the petroleum geology of the offshore basins is available in Van Vuuren et al., 1998.

Exploration activity in the world has made significant advances in recent years into water depths previously considered unacceptably deep for drilling and production, with a well drilled offshore Gabon in 2800m of water. Other countries on the western coast of Africa have experienced dramatic successes in the search for oil in deep water in the last decade. Advances in both exploration and production technology and the use of floating storage and offloading vessels (FPSOs) have made fields in such deepwater commercially and technically viable (International Petroleum Encyclopedia, 2010).

According to the International Petroleum Encyclopedia, 2010, Soekor (Pty.) Ltd., (Cape Town) identified what it described as "exciting" potential in the deepwater frontier off South Africa. It focused on an unexplored area, the Southern Outeniqua basin.

It is therefore important to venture with current and advanced exploration techniques into locating new potential reservoirs in the deep waters off the South Coast of South Africa in the Southern Outeniqua basin.

Conventional wisdom holds that for any given basin or play, a plot of cumulative discovered volumes versus time or number of wells drilled usually show a steep curve (rapidly increasing volumes) early in the play history and later plateau or terrace (slowly increasing volumes). Such a plot is called a creaming curve (Snedden et al., 2003). They further explain that by examining plays or basins with sufficiently long histories and range of reservoir paleoenvironment and trap types, one actually finds two or three “terraces” to the creaming curve.

The first string of successes in a given basin usually corresponds to exploitation of the highstand systems tract or sequence set reservoirs developed in updip structural traps. These reservoirs are typically marginal to shallow marine "shelfal" deposits, laterally continuous but lacking internal sealing facies and are seldom self-sourcing. The second or third terrace in the creaming curve usually involves the lowstand reservoir component (systems tract or sequence set), which is often developed in downdip deepwater or slope paleoenvironments. Explorationists use a variety of methods to evaluate oil and gas plays. One of these is the “creaming curve” (Figure 1.2)

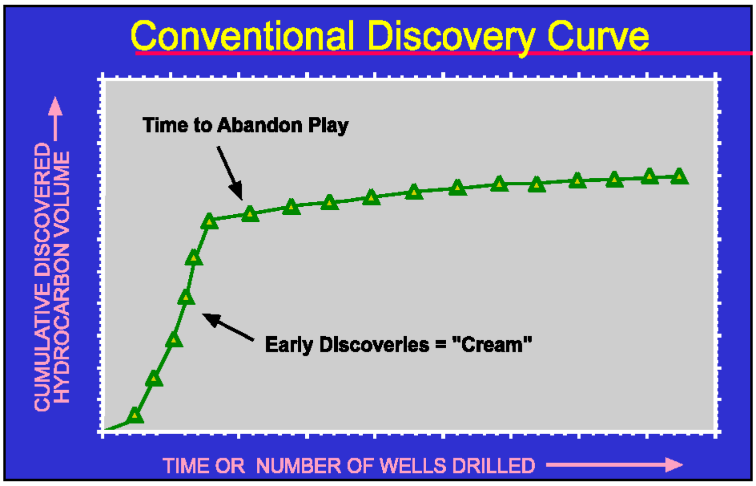


Figure 1.2: Idealized simple creaming curve (cumulative discovered volumes versus time) from Meisner and Demirmen, 1981),

One could explain more complex play histories from a sequence stratigraphic standpoint. In fact, the sequence stratigraphic model predicts that an ideal creaming curve for an exploration play should actually have two or three-paired rising limbs and plateaus (Figure 1.3; Snedden *et al*., 1996a).

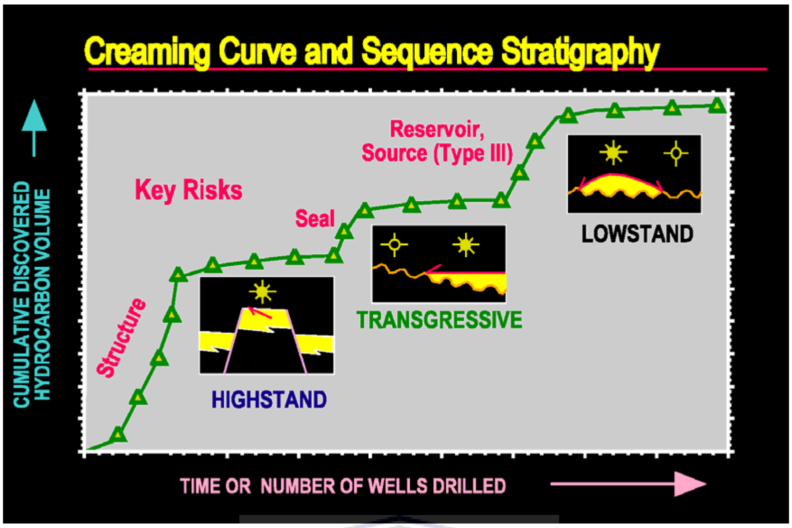


Figure 1.3: Idealized creaming curve from a sequence stratigraphic perspective. The components of the creaming curve refer to systems tract or sequence set, depending upon the size and scale of the play being considered. From Snedden et al., 1996a

One way to identify an under- or unexplored play is to compile field statistics by systems tracts or sequence set-type. For example, analysis of the Texas lower coastal province (onshore) reveals that the HST (HSS) components contain the bulk of gas reserves discovered to date in 32 onshore plays (Figure 1.4). This predominance of fields developed in structural traps in thick, laterally continuous shallow water sandstones of the HST or HSS accounts for such a disparity (Kosters *et al*., 1989).

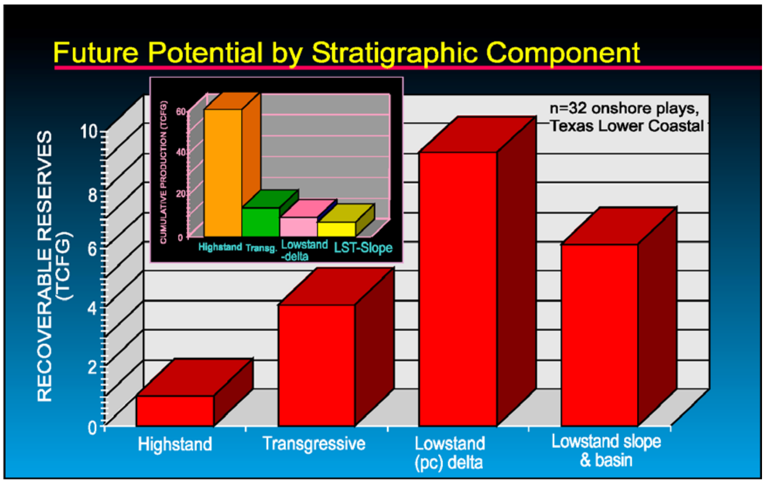


Figure 1.4: Future potential by sequence stratigraphic package, onshore Gulf of Mexico, Lower coastal province, Texas (n=32 plays). Inset shows cumulative production by sequence set or systems tract type. Data from Kosters et al. (1989) and Seni et al. (1994) but interpretation by the authors as to systems tract/sequence set. Modified from Snedden et al. (1996b). TCFG=Trillion cubic feet of gas.

Conventional lithologic correlation, maps formation tops by interpreting well log data alone (Neal et al., 1993). It looks at what is where without taking into account how it got there. "*Sequence stratigraphic characterization of petroleum reservoirs in block 11B/12B of the Southern Outeniqua basin of South Africa*" was an attempt at going past this conventional route by incorporating both the interpretation of well log data, cores from the Pletmos Basin as well as seismic data in the characterization of reservoirs in the Southern Outeniqua Basin of South Africa.

Sandstones form the frameworks of depositional systems and the reservoirs of hydrocarbon systems (Hamlin, 2009). According to him, sandstone geometries, thicknesses, and vertical bedding styles are all amenable to analysis using log and core data. Lateral continuities can be characterized using interwell correlation and interpolation techniques. Delineation of sandstone geometries and depocentres provide evidence for interpreting depositional systems, reconstructing sediment input and dispersal patterns, and timing and location of tectonic events.

1.3 Study Area: Southern Outeniqua Basin, off the South Coast of South Africa

The Outeniqua Basin consists of a series of en echelon sub-basins (the Bredasdorp, Pletmos, Gamtoos and Algoa Basins) each of which comprises a complex of rift half-graben overlain by a variable thickness of drift sediments. The deepwater extensions of these basins (excluding the Algoa Basin) *merge into the* ***Southern Outeniqua basin*** (PASA, 2008).

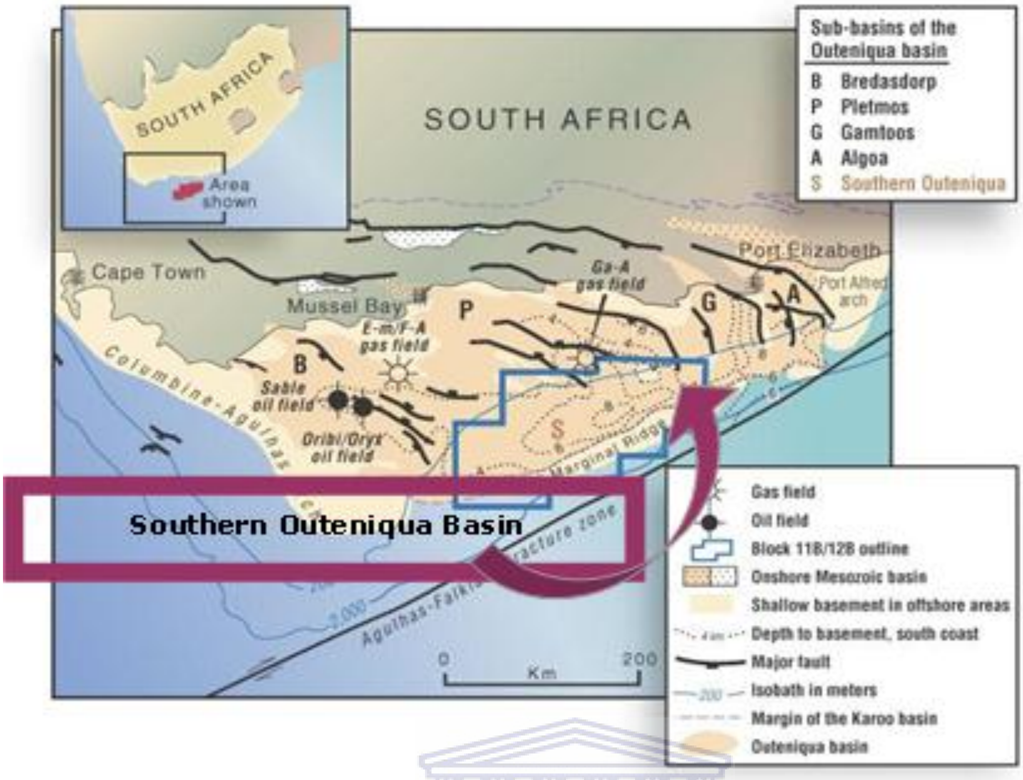
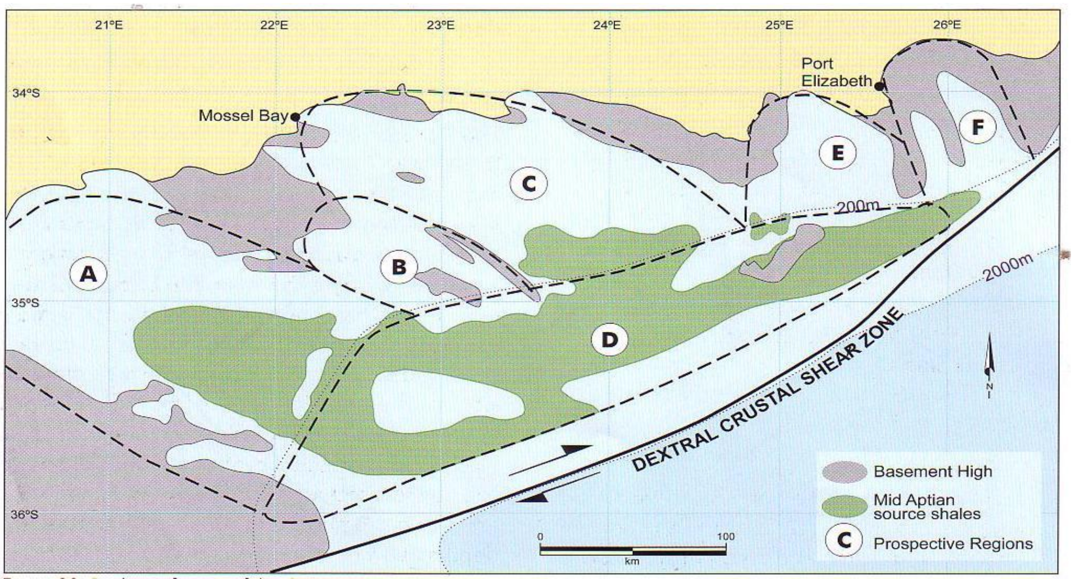


Figure 1.5: The location and structural setting of the Outeniqua basin and sub-basins by Roux et al., 2004

Combined mapping and evaluation by Soekor (now PetroSA) and Ranger Oil (now CNR) suggest there is enough potential in this basin in water depths in excess of 300 meters. The inferred distribution of reservoirs and source rocks in the untested Southern Outeniqua basin suggests that there is substantial potential in this large 20,000 sq km, (4,942,000 acre) area. Exploration here would require relatively deepwater drilling (in excess of 300 m) (Roux, 1997).

A number of untested synrift structures have recently been mapped. These domal structures are large, ranging from 300 to 1,600 million bbl, or 500 to 2,750 bscf gas (excluding additional subcrop potential). Deep marine fans that developed within the drift succession are expected to contain oil and gas sourced from the same succession. These fans are expected to include good quality reservoir sandstones similar to those intersected in the 13A and 14A sequences in the Bredasdorp basin to the west (Roux, 1997).

Figure 1.6 below shows a ranking of sub basins in the Outeniqua Basin as well as their hydrocarbon potential.



PROSPECTIVE REGIONS					
(A) Bredasdorp	**(B) Infanta Embayment**	**(C) Pletmos**	***(D) Southern Outeniqua***	**(E) Gamtoos**	**(F) Algoa**
KITCHEN AREA					
Large	Small	Moderate	***Large***	Small	Small
MIGRATION DISTANCES					
Short	Long	Short	***Short***	Long	Short
TRAPS					
Abundant	Limited	Abundant	***Abundant***	Limited	Limited
EFFECTIVE SEALS					
Widespread	Limited	Widespread	***Widespread***	Limited	Limited
OIL AND GAS FINDS					
Proven Oil and gas finds. Undrilled to E	Little potential to North. Undrilled to South	Proven gas potential to N. Undrilled in South.	***Undrilled***	Gas shows	Oil shows. Undrilled to South
HYDROCARBON POTENTIAL					
Excellent	Poor	Good	***Excellent***	Good for gas	Excellent

Figure 1.6: Ranking of areas and potential in the Outeniqua Basin from PASA 2008.

1.4 Methodology and Objectives

Weimer and Slatt, 2004 explain that deepwater depositional systems are the one type of reservoir system that cannot be easily reached, observed, and studied in the modern environment in contrast to other siliclastics and carbonate reservoir systems. It requires many remote observation systems, each of which can provide only one view of the entire depositional system. Thus, the study and understanding of deepwater depositional systems and reservoirs have lagged behind those of the other reservoir systems, whose modern processes are more easily observed and documented. The study of these systems require multiple data types which include detailed outcrop studies, 2D and 3D seismic-reflection data (both for shallow and deep resolution), cores, log suites, and biostratigraphy. These data sets are routinely incorporated in into computer reservoir modelling and simulation.

According to *Peel, 2004, a* normal approach to evaluate a frontier basin (such as the Southern Outeniqua Basin) might be:

(i) Acquire regional seismic data spanning the basin
(ii) Identify and map the important unconformity-bounded mega sequences
(iii) Define the major tectonic/depositional events
(iv) Define the major source/reservoir/seal units and hence the likely “sweet spots” within the basin
(v) Focused seismic acquisition and exploratory drilling.

According Bradshaw, 2007, good quality regional seismic lines comprise the essential data for integrated basin studies, given that well data is often sparse or absent in frontier basins.

This research project went in line with the above approach to evaluate block 11B/12B of this frontier basin using the sequence stratigraphic approach. It entailed the incorporation of 2D seismic-reflection data (both for shallow and deep resolution) spanning the shallow Pletmos Basin to the deepwater Southern Outeniqua Basin. Analyses and interpretation of log suites from six (6) wells in the shelf area/basin margin (Pletmos Basin) was conducted. Due to the absence of drilled wells in this deepwater region of the Southern Outeniqua Basin all the wells studied were from the basin margin Pletmos basin.

Seismic lines were analysed and interpreted for basic structural reading/imaging and interpreted to view the basin as a whole. These lines were used to identify and map the important unconformity-bounded mega sequences as well as define the major tectonic/depositional events.

Basic petrophysical analyses were performed, where loaded wireline log data from the six (6) wells were used to identify the various subsurface lithologies. The wells were correlated to determine the lateral extent/continuity of the various lithologies, the depth variations of the stratigraphic surfaces as well as the various pinch-outgeometries of the lithologies.

The available cores from two of the wells in the Pletmos basin were used for an in-depth study and closer appraisal of the various lithostratigraphic, turbidite facies and facies associations units as well as for calibrating the detailed seismic and borehole log interpretations.

The sequence stratigraphic job simply comprised

- The identification and capture of relevant seismic geometries at scales in the range of hundreds to thousands of seismic traces, properties of unconformity surfaces and conformable surfaces and how these can be used to define sequences and sequence architecture.
- Depositional facies in time and space as a function of sedimentary regimes and variations in allogenic and autogenic factors.
- Local and regional correlation of litho facies and sequences.

According to *Neal et al. 1993,* no exploration technique flawlessly locates a potential reservoir, but sequence stratigraphy may come close. By understanding global changes in sea level, the local arrangement of sand, shale and carbonate layers can be interpreted. This enhanced understanding of depositional mechanics steers explorationists toward prospects missed by conventional interpretation. This is done by the combination of logs with seismic reflection patterns to explain both the arrangement of rocks and the depositional environment. Understanding the relationships between rock layers, their seismic expression and depositional environments allows more accurate prediction of reservoirs, source rocks and seals, even if none of them intersect a well. *Neal et al*., *1993,* believed that as more people learn the technique of sequence stratigraphy, it will become an exploration tool for constraining *the shape, extent* and *continuity* of reservoirs.

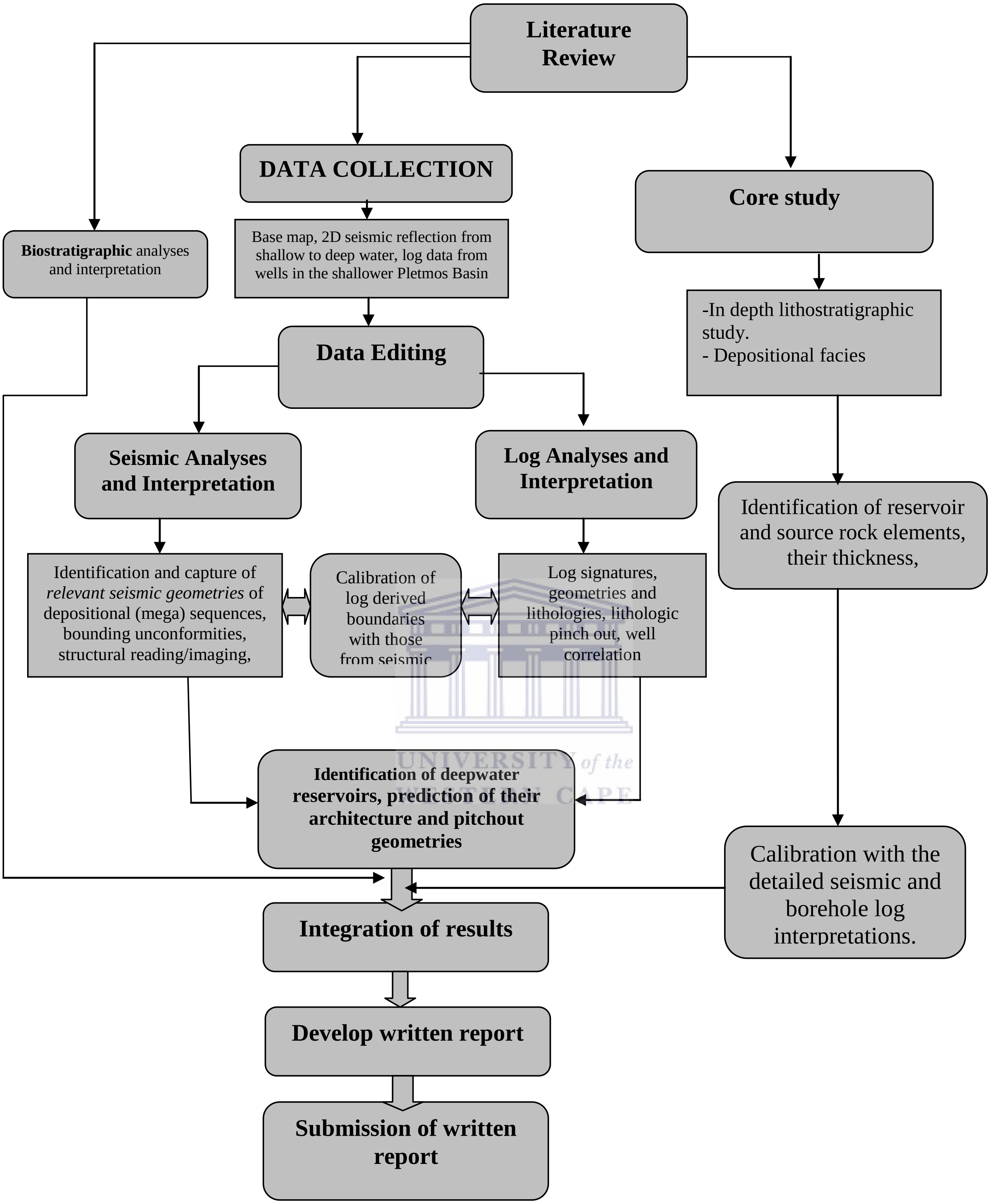


Figure 1.7: Methodology flow chart

Figure 1.7 above outlines the various steps undertaken in this research work. Extensive literature review was conducted about the area of study and method used- deepwater sequence stratigraphy. Data was collected. Collected data included seismic, wireline log, core and biostratigraphic data. It was followed by independent seismic, core, biostratigraphic analyses and interpretation. Results and conclusions from the independent analyses and interpretation were integrated and this thesis was written.

Seismic reflection lines were used to identify main seismic reflections further used to identify each depositional sequence and separate younger layers from older layers. Sequence boundaries were identified on seismic lines as surfaces defined by onlap terminations, truncation terminations as well as downlaps (Mitchum et al., 1977a, P58). Seismic reflections were seen as time lines (Vail and Sangree, 1971) and the interpretation of seismic onlap patterns as indicators of sedimentary responses to eustasy (Vail, 1975).

Each systems tract exhibits a characteristic log response, seismic signature and paleontologic finger print, and performs a predictable role in the oil and gas play-source rock, reservoir, seal, trap etc (Neal et al., 1993). Seismic data and logs were interpreted to identify sequences and their boundary unconformity. Log derived boundaries were compared with those from seismic data and the interpretation refined.

The surface of maximum sediment starvation and the maximum flooding surface are commonly marked by a concentration of microfossils, authigenic glauconite, phosphatic and sideritic fossil molds (steinkern), and encrusted and bored fossils (Baum and Vail, 1988; Loutit et al., 1988).

Petrophysical analyses and interpretation entailed the use of wireline logs- gamma ray (GR), spontaneous potential (SP), neutron porosity hydrogen index log (NPHI), caliper log (CAL), sonic log (DT) and bulk density (RHOB) logs from six (6) wells in the Pletmos basin area to:

- Define different sand and reservoir zones
- Depositional sequences and their boundaries
- Do a correlation of the wells under study.

These data sets were incorporated into computer reservoir modelling using *Schlumberger Petrel software* which was used for

- Quality checking of log data to perform complex tasks of multi-zone.
- Multi-well petrophysical analyses.
- Structural and Stratigraphic analysis and interpretation of reservoirs.

It is difficult to predict the occurrence and distribution of reservoir sandstone into the undrilled deep parts of frontier basins. Challenges stem from the fact that all deepwater clastic depositional systems are unique in time and space. Successful screening for deep-marine reservoirs is dependent on three key factors: (1) an awareness of their variability, (2) assessment of the range of depositional attributes in different systems, and (3) recognition that their lithological character is linked fundamentally to sedimentary provenance (Richards et al., 1998).

Thus, because deep-water reservoirs tend to be highly variable in geometry, size, and internal character, geometries derived from seismic mapping and attribute analysis alone commonly fail to give an adequate basis for a correct risk analysis of the reservoir.

It was therefore important for us to bridge this knowledge-gap by using the analyses and interpretation of well logs and core.

Information that helps in predicting reservoir quality is commonly embedded in the seismic response of the sediments and the challenge for seismic analysis, therefore, is the proper interpretation of these seismic responses (Fugelli and Olsen, 2005).

1.5 General Overview of Deepwater Systems

Deep water is a complex, high-risk environment, with no shortcuts to success. Formidable risks must be addressed and mitigated to meet deepwater objectives. Critical decisions require both breadth of global experience and depth of knowledge—to reduce uncertainties and minimize both timescales and costs. It is therefore of utmost importance to have an understanding of deepwater systems.

1.5.1 Petroleum Systems of Deepwater settings

- Deepwater Systems: Definitions and Concepts

Definitions of Deepwater systems

Geoscientists routinely use several terms to describe the sedimentary processes and characteristics of deepwater settings and deposits. For the sake of consistency, Weimer and Slatt, 2004, define them as follows:

First, deepwater deposits refer to sediments deposited in water depths considered to be “deep”, i.e., those under gravity flow processes and located somewhere in the upper- to middle-slope region of a basin. So, unless stated otherwise, they use deepwater systems to refer to marine-sediment gravity flow processes, environments, and deposits. Other authors use slightly different terms for describing them e.g. Turbidite systems (Mutti and Normark, 1987, 1991), turbidite system complex (Stelting et al., 2000), and Submarine fans (Bouma et al., 1985).

Second, the engineering definition of deep water refers to modern water depths- specifically, to depths greater than 500m. These are water depths from 500 to 2000m. That is the water depth at which traditional development rigs cannot be implemented. Ultra deep water is any water deeper than 2000m.

1.5.2 Common Deepwater Elements and Terminology

In August 1982, a group of leading deepwater experts met in Pittsburgh, Pennsylvania, for what was termed the COMFan I conference (COMFan = COMmittee on FANs). The meeting produced the consensus that it was extremely difficult to compare the modern submarine fans studied on the modern ocean floor with ancient ones studied primarily in outcrop (Bouma et al., 1985). There was therefore a need to develop a common language used by different workers in the field. Weimer and Slatt, 2004, propose that although many classifications have been proposed for deep water systems that link disparate data sets, three groups of studies were influential in defining terminologies that industry geoscientists now use routinely: (1) Mutti and Normark (1987, 1991); (2) Chapin et al., 1994, and Mahaffie, 1994; and (3) Reading and Richards, 1994; Richards et al., 1998; and Richards and Bowman, 1998.

These classifications focused on the kinds of *reservoir elements, their architecture and geometry, and related deposits.*

Mutti and Normark (1987, 1991) identified five elements common to modern and ancient turbidite systems: channels, overbank, lobes (sheets), channel-lobe transition and erosional features.

Chapin et al., 1994, and Mahaffie, 1994, presented a reservoir classification developed by Shell Oil Company during their deepwater discoveries in the northern Gulf of Mexico and emphasized three main sand-bearing reservoir elements: sheets (layered and amalgamated), channels (single and multi-storey), and thin beds comprising levees.

Richards et al., 1998, identified five architectural elements common to all turbidite systems: wedges, channels (including chutes, and braided and leveed channels), lobes, sheets and slides.

Elliot, 1998, proposed three additional elements common to modern and ancient deepwater systems: mass transport complexes, condensed sections and slides.

1.5.3 Sequence Stratigraphic Expressions of Key Surfaces and Intervals

Two key intervals/surfaces are present in deepwater systems: *condensed sections* and *sequence boundaries*. These intervals and surfaces have been defined by integrating observations from modern and ancient turbidite systems, as derived from 2D and 3D seismic data, wireline logs, biostratigraphic data, reservoir pressure data, and outcrops (Weimer and Slatt, 2004).

Condensed sections are relatively thin layers of strata that reflect reduced sedimentation rates (Loutit et al., 1988). In deepwater systems, they can form during

- relative highstands of sea level
- a major switch in the shallow marine development or
- a regional subsidence event with reduced rates of sedimentation

On seismic profiles, a condensed section exhibits a laterally continuous reflection that drapes the underlying sequence (Weimer and Slatt, 2004). The seismic stratigraphic expression will differ depending on its thickness and the frequency of the seismic data while the lithologic expression varies greatly within and between basins reflecting different depositional conditions at the time it was formed.

Sequence boundaries have both erosional and conformable stratigraphic expressions in deepwater. Where the sequence boundary is erosional, the condensed section and additional sediments are removed from the underlying sequence. Generally, the greatest amount of erosion occurs in submarine canyons in the upper slope/outer shelf, where the largest volume of sediment is removed. In most places, the erosional sequence boundary can be traced laterally to a point where the erosion surface ends and grades into a depositional surface directly overlying the condensed sections.

1.5.4 Regional Controls on Deepwater systems

To properly interpret reservoir characteristics such as sand content, sand trend, continuity, connectivity, and reservoir quality, we must be cognizant of the processes by which these deposits formed.

The three main influences that control the nature of deepwater depositional systems are *tectonics, sediment supply* and *sea-level fluctuations* (Richards et al., 1998) as can be seen on Figure 1.8 below.

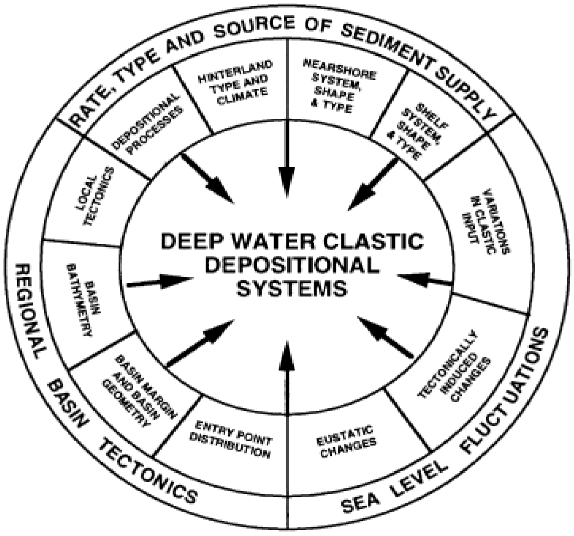


Figure 1.8: Controls on the development of deep marine clastic systems. The genesis of deep marine clastic systems represents the end product of a complex interplay between a variety of autocyclic and allocyclic controls. The controls are rarely mutually exclusive but commonly interdependent leading to a wide range of deep marine clastic deposits. After Richards et al., 1998.

1.5.5 Petroleum Geology of deepwater basins

Worrall et al., 2001, divided the global deepwater play into four broad types:

- Basins with mobile substrates (salt, shale) fed by large rivers
- Basins with mobile substrates fed by small rivers
- Basins with non mobile substrates fed by small rivers
- Basins containing non deep water reservoirs.

1.5.5.1 Petroleum systems of deepwater basins

The six main elements of a petroleum system are: reservoir, traps, seals, source rocks, generation, migration and timing.

As at 2004, most deepwater reservoirs were Cenozoic in age though there is a modest but growing contribution from Cretaceous reservoirs. Porosity and permeability in deepwater reservoirs can be excellent (>30% porosity and thousands of millidarcys permeability) because many are fed from mature river systems that drain stable cratons (Weimer and Slatt, 2004). The high porosities are maintained by low geothermal gradients. Reservoir architecture (connectivity and continuity) ranges from poor to excellent.

Trap styles vary but a significant proportion of resources are from fields having a stratigraphic component.

Adequate top seals are generally present in deepwater environments, though their integrity is often a serious risk because of overpressures and crestal faulting.

Source rock potential is good with world-class source rocks found in Jurassic, Cretaceous and Tertiary strata.

Because source rocks in most of the major producing regions have become mature only recently, timing is often a lower risk in deep water. Migration routes into traps are often straightforward via adjacent depocentres and faults (Weimer and Slatt, 2004).

1.5.6 Critical geologic success factors in deepwater basins

Four critical factors have been identified for successful exploration and development in deepwater settings (Worrall et al., 2001).

- Multiple large traps in an area tend to lead to the discovery and development of multiple fields with multiple reservoirs.
- High-rate, high-ultimate recovery (HRHU) reservoirs are necessary for economic development in deepwater.
- A working charge system is required with the following components: source rocks with good potential, late generation, and clear migration pathways.
- Multiple play concepts targeting different trapping styles are necessary for drilling and testing different kinds of plays.

1.6 Sequence Stratigraphy

Sequence stratigraphy is the most recent and revolutionary paradigm in the field of sedimentary geology and completely revamps geological thinking and the methods of stratigraphic analysis (Catuneanu, 2002). He further highlights that as opposed to the other, more conventional types of stratigraphy, such as biostratigraphy, lithostratigraphy, chemostratigraphy or magnetostratigraphy, which are mostly concerned with data collection, sequence stratigraphy has an important built-in interpretation component which addresses issues such as (i) the reconstruction of the allogenic controls at the time of sedimentation, and (ii) predictions of facies architecture in yet unexplored areas. The former issue sparked an intense debate, still ongoing, between the supporters of eustatic versus tectonic controls on sedimentation, which is highly important to the understanding of Earth history and the fundamental Earth processes. The latter issue provides the petroleum industry community with a new and powerful analytical and correlation tool for exploration and basin analysis.

The focus in this research was on the latter aspect above.

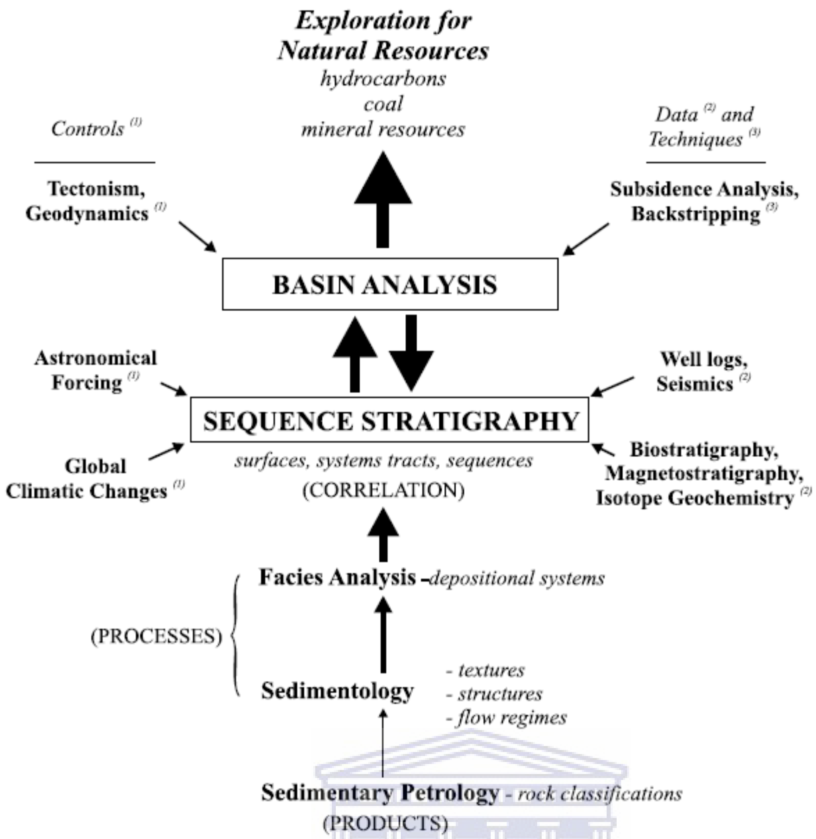
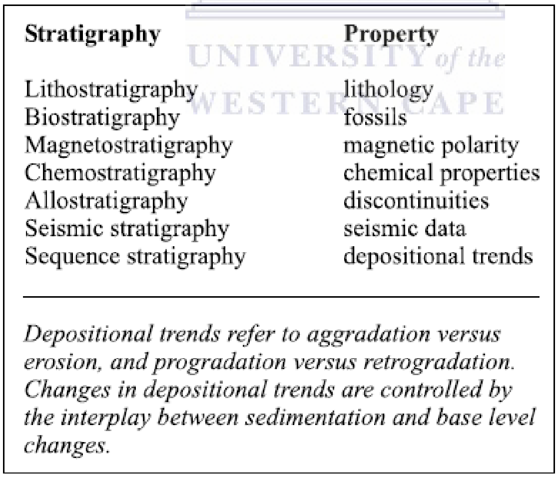


Figure 1.9: Sequence stratigraphy in the context of interdisciplinary research (Catuneanu, 2002)



Stratigraphy	Property
Lithostratigraphy	lithology
Biostratigraphy	fossils
Magnetostratigraphy	magnetic polarity
Chemostratigraphy	chemical properties
Allostratigraphy	discontinuities
Seismic stratigraphy	seismic data
Sequence stratigraphy	depositional trends

Depositional trends refer to aggradation versus erosion, and progradation versus retrogradation. Changes in depositional trends are controlled by the interplay between sedimentation and base level changes.

Figure 1.10: Type of stratigraphy, defined on the basis of the property they analyze (Catuneanu, 2002).

The term ‘‘sequence’’ was introduced by Sloss et al., 1949, to designate a stratigraphic unit bounded by subaerial unconformities. Sloss emphasized the importance of such sequence-bounding unconformities and subsequently subdivided the entire Phanerozoic succession of the interior craton of North America into six major sequences (Sloss, 1963). Sloss also emphasized the importance of tectonism in the generation of sequences and bounding unconformities, an idea which is widely accepted today but was largely ignored by the proponents of seismic stratigraphy (Catuneanu, 2002).

Seismic stratigraphy emerged in the 1970s with the work of Vail, 1975, and Vail et al., 1977. This new method for analyzing seismic-reflection data stimulated a revolution in stratigraphy, with an impact on the geological community as important as the introduction of the flow regime concept in the late 1950s–early 1960s and the plate tectonics theory in the 1960s (Miall, 1995). The concepts of seismic stratigraphy were published together with the global cycle chart (Vail et al., 1977), based on the underlying assumption that eustasy is the main driving force behind sequence formation at all levels of stratigraphic cyclicity.

Seismic stratigraphy and the global cycle chart were thus introduced to the geological community as an inseparable package of new stratigraphic methodology (Catuneanu, 2002). These ideas were then passed on to sequence stratigraphy in its early years, as seismic stratigraphy evolved into sequence stratigraphy with the incorporation of outcrop and well data (Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990).

1.6.1 Definition and key concepts of sequence stratigraphy

Sequence stratigraphy (Posamentier et al., 1988; Van Wagoner, 1995): the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition, or their correlative conformities.

- "*time framework": in the early days of sequence stratigraphy, the bounding surfaces were taken as time lines, in the view of the global-eustasy model. Today, independent time control is necessary for large scale correlations;*
- *"genetically related strata": no major hiatuses are assumed within a sequence.*

Depositional systems (Fisher and McGowan, 1967, in Van Wagoner, 1995): three-dimensional assemblages of lithofacies genetically linked by active (modern) processes or inferred (ancient) processes and environments.

- *depositional systems represent the sedimentary product of associated depositional environments. They grade laterally into coeval systems, forming logical associations of paleo-geomorphic elements (cf., systems tracts).*

Systems tract (Brown and Fisher, 1977): a linkage or contemporaneous depositional systems, forming the subdivision of a sequence.

- *systems tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces. The timing of systems tracts is inferred relative to a curve that describes the base level fluctuations at the shoreline.*

The concept of systems tract was introduced to define a linkage of contemporaneous depositional systems (Brown and Fisher, 1977), which form the subdivision of a sequence. Systems tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces, and are assigned particular positions along an inferred curve of base level changes at the shoreline (Figure 1.11)

The early Exxon sequence model includes four systems tracts; the lowstand, transgressive, highstand, and shelf-margin systems tracts (Catuneanu, 2002).

The *lowstand systems tract* is bounded by the subaerial unconformity and its marine correlative conformity at the base and by the maximum regressive surface at the top. It forms during the early stage of base level rise when the rate of rise is outpaced by the sedimentation rate (case of normal regression). The lowstand systems tract includes the coarsest sediment fraction of both marine and non marine sections, i.e. the upper part of an upward-coarsening profile in a marine succession and the lower part of a fining-upward profile in non marine strata (Catuneanu, 2002).

The *transgressive systems tract* is bounded by the maximum regressive surface at the base, and by the maximum flooding surface at the top. It can be recognized from the diagnostic retrogradational stacking patterns, which result in overall fining-upward profiles within both marine and non marine successions (Catuneanu, 2002).

Catuneanu, 2002, goes further to define *highstand systems tract* as bounded by the maximum flooding surface at the base, and by a composite surface at the top that includes the subaerial unconformity, the regressive surface of marine erosion, and the basal surface of forced regression.

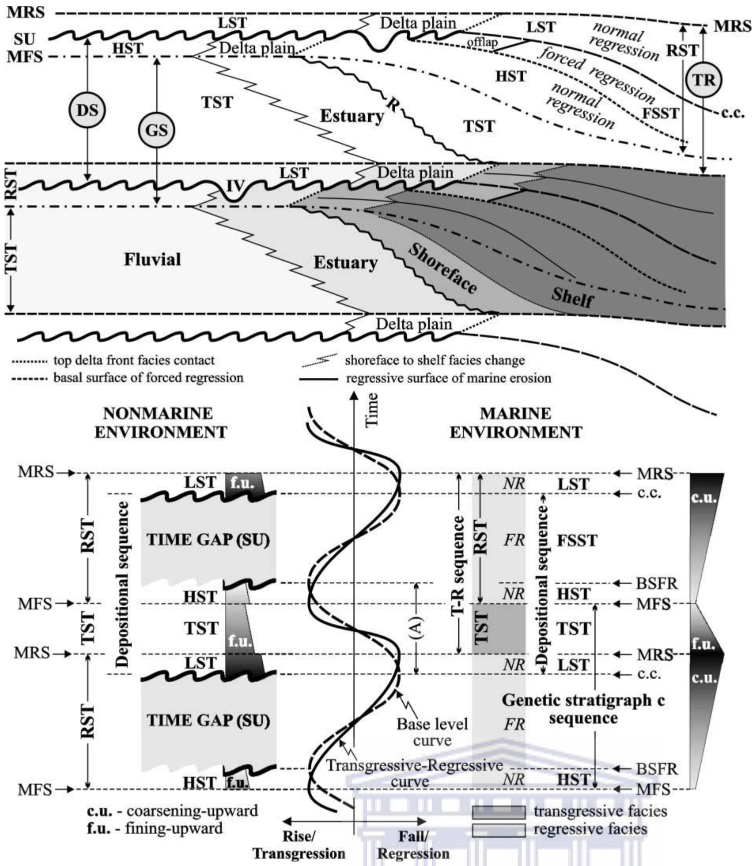


Figure 1.11: Sequences, systems tracts, and stratigraphic surfaces defined in relation to the base level and the T–R curves. Abbreviations: SU—subaerial unconformity; c.c.—correlative conformity; BSFR—basal surface of forced regression; MRS—maximum regressive surface; MFS—maximum flooding surface; R—ravinement surface; IV—incised valley; (A)—positive accommodation (base level rise); NR—normal regression; FR—forced regression; LST—lowstand systems tract; TST—transgressive systems tract; HST—highstand systems tract; FSST—falling stage systems tract; RST—regressive systems tract; DS—depositional sequence; GS—genetic stratigraphic sequence; TR—transgressive–regressive sequence (Catuneanu, 2002)

Sequence (Mitchum, 1977): a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities.

- Sequences and systems tracts are bounded by key stratigraphic surfaces that signify specific events in the depositional history of the basin. Such surfaces maybe conformable or unconformable, and mark changes in the sedimentation regime across the boundary.

- Sequences correspond to full stratigraphic cycles of changing depositional trends. The conformable or unconformable character of the bounding surfaces is not an issue in the process of sequence delineation, nor the degree of preservation of the sequence.

Sequence models

Methods of sequence delineation

Five sequence stratigraphic models are currently in use, all stemming from the original depositional sequence of seismic stratigraphy (Figure 1.12). These models may be grouped into two main categories: one group defines the sequence boundaries relative to the base level curve (depositional sequences II, III, and IV in Figure 1.12) whereas the other group defines the sequence boundaries relative to the T–R curve (genetic and T–R sequences in Figure 1.12).

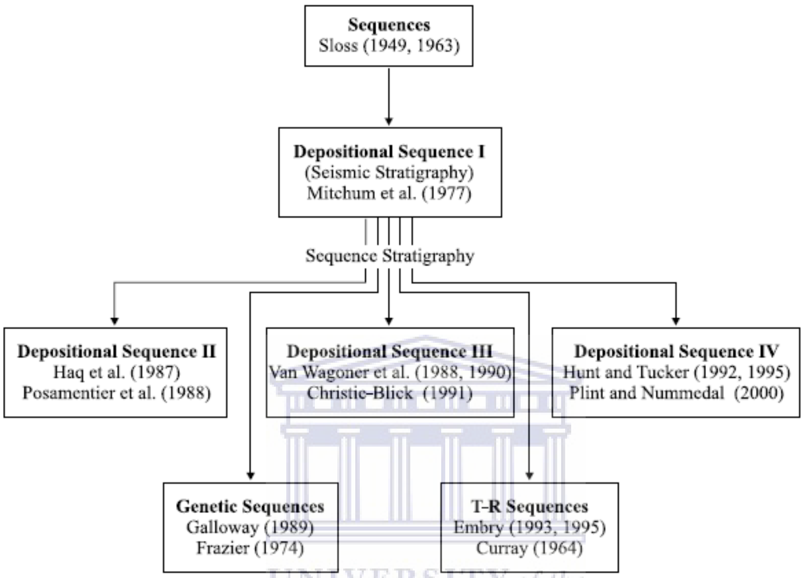


Figure 1.12: Family tree of sequence stratigraphy (modified from Donovan (2001)). The various sequence stratigraphic models mainly differ in the style of conceptual packaging of strata into sequences, i.e. with respect to where the sequence boundaries are picked.

The diversity of sequence models that are currently in use (Figure 1.12) may in part be attributed to the fact that their proponents draw their own research experience from different types of basins (Catuneanu, 2002). Hence, each model is designed to fit the field observations from a particular tectonic setting. For example, the models of Posamentier et al., 1988, and Galloway, 1989, describe a divergent continental margin, Van Wagoner and Bertram, 1995, as well as Plint and Nummedal, 2000, refer to foreland basin deposits, whereas Embry, 1995, proposed a T–R sequence model based on the study of the Sverdrup rift basin (Failed rift on continental margin superimposed on megasuture, evolving to a confined passive margin-type- http://www.ainc-inac.gc.ca/).

All sequence models have merits and limitations, and work best in the tectonic setting for which there were designed. Careful analysis and a thorough understanding of all controls on sedimentation are thus required when doing sequence stratigraphic interpretations, as opposed to a dogmatic application of rigid theoretical models (Catuneanu, 2002).

The models of Posamentier et al., 1988, and Galloway, 1989, which describe a divergent continental margin was the underlining model in this research.

1.7 Rationale: Why Sequence Stratigraphy?

The development of modern sequence stratigraphy has revitalized the science of stratigraphy, and has therefore been characterized as the third revolution in sedimentary geology, the development of process-response models and of plate tectonics being considered the first two such revolutions (Miall, 1995).

Sequence stratigraphy has become a practical tool in petroleum exploration and reservoir characterization. Sequence stratigraphic analysis has been claimed to be a predictive method in finding reservoir and source rocks, as well as in characterization of rock heterogeneities on reservoir scale (Gradstein et al., 1998).

“No exploration technique flawlessly locates a potential reservoir, but sequence stratigraphy may come close”. A close look at systems tracts, their geometries and lithologies shows how sequence stratigraphy can be used to foretell reservoir location and quality. As more people learn the technique of sequence stratigraphy, it will become an exploration tool for constraining the shape, extent and continuity of reservoirs (Neal et al., 1993).

1.8 Terrigenous Slope and Basin Systems

Slope and basin systems originate in relatively deep water beyond the shelf break (Galloway and Hobday, 2000).

The modern slope commences at the shelf break between 150 and 1000 ft (45 – 300 m) below sea level and is typically inclined at 1 to 3 degrees, locally approaching 10 degrees. This geometry varies according to tectonic setting, progradational history, and erosional modification (Galloway and Hobday, 2000).

Continental rises and slopes represent the new frontier of offshore oil exploration, yet they remain one of the least understood parts of the earth (Heezen, 1974).

They constitute a vast area exceeding all of the onshore sedimentary basins, with ancient slope and basin systems providing the ideal relationship between hydrocarbon rich source rocks and sandy reservoir rocks, with most reservoir units draped with muddy seals deposited during temporary cessation in aggradatation (Galloway and Hobday, 2000).

Subaqueous slope systems are characterized by the dominance of gravity mass-transport and density underflow processes and their depositional products (Galloway and Hobday, 2000).

1.8.1 Gravity Flows

Gravity mass transport ranges from discrete free-falling masses, or olistoliths, to slow-moving, dilute, muddy suspensions or nepheloid layers Figure 1.13 (Galloway and Hobday, 2000).

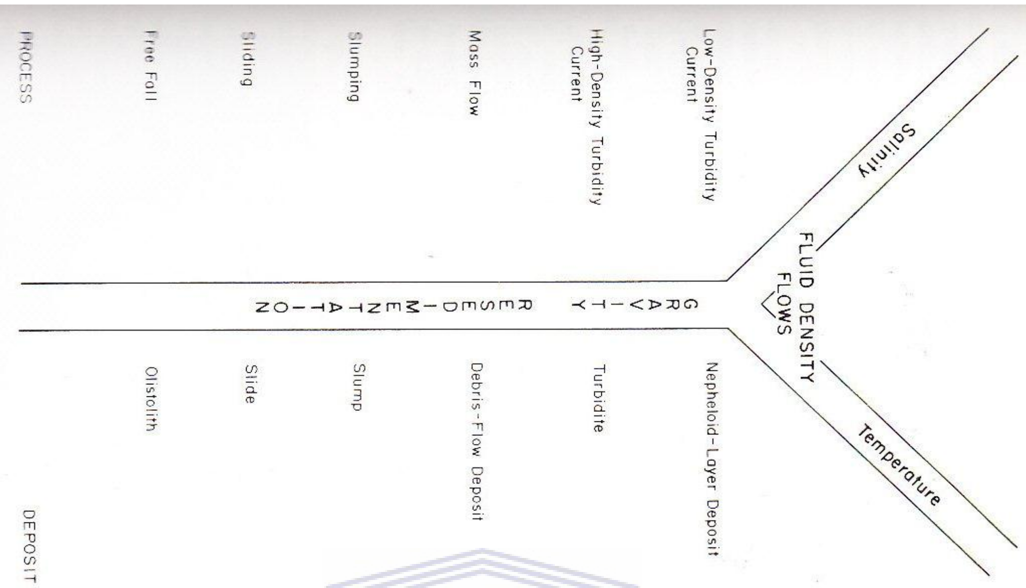


Figure 1.13.: Schematic family tree of submarine slope processes produced from conversion of gravitational potential to kinetic energy. (After Galloway and Hobday, 2000).

Downslope movement occurs when the gravity shear stress exceeds the shear strength of the sediment, a function of intergranular friction and cohesion (Rupke, 1978).

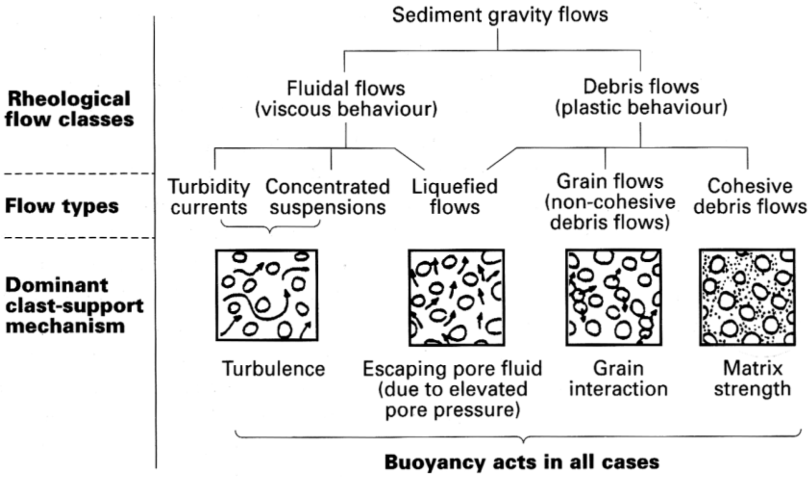


Figure 1.14: Sediment gravity flows - Stow et al., in Reading 1996, modified from Middleton and Hampton, 1976)

Turbidites are volumetrically the dominant slope and basin facies by far and alone may constitute as much as 45 percent of the total volume of all sedimentary rocks (Walker, 1980).

Turbidity currents in oceans are usually catastrophic surges (Middleton and Hampton, 1976) resulting from excess density imparted to sea water by the mass of suspended sediment (Galloway and Hobday, 2000).

The “margin affected basins” (Gorsline, 1980) subject to terrigenous clastic influx may be divided into three distinct but interrelated morphogenic types: submarine aprons, submarine rise prisms, and submarine fans. In this study, our focus was on submarine fans.

Fans are fed from point sources, either river mouths or submarine canyons, and receive the bulk of their sediments from turbidity currents and are therefore located at the mouths of submarine canyons, off deltas, and in deep-basin plains (Galloway and Hobday, 2000).

Upper-fan channels or canyons serve as sediment conduits with coarsest sediments accumulating in the thalweg of the upper fan channels and occasionally spills out across the flanking levees and terraces, which are normally the site of fine sediment deposition in thin graded units (Galloway and Hobday, 2000).

The mid fan of sand rich systems is characterised by shifting suprafan lobes (Normark, 1970).

The lower fan has a smooth, gently sloping surface and receives slowly deposited increments of suspended sediment punctuated by pulses of fine-grained turbidites. The resulting graded beds are thin, laterally persistent, and monotonously superimposed, commonly through considerable stratigraphic thickness (Galloway and Hobday, 2000).

CHAPTER TWO
GEOLOGICAL OVERVIEW OF THE SOUTHERN OUTENIQUA BASIN

South Africa is a large country. Its land is more than 1.1 million sq km and its coastline has a total length of nearly 3000 km. The west coast from the Orange River to Cape Point is almost 900km long and the remainder, from Cape Point to the Mozambique border, is more than 2000 km long (Petroleum Agency SA Brochure, 2008).

Sedimentary environments can be classified as below:

- Continental environments: Alluvial fan, fluvial, lacustrine, desert and paludal sediments.
- Transitional environments: Delta, barrier beach, lagoon and tidal flat sediments.
- Marine environments: Reef, continental shelf, continental slope and rise, and abyssal plain.

The continental slope connects the shelf area with the deep marine environment. It follows a similar trend in width and fairly wide on the west and south coast but becomes narrower to the eastern coast (Figure 2.1). On the South African coast, the continental shelf is 20-160 km wide off the west coast, 50-200 km wide off the south coast, but rarely more than 30km on the east coast except along the Durban basin. Similarly the continental slope is fairly wide on the west and south coasts but narrow to the east (Petroleum Agency SA Brochure, 2008).

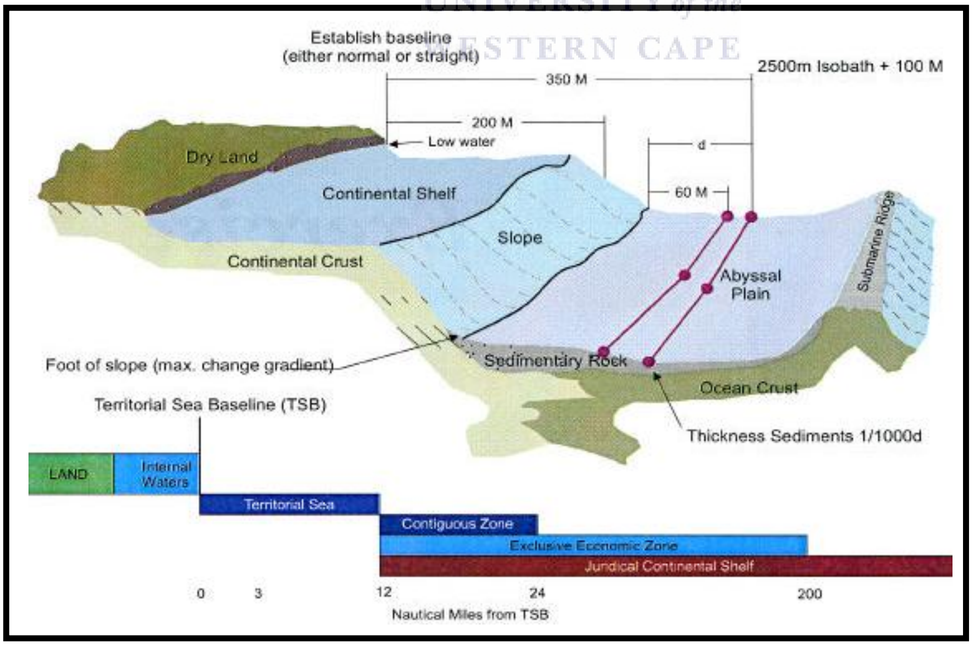


Figure 2.1: South Africa continental margin and oceanic crust (modified from Broad, 2004)

2.1 Offshore Basins

Exploration for oil and gas has been conducted for more than 40 years (since 1968) offshore South Africa. There is production of gas and more modest production of oil, from the Bredasdorp Basin.

While production is currently limited to that basin, there have been discoveries and shows in all the other basins offshore. Deep water remains unexplored, stimulating expectations of future commercial discoveries and further production.

There are three major basins offshore South Africa, corresponding roughly to the west, south and east coasts. These are the Orange, Outeniqua and Durban basins respectively. The Outeniqua Basin, to the south of the country, is made up of a number of inner sub-basins, viz: The Bredasdorp, Pletmos, Gamtoos and Algoa basins, and a large outboard basin, *the Southern Outeniqua Basin*.

South Africa's offshore basins have been divided into three distinct tectonostratigraphic zones: western, southern and eastern offshore (Petroleum Agency SA Handbook, 2004/2005). These basins developed in the Permo-Triassic -Jurassic period or earlier. A narrow passive margin describes the eastern offshore. It is a part of the East African Rift system which was formed as a result of the breakup of Africa, Madagascar and Antarctica in the Jurassic (Figure 2.7). Unlike the western and southern margin, this zone has limited deposition with only the Durban and Zululand basins containing an appreciable sedimentary succession. The western zone known as the Orange Basin is a divergent plate margin with graben structures trending sub parallel to the coast line (Jikelo, 1999). It is related to the opening of the South Atlantic in the Early Cretaceous.

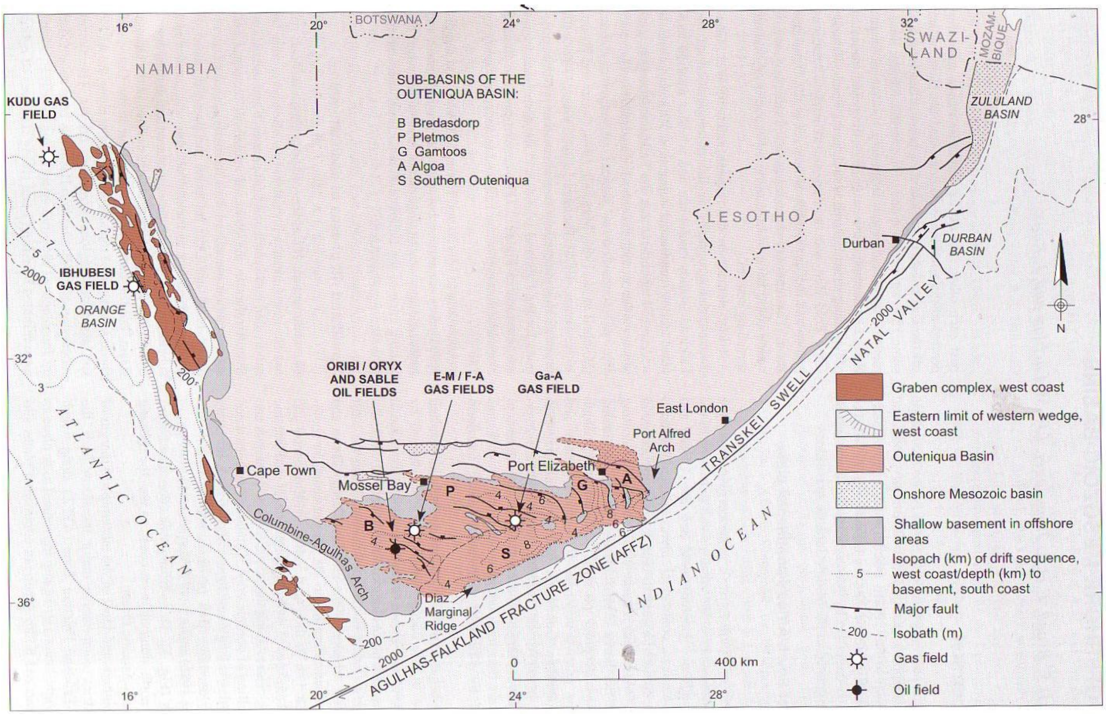


Figure 2.2: Onshore and offshore South African Mesozoic basins (From Broad et al., 2006)

The southern margin, known as the Outeniqua Basin, is basically an interplay of pull-apart basins and transform margins. The Bredasdorp, Pletmos, Gamtoos and Algoa basins are the sub-basins of the Outeniquia Basin (Figure 2.3).

2.2 The south coast offshore basin (Outeniqua) and adjacent onshore basins

Situated off the southern tip of Africa, the Outeniqua Basin is bounded to the west by the Columbine-Agulhas Arch, to the east by the Port Alfred Arch and to the South by the Diaz Marginal Ridge (Figure 2.2). The Diaz Marginal Ridge is a non-magnetic basement feature of probable continental origin, which trends sub parallel to, and is truncated by the Agulhas Falkland Fracture Zone (AFFZ) (Ben-Avraham et al., 1993, 1997). Onlap of seismic reflectors onto the basinal side of the ridge suggests that it was a positive feature during synrift as well as drift sedimentation, and thus pre-dates continental separation and movement on the Agulhas-Falkland Fracture Zone (AFFZ) (Broad et al, 2006).

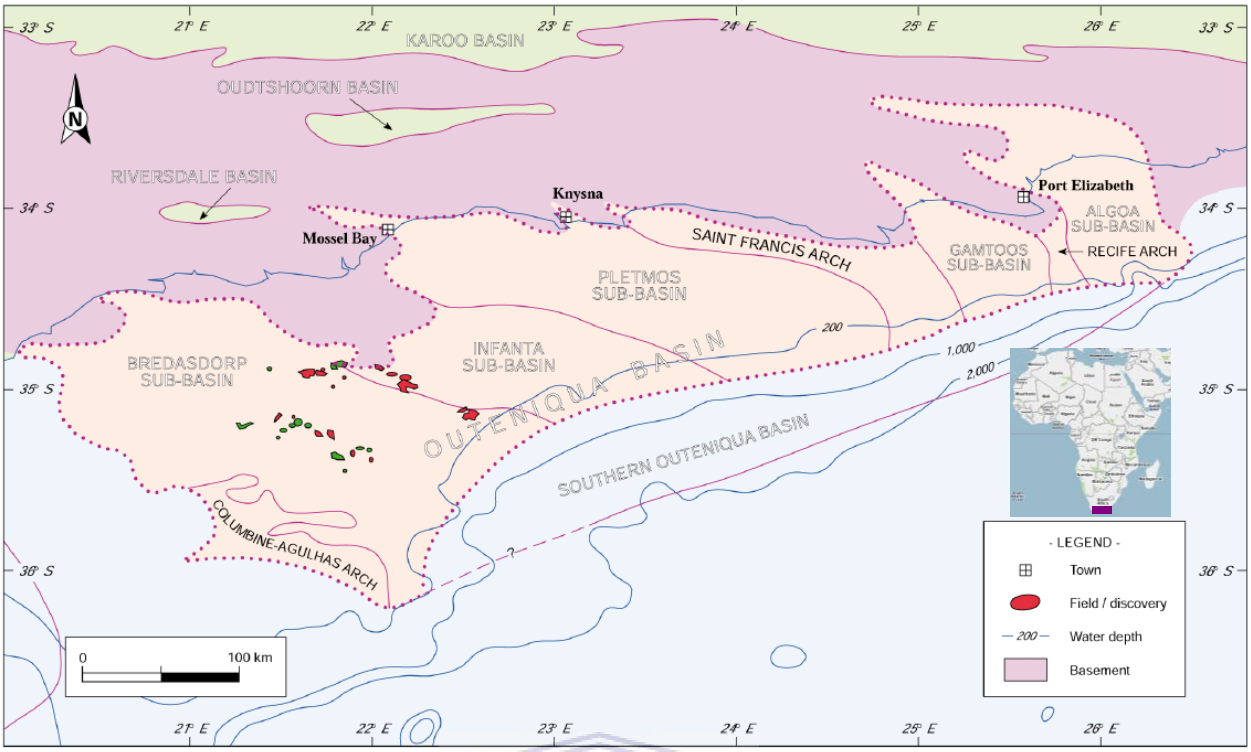


Figure 2.3: Basin location map- Outeniqua basin and Southern Outeniqua Basin (After IHS basin Monitor report, 2010)

The Outeniqua Basin comprises a series of rift sub basins named, from west to east: the Bredasdorp, Pletmos, Gamtoos and Algoa sub- basins which are separated by fault-bounded basement arches composed of Ordovician to Devonian metasediments of the Cape Supergroup (Figure 2.3). The arcuate trend of the basin-bounding fault system is most likely inherited from the underlying orogenic Cape Fold Belt (De Swardt and McLachlan, 1982).

Southwards, these sub-basins merge into the deepwater Southern Outeniqua basin. It is the distal extension of the northern sub-basins below the 300m isobath. In this area Mesozoic sediments attain a thickness of about 8000m (Broad et al., 2006). SOEKOR (1994b) refers to all these basins collectively as the Outeniqua basin.

The Bredasdorp Basin is the most south westerly of the southern African offshore basins and is delimited by the Infanta arch in the north and by the Agulhas Arch in the south. These arches are basement highs comprising Cape Supergroup sediments, granite and Precambrian metamorphic rock (Van der Merwe and Fouché, 1992). The regional geology of the Bredasdorp basin is dominated by the east-west branch of the Permo-Triassic Cape Fold Belt to the north and by the Lower-Cretaceous Agulhas-Falkland Fracture Zone (AFFZ) to the south east. Currently the AFFZ forms a boundary between continental and oceanic crust (Van der Merwe and Fouché, 1992). Basin forming rifting was the result of the separation of East and West

Gondwanaland which resulted in the negative inversion of Cape Fold Belt thrust faults (Hälbich, 1983). According to Van der Merwe and Fouché, 1992, the post rift stage of basin evolution took place during the separation of Africa and South America (i.e. the break-up of West Gondwana). The syn-rift sedimentary sequence is composed of fluvial and shallow-marine sediments while the post-rift sequence is dominated by deep-marine sediments. Existing models of basin evolution (e.g. Du Toit 1976, 1979) regard the Bredasdorp basin as having formed in response to a single rifting event. According to these models tectonism ceased after rifting and the subsequent basin development was purely related to thermal subsidence. No late extension or compression has been described.

The Algoa, Gamtoos and Pletmos Basins are Mesozoic half grabens also situated on the southern continental shelf of South Africa. The breakup of Gondwana in the Middle to Late Jurassic induced extensional stresses which reactivated Late Precambrian and Palaeozoic tectonic lineaments. Active rifting along these re-activated structures resulted in the formation of Mesozoic depocentres. Varying rates of movement along the basin-bounding faults led to the development of several tectonostratigraphic packages. Initial rapid subsidence outstripped deposition leading to the formation of a divergent wedge. Following this, the decelerated faulting allowed deposition to keep pace with subsidence, producing a more conformable sequence. Later, tilting and acceleration of faulting resulted in the formation of a divergent wedge dipping at a high angle to the previous two packages. Rifting ceased in the Valanginian with the formation of the rift-drift unconformity marking a change to thermal subsidence with the Pletmos basin experiencing accelerated subsidence relative to the Algoa and Gamtoos basins (Bate and Malan, 1992).

The Algoa, Gamtoos and Pletmos Basins are eastern sub-basins of the Outeniqua. These Mesozoic half-grabens, with areas of respectively 8,200km^2, 5,000km^2, and 12,500km^2 are filled with up to 10km of synrift and 4km of postrift sediments (Bate and Malan, 1992). Negative inversion along Late Proterozoic and Palaeozoic thrust zones in the Late Jurassic, resulted in the creation of the basin boundary faults zones, namely the St. Croix, Port Elizabeth, Gamtoos and Plettenberg Faults (cf Nicolayson, 1986; De Wit and Ransome 1991; Greese et al., 1992).

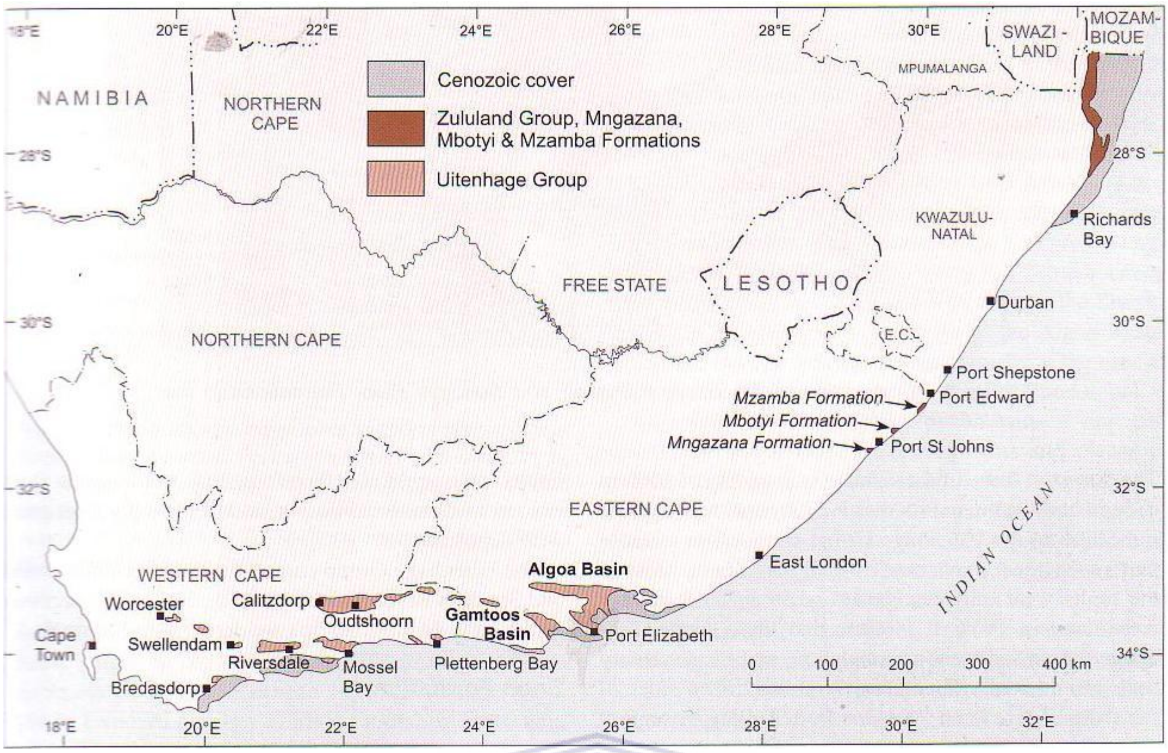


Figure 2.4: Distribution of Jurassic and Cretaceous strata in the South coast of South Africa. (After Shone, 2006).

2.3 Stratigraphic nomenclature

During the course of exploration Soekor (now PetroSA), the state oil company founded in 1965, developed a stratigraphic nomenclature for the sedimentary successions encountered offshore and has given names to various structural elements such as basins, sub-basins, structural highs and faults(PASA, 2008).

Current stratigraphic nomenclature reflects a committed sequence stratigraphic approach based on the seismic recognition of multiple unconformities within the drift successions. Sequences initially defined by significant unconformities, as recognised on seismic sections, were assigned numbers (1 to 22) (Brown et al., 1995). Third and higher order sequences, composite sequences and sequence sets recognised subsequently were designated by letters (A, B, C etc.). Unconformities are designated by the sequence overlying them (e.g. 1A, 4B etc) and by their nature (type 1 = t1 etc), as illustrated in the Chronostratigraphic chart (Figure 2.5).

2.3.1 Stratigraphy of the Outeniqua Basin

Six second-order tectonically enhanced unconformities were recognised in the drift sequences of the southern offshore by extensive seismic surveys and drilling (SOEKOR 1994b) (Figure 2.5).

Unconformity 6At1 marks the end of half-graben infilling and the beginning of prograding shelf deposition. Severe erosion occurred at 6At1, in places down to 1At1 in the Gamtoos and Algoa basins. Restricted marine conditions prevailed until Mid-Aptian times (13At1), which marks the beginning of open marine conditions across the entire Outeniqua Basin and free connection with the Atlantic and Indian Oceans (Visser, 1998). According to him, drift sedimentation, influenced by thermal subsidence, tectonic events and eustatic sea-level changes, is characterised by repeated episodes of progradational and aggradational deposition.

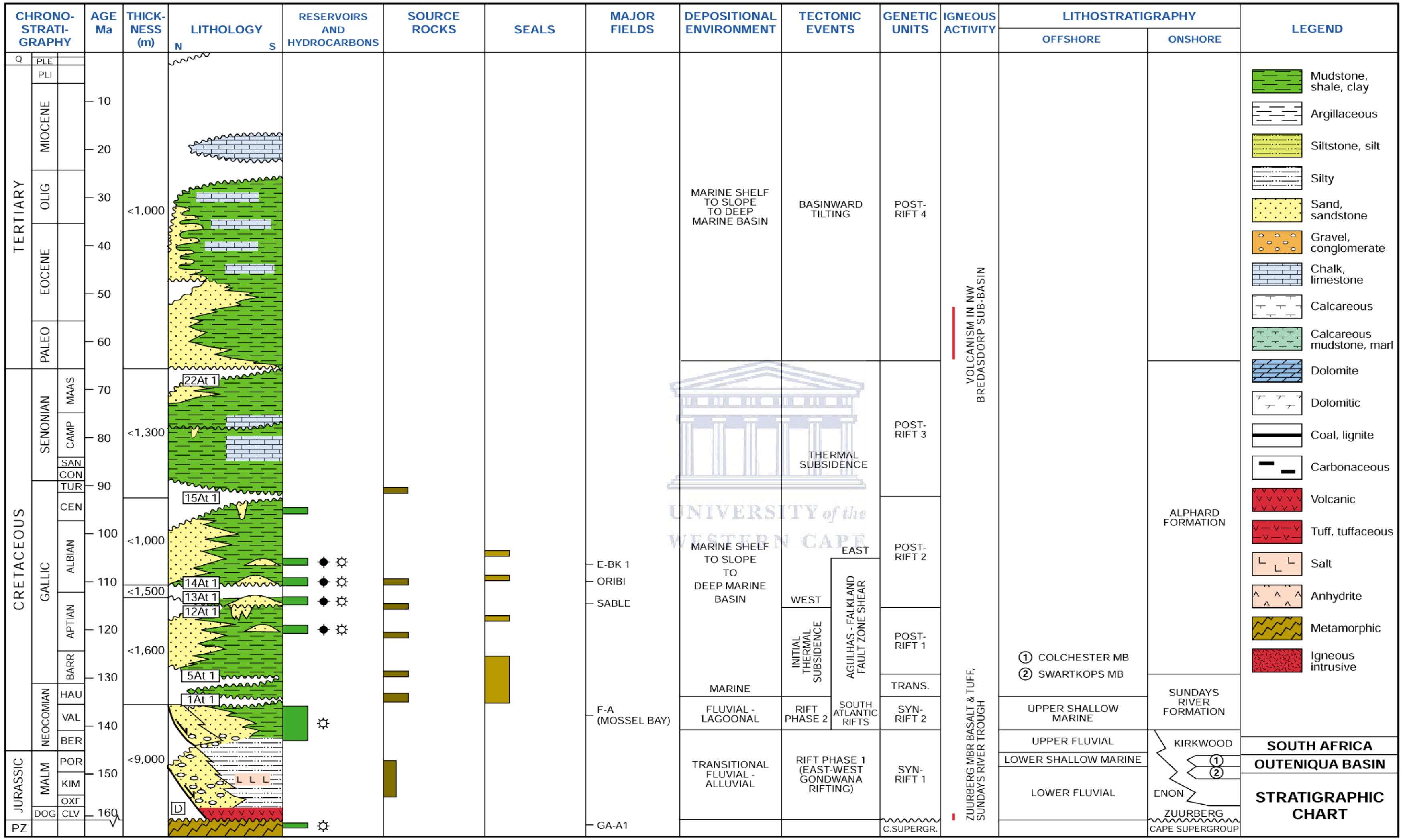


Figure 2.5 Stratigraphy of the Outeniqua Basin (After IHS basin Monitor report, 2010)

2.4 Study area: The Southern Outeniqua Basin and the adjacent Pletmos Basin

The Outeniqua Basin is a largely offshore basin located off the south coast of South Africa. The basin extends onshore in a few places, mainly near Port Elizabeth. As earlier said, it comprises a number of northwest-southeast trending en-echelon sub-basins and interbasinal highs; the main sub-basins are (from west to east) the Bredasdorp, Infanta, Pletmos, Gamtoos and Algoa sub-basins (IHS, 2010).
To the south, the northwest-southeast shallow water fault trend (F3 splay; Jones, 2000) separates the Outeniqua from the Southern Outeniqua Basin.

The combined four sub basins (Bredasdorp, Pletmos/Infanta, Gamtoos, and Algoa) and their contiguous deepwater extension, referred to as the Southern Outeniqua basin, form a large intracratonic rift basin, the Outeniqua basin. This basin developed during the middle to late Jurassic, before the separation of east and west Gondwana, and extended onto what is known today as the Falkland plateau (Roux, 1997).

The Southern Outeniqua basin is situated off the south coast of South Africa within blocks 11 to 13. The area of study for this research was block 11b/12b.

This basin consists of the south-eastern deepwater extensions of the Bredasdorp basin, Gamtoos, Algoa basins, and Pletmos basins (beyond the 300 m isobath). In the absence of well data, the geology of the Southern Outeniqua sub-basin is inferred from sparse seismic coverage and extrapolation from well control in the northern sub-basins (Broad et al., 2006) such as the Pletmos.

Interpretation of a few seismic lines, which extend as far as the Diaz Marginal Ridge, indicates the presence of a complete succession of synrift and drift sequences (Roux, 1997; Ben-Avraham et al., 1997).

2.4.1 The Pletmos Basin

The Pletmos sub-basin, which covers approximately 18 000 km^2, is the offshore extension of a series of small basins extending from Worcester through Robertson, Swellendam, Heidelberg and Mossel Bay (Visser, 1998). Sediment thickness in the Pletmos sub-basin is up to 11 000 m in local depocentres (Broad et al., 2006).

The lithostratigraphy and chronostratigraphy of the Pletmos sub-basin are similar to those of the Bredasdorp sub-basin and have been described by Brown et al., 1995. The north-eastern and southwestern flanks of the Pletmos basin, the St. Francis arch and Infanta arch, are elongate basement highs (Figure 2.3). Basement in the Pletmos basin comprises slates and quartzites of the Ordovician to Devonian Cape Supergroup (Roux, 1997).

Three tectonostratigraphic packages reflecting varying rates of subsidence and sediment supply constitute the synrift sequence in the Pletmos basin (Bate and Malan, 1992).

2.4.2 Geology

Basin Evolution

Northwest-southeast trending half-grabens developed during the initial breakup of Gondwana in the Middle to Late Jurassic. Further rifting took place in the Valanginian, as South America separated from Africa. Tectonic activity persisted until the Aptian, especially in the eastern sub-basins, so long as transcurrent movement continued between the Falkland Plateau and the southern margin of Africa along the Agulhas-Falkland Fracture Zone (IHS, 2010). According IHS 2010 report, the syn-rift grabens are infilled with continental clastic sediments and red beds, becoming lagoonal to shallow marine at the top of the syn-rift succession. A Late Valanginian unconformity marks the onset of drifting.

2.4.2.1 Rifting (Synrift Phase) (Portlandian – Valanginian)

Initiation of rifting and formation of the Mesozoic half grabens in the southern offshore began in the Middle Jurassic and is related to the separation of East and West Gondwana (Dingle et al., 1983). The resultant extensional stresses reactivated the earlier compression related, pre-Cape and Cape lineaments to form the major basin-bounding normal faults such as the St Croix, Port Elizabeth, Gamtoos and Plettenberg Faults, where negative inversion (collapse) along these boundary faults created several Mesozoic depocentres namely the Sundays River, Uitenhage and Port Elizabeth Troughs and the Gamtoos and Pletmos basins (Bate and Malan, 1992). The arcuate shape of the basin boundary faults is likely to be inherited by the Cape Fold Belt tectonic grain as noted by De Swart and McLachlan, 1982.

According to Bate and Malan, 1992, the synrift succession (Horizon D to 1At1) can be divided into several tectonostratigraphic sequences recognisable in the study area:

1- A basal divergent wedge inferred to be Portlandian (above Kimmeridgian and below Berriasian) and older onlapping into crystalline basement and Cape Supergroup rocks.

2- A sequence with a high frequency/high amplitude seismic character displaying moderate to weak divergence of seismic reflectors dated Berriasian to Valanginian.

3- A Valanginian slope wedge with the rate of divergence increasing in thickness towards the fault far exceeding that of the previous packages.

These sequences suggest a multi-phase motion history of the boundary faults where a rapid initial propagation and subsequent creation of depocentres outstripped sediment supply leading to the formation of a highly divergent wedge onlapping basement. It can be inferred that the basal wedge consists of coarse and fine continental sediments typical of the initial stages of synrift sedimentation (Lowell, 1990).

The slightly diverging second sequence is more conformable and considerably thicker than the adjacent packages. The continuity of a seismic character across the half grabens and the more conformable nature of the reflectors point to decelerated tectonic subsidence allowing sediment supply to keep pace with fault-controlled subsidence. Slow and protracted rifting occurred over a wide zone forming sedimentary packages typical of an outershelf to inner slope environment (Bate and Malan, 1992).

Early graben fill consists of Synrift I sediments, which have been dated Kimmeridgian, but may be as old as Oxfordian in the deep, undrilled areas. Where intersected, Synrift sediments comprise thick aggradational fluvial sediments in the north and marginal marine sandstones in the south (Broad et al., 2006). They go on to state that later synrift I interval (Potlandian to Valanginian) comprise fluvial, shallow-marine and shelf deposits, which were sourced from the south-western and north-western margins of the basin and that the overlying horizon 1At1 unconformity has previously been referred to as the drift-onset unconformity but by analogy with the Bredasdorp sub-basin, it must also mark the onset of transform movement on the AFFZ and the onset of the second phase of rifting (Synrift II).

Synrift sedimentation continued until the Late Valanginian, when a further pulse of tectonism influenced the southern offshore basins. This second phase of tectonism was again extensional but of less intense nature that the earlier rifting stage forming Horizon D

(Bate and Malan, 1992). This phase of extensional tectonics occurred as separation between South America and Africa was initiated (Norton and Sclater, 1979; Dingle et al., 1983). Movement of South America away from Africa along a transform system, the Agulhas Falkland Fracture Zone situated off the southern edge of the African continental plate, was accompanied by the creation of oceanic crust in the Proto-Atlantic at 135 m.y. (Martin et al., 1982)

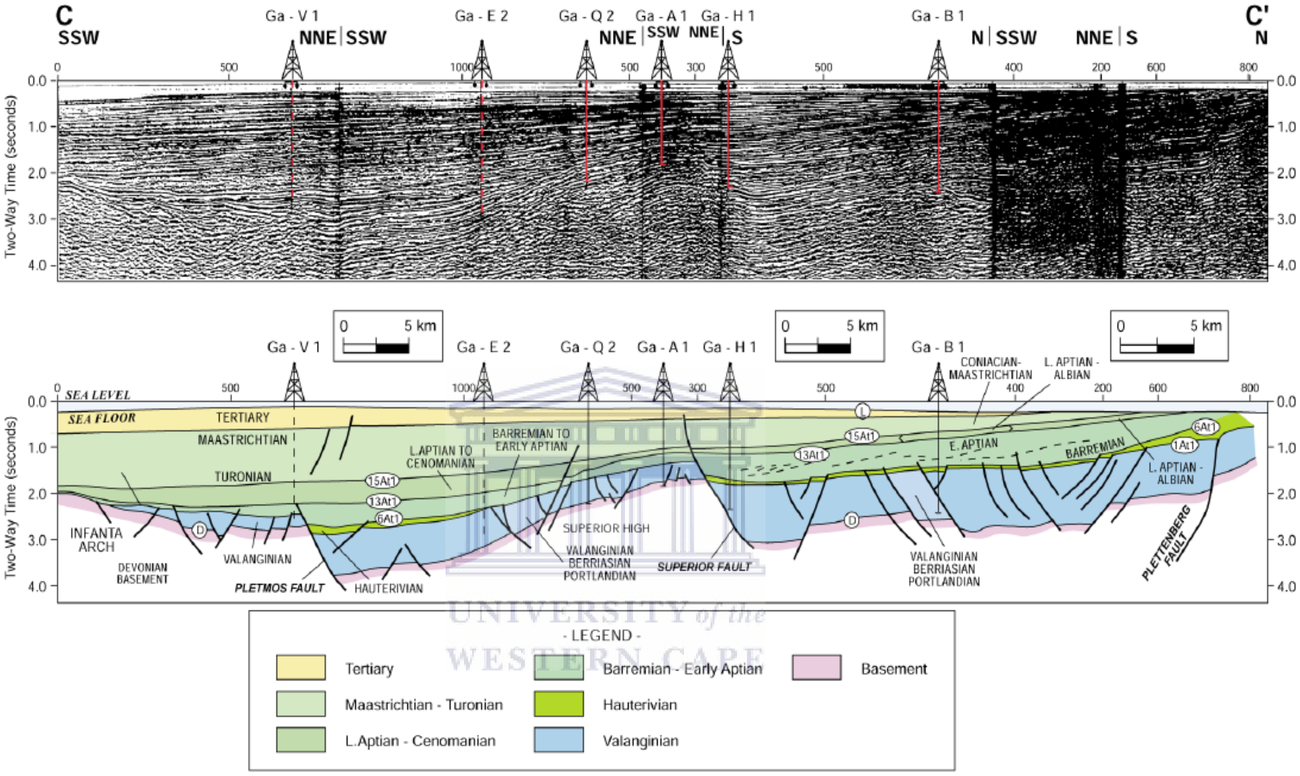


Figure 2.6: Seismic/interpreted geologic profile across the Pletmos Basin, illustrating tectonostratigraphic units. (Modified after McMillan et al., 1997)

In the Algoa, Gamtoos and Pletmos Basins, 1At1 appears to be a non-erosive or only locally erosive unconformity with limited erosion of fault block crests and subsequent redeposition adjacent to the fault scarps. Thus 1At1 represents a slightly modified rifted landscape which has subsequently become buried by the thermal subsidence succession. It also represents the boundary between two different tectonostratigraphic styles (Bate and Malan, 1992).

These sediments were sourced directly off the flanks of the basin and down the axis of the grabens in a south-easterly direction (Roux, 1997).

Major subsidence of the Outeniqua Basin after the transform-onset unconformity (1At1) led to deep-marine, poorly oxygenated conditions within the Pletmos and other sub-basins. Sequences 1A to A, which constitute syn-rift II deposition, comprise aggradational deep-marine claystones and thin turbidites and contain organic-rich shales which are significant petroleum source rocks (Broad et al., 2006).

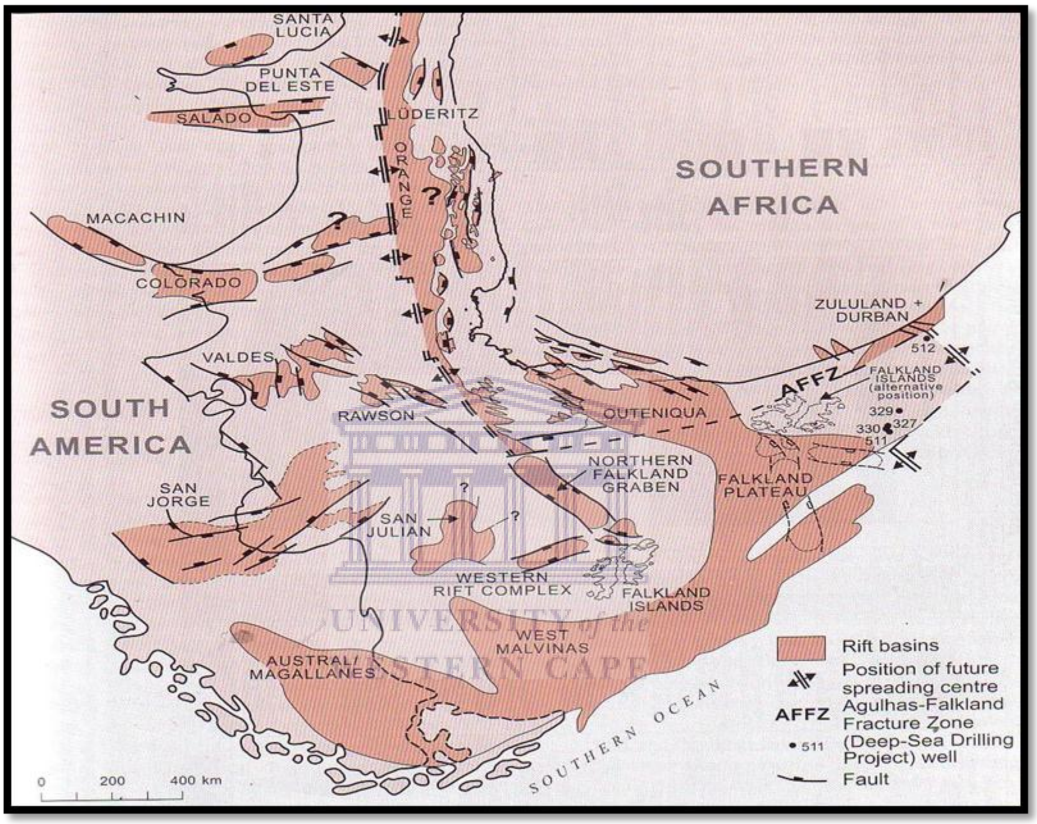


Figure 2.7: Plate tectonic reconstruction illustrating the likely pre-break-up configuration of Late Jurassic to Early rift basins within southwest Gondwana. An alternative inverted northeast position of the Falkland Islands illustrates the possibility that the Falklands microplate may have undergone clockwise rotation of 180^{o} during continental separation (After Jungslager, 1999a).

According to Roux, 1997, the normal faults associated with rifting are parallel to the compressional tectonic grain of the Permo-Triassic Cape fold belt. The St. Francis and Infanta arches are bounded by major normal faults between which the Pletmos basin depocenter is developed.

The early rift fill consists of thick Kimmeridgian age sediments that filled a number of south-easterly trending grabens during horizon D (top basement) to horizon O times (Figures. 2.6). Some of these early depocentres, like the Plettenberg graben and the Southern Outeniqua basin are expected to contain Kimmeridgian oil-prone shales, similar to those intersected in the adjacent Gamtoos and Algoa basins and in the Deep Sea Drilling Project boreholes on the Falkland plateau (Roux, 1997).

He further explains that early fill is overlain by thick aggradational fluvial sediments in the northern Pletmos basin and marginal sandstones in the southern Pletmos basin. The late synrift interval from horizons O to 1At1 comprises fluvial, shallow marine, and shelf deposits of Portlandian to Valanginian age. The sandstone content of the entire synrift succession increases towards the Southern Outeniqua basin in a south-westerly direction away from the sand-starved Plettenberg graben.

2.4.2.2 Thermal subsidence and drift sedimentation

1At1 to 6At1 (Late Valanginian – Hauterivian)

During the Valanginian, right-lateral shear stresses developed along the Agulhas-Falkland Fracture Zone, a major Gondwana break-up structure. This resulted in folding and strike-slip movement along existing normal faults. The resultant right lateral movement along the fracture zone separated the Falkland plateau from the African plate and bisected the Outeniqua rift basin (Roux, 1997).

According to him, the angular unconformity marked by horizon 1At1 at the top of the synrift succession is regarded as the drift-onset unconformity. It is highly erosional on the basin flanks and on other basements highs. The Outeniqua sub-basins subsided, resulting in deep marine, poorly oxygenated conditions over most of their extent.

He again asserts that during a transitional phase between 1At1 and 6At1, also characterized by transform tectonics, an aggradational onlap infill succession of deep marine claystones and thin bedded turbidites of late Valanginian to Hauterivian age was deposited. Good quality wet gas to oil-prone shales are postulated to occur at the base of this interval over the Southern Outeniqua basin (Table 1). Characteristics of petroleum source rocks (from well data of a well adjacent to the Southern Outeniqua basin) are shown in Table 1 below.

Table 1: Pletmos Basin source rocks- From Roux, 1997.

Interval	**Kerogen type**	**Ultimate yield kg/tonne**	**Thickness (m)**	**Present maturity level**
15A	I/II (wet gas) - oil	8-10	10-15	Top oil
13A	II wet gas - oil	6-8	40-60	Mid. oil window
9A	(II)/III wet gas - oil	3-6	50-100	Oil-wet gas window
East	II/III wet gas - oil	4-7	40-60	Top oil
6A West	III dry gas	3-5	30-50	Wet gas window
1A	II/III wet gas - oil	3-6	40-80	Wet gas window
Pre-hor "O"	?	Unknown	?	Dry to wet gas window

Uniform thermal subsidence occurred during the Late Valanginian (1At1) to the Hauterivian (6At1) period resulting in the formation of a tectonostratigraphic sequence decreasing in thickness away from the boundary faults (Bate and Malan, 1992). They further affirm that a 1At1 to 6At1 package with a maximum thickness of 3200m, accumulated in the hanging wall of the Plettenberg Fault.

6At1 to 13At1 (Hauterivian – Aptian)

The overlying late Hauterivian to early Aptian interval is characterised by high-energy southward shelfal progradation from the northern margin of the sub-basin (Figure. 2.5) (Broad et al., 2006). They proceed to affirm that these deposits consist of interbedded claystones and shelf sandstones around the northern rim, and postulated basin-floor fan sandstones within the depocentres.

According to Bate and Malan, 1992, it is apparent that from 6At1 times whilst the Algoa and Gamtoos Basins experienced uplift on a regional scale, the western area of the southern offshore experienced subsidence. The position of the fulcrum or hinge of this relative movement is suggested to be near the prominent positive inversion feature (“pop-up” structure seen in the western part of the Gamtoos basin. To the west of this feature the thickness of the thermal subsidence package increases to a maximum in the Pletmos basin whereas to the east, in the Gamtoos and Algoa Basins, these deposits thin substantially. This last phase of wrench tectonics tilted and rotated normal faults along the eastern flank of the St Francis Arch resulting in both the 1At1 and Horizon D being overstepped onto their present configuration.

Shelf to shallow marine sandstone occurs around the northern rim of the basin and across the entire Infanta embayment. Slope and basin floor fan sandstones have been proven by drilling toward the south, downdip of the paleontological shelf edge. Good reservoirs are expected within prognosed deep marine fan and channel sandstones in the Southern Outeniqua basin (Roux, 1997).

He asserts that source shales varying from dry gas to wet gas and oil prone have been intersected in the southern Pletmos basin and Plettenberg graben and are expected to follow the established regional trend of improvement in quality towards the Southern Outeniqua basin (Table 1). They presently fall in the wet gas to oil maturity window.

Bate and Malan, 1992, further suggest that the degree of post-6At1 uplift increases eastwards, with the area to the east of the Recife Arch experiencing more uplift and deeper erosion than the Gamtoos Basin. In the Hauterivian, relative uplift of the Uitenhage and Port Elizabeth Troughs caused dramatic erosion of the Synrift sediments producing deep incised channels and canyons.

Erosion probably culminated in the Middle Aptian with the formation of the 13At1 regional unconformity followed by a transgressive period during which the channels and canyons were rapidly filled by shelf and slope sediments (Doherty, 1987).

Post 13At1 (Post Aptian)

A period of sand starvation followed the mid-Aptian unconformity (13At1) and organic-rich shales were deposited in the southern Pletmos sub-basin and probably also in the Southern Outeniqua sub-basin (Broad et al., 2006).

During the Santonian a number of channels were eroded into the thermal subsidence (drift) package of the southern Algoa and Gamtoos Basins in the area of the palaeo-shelf break. At some localities this Late Cretaceous erosion was quite intense, even cutting down into the Synrift package. These channels could be in response to either scouring by the proto-Agulhas current or more likely due to thermal flexure or relation of the basin margin uplifting the hinterland leading to incision of the shelf (Bate and Malan, 1992).

Late Cretaceous and Tertiary sediments are of shelfal origin, comprising interbedded calcareous sandstones and marls (Broad et al., 2006).

The development of the mid-Aptian unconformity (13At1) is also associated with the deposition of an extensive 13A lowstand wedge prognosed to be present throughout most of the Southern Outeniqua basin. This was followed by a period of relative sand starvation over a large area of the basin during which time organic rich shales were deposited in the southern Pletmos basin and the Southern Outeniqua basin.

A high subsidence rate during this period diminished the effect of eustatic sea level changes, which resulted in an aggradational shelf build-up throughout late Aptian to mid-Albian times. The late Aptian to Cenomanian sediments just below 15At1 prograded from the north-western rim of the basin (Figure 2.5). The deep marine intervals in the 13A to 15A sequences over the Southern Outeniqua basin and the southern Pletmos basin remain untested, but the regional geological model suggests that deep marine fan systems fed by canyons from the proximal parts of the basin can be expected (Roux, 1997).

Throughout the thermal history of the southern offshore, continuing to the present day, it is evident that the basins have experienced a degree of tilting, with the basin margins undergoing uplift relative to the subsidence of basin centres which has resulted in the sea floor erosion of the thermal package as is clearly illustrated by the truncations of 13At1, 15At1 and Horizon L in the northern part of the Pletmos Basin (Bate and Malan, 1992).

Reservoir Rock: The reservoirs for the Mossel Bay area gas fields in the northern Bredasdrop Sub-basin are Valanginian shallow marine sandstones underlying the rift-drift unconformity. These are typically well sorted and have significant secondary porosity (IHS, 2010).

They go further to affirm that the other major reservoirs are deepwater mass flow sandstones in channels and fans within the mudstone-dominated sequences that overlie the rift-drift unconformity; the most important of these sequences for reservoir development is the 14A sequence of Albian age. Fractured basement forms a secondary, minor, reservoir in a single discovery.

Source Rocks: Deepwater conditions with a tendency to anoxia were established repeatedly through the Lower Cretaceous succession, overlying each of a number of basin-wide unconformities. Organic-rich mudstones were deposited in each of these episodes, forming potential source rocks. The Aptian 13A sequence contains the most significant of these, and much of it is in the oil-generating window at the present time. Older source rocks are more deeply buried and are over mature. Younger source rocks could be mature in the deeper water areas of the basin, including the undrilled Southern Outeniqua Sub-basin (IHS, 2010).

Seals: Early post-rift deepwater mudstones directly overlying the rift-drift unconformity provide seals for the Valanginian syn-rift reservoirs. The post-rift deepwater sandstone reservoirs are sealed and enclosed by the deepwater mudstones into which they were deposited (IHS, 2010).

2.4.3 Adjacent Onshore Basins

In the southern Cape, Middle Jurassic to Lower Cretaceous sediments occur as a series of small elongate outliers in the north tilting half graben within the Cape Fold Belt that stretches from Worcester in the west to Algoa in the east, a distance of about 600km (Figures 2.4 and 2.8) (Dingle et al., 1983). According to them, these structures continue offshore under the Agulhas Bank where they form graben and half graben sub basins within the Outeniqua Basin, the name given to the regional depocentre that lies between the buoyant Columbine/Agulhas Arch in the West and Port Alfred Arch in the east and is bounded to the SE by the Agulhas Marginal Fracture Ridge.

In the south eastern Cape Province of South Africa at Knysna, Plettenberg Bay and between Humansdorp and Alexandria, Late Jurassic to Early Cretaceous sediments occur in several elongate outliers in northward tilted grabens and half grabens within the Cape Fold Belt as well (Bate and Malan, 1992).

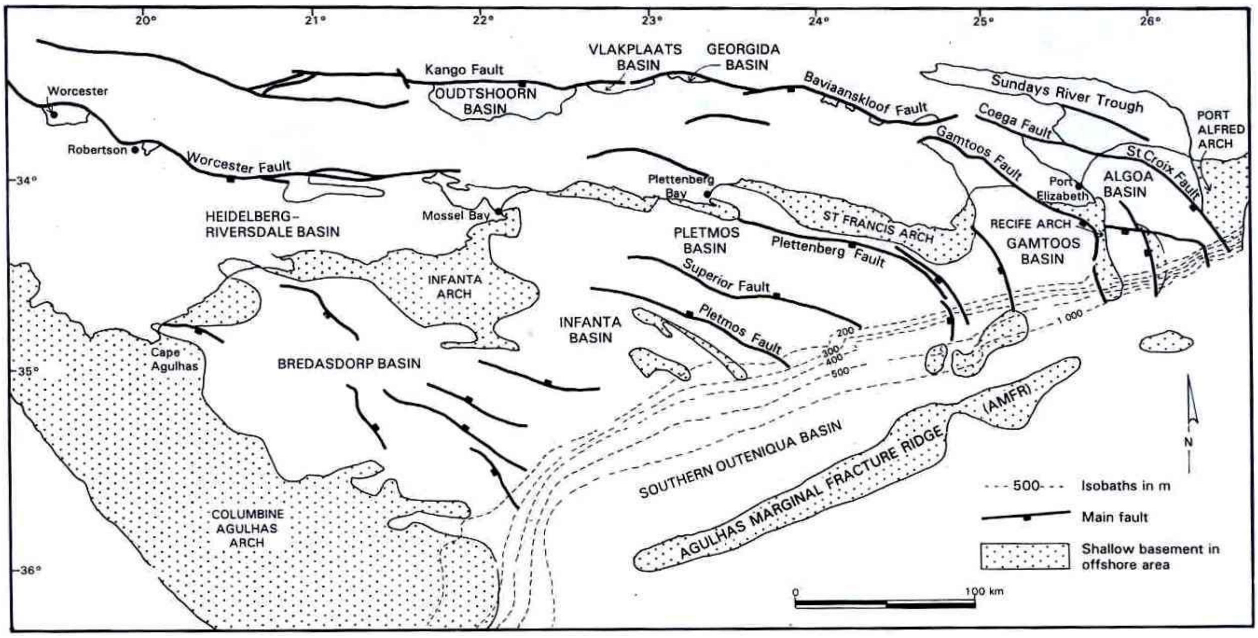


Figure 2.8: Mesozoic basins of the southern offshore and onshore. (Offshore information from Soekor 1994b)

Algoa Basin, the largest of the onshore outliers, has a thick succession of fossiliferous marine and freshwater sediments, which have long attracted the attention of palaeontologists (the earliest reference is by Hausmann, 1837), and it is here that the majority of stratotypes for the southern cape have been established. The other onshore basins are less well known because their lithofacies (predominantly continental and fluviatile) are sparsely fossiliferous and are difficult to correlate on a regional basis (Dingle et al., 1983).

The Bredasdorp Basin which is approximately 200 km long and 80 km wide, and occupying 18 000 km ^{2} has minor onshore extensions occurring but outcrops are minimal (Broad et al., 2006).

The Pletmos sub-basin, which covers approximately 18000 km^2, is the offshore extension of a series of small basins extending from Worcester through Robertson, Swellendam, Heidelberg/ Riversdale and Mossel Bay (Visser, 1998).

Heidelberg-Riversdale Basin is situated in a syncline of the Cape Fold Belt and is underlain by shale of the Bokkeveld Group. Only the lowermost formations of the Uitenhage Group, i.e. the rudaceous Enon and Beffelskoof Formations separated by the arenaceous–argillaceous Kirkwood Formation are represented in this basin (Visser, 1998).

The Gamtoos basin lies south of the Kango-Gamtoos line of faults (Figure 2.8). Outliers of Cretaceous strata along the Baviaanskloof Fault are separated from onshore Gamtoos Basin by an east-west cross-fold which also deflects boundary faults to the northeast and southwest respectively (Dingle et al., 1983). It becomes wider and deeper towards the southeast, where it extends offshore. The synrift sequence is thicker than in other basins (approximately 7000 m) and developed in a manner similar to that in the Pletmos Basin (Bate and Malan, 1992). In the onshore part of the basin only the lowermost part of the synrift sequence, the rudaceous Enon Formation and the red arenaceous to argillaceous Kirkwood Formation are represented (Visser, 1998).

The Oudtshoorn Basin is the largest onshore repository of early Mesozoic strata (Visser, 1998). The fill of this basin and the Vlakplaats and Georgida Basins has been described by Du Preez, 1994,; Du Toit, 1954,; Lock et al., 1975 and Lock,1978. It comprises conglomerate at the base, followed by red sandstone and an upper unit consisting of coarse conglomerate and breccias interbedded by red sandy layers, all of which belong to the Enon Formation with boundaries between lithological units being somewhat diachronous (Visser, 1998). According to Lock, 1978, finer sediments were deposited in the lower energy environments towards the basin’s centre, where sandstones similar to those of the Kirkwood formation were deposited, and pebble imbrication studies indicate that the basal conglomerate was transported from the south and north, while sandstone in the centre of the basin was transported axially from west to east. According to Visser, 1998, the basin was therefore probably symmetrical during its early history and this symmetry was later destroyed owing to reactivation of the bounding faults, which resulted in deposition of the upper conglomerate/red beds. A further episode of movement during Late Cretaceous-early Tertiary resulted in tilting of the Cretaceous strata northwards and exposure of Kango Group rocks on the north side of the Kango fault. Tertiary to sub-Recent conglomerates and breccias, similar to those of the Enon Formation, were deposited on the tilted Cretaceous rocks.

The Algoa basin, about 8km deep in its southern offshore part, is a composite structure subdivided into three half-grabens: the offshore Port Elizabeth and Uitenhage Troughs and onshore Sundays River Trough (Figures 2.8). It is bounded by the Recife Arch and the Port Alfred Arch in the southwest and the northeast respectively, both of which consist of Table Mountain Group quartzite (Visser, 1998). Sedimentary fill in the onshore part of the Algoa Basin is synrift in age. A complete succession is preserved from torrential conglomerates (Enon Formation) through red mudstones, sandstones and dark mudstone deposited in low energy environments and estuarine and tidal-flats muds (Kirkwood Formation), to tidal and fully marine clays, silts, sands and impure limestone of the Sundays River Formation (Lock, 1978).

2.5 Structural Elements

The Outeniqua Basin consists of a series of en-echelon sub-basins (the Bredasdorp, Pletmos, Gamtoos and Algoa Basins) each of which comprises a complex of rift half-graben overlain by variable thicknesses of drift sediments. The deepwater extensions of these merge into the Southern Outeniqua basin (Visser, 1998).

The syn-rift gas accumulations are trapped in tilted fault-block structures formed, or accentuated, during the second rifting phase in the Valanginian. These structures depend on the presence of mudstones overlying the rift-drift unconformity for their seal. The traps for the post-rift oil, gas and condensate accumulations are primarily stratigraphic, depending on depositional enclosure of the sandstone bodies within the thick mudstone succession, and modified by structural elements (IHS, 2010).

In the southern Cape, the elongate asymmetric anticlines and synclines of the Cape Fold Belt trend approximately E-W between about 20 and 24°E, before swinging sharply SE in the vicinity of Port Elizabeth (Figure 2.8 Dingle et al., 1983). According to them, the major anticlines are typically bounded on their southern sides by large, southward throwing normal faults, and it is within the resultant, asymmetric, northward-tilting half grabens that the onshore mid-Jurassic to Lower Cretaceous taphrogenic basins developed. Although individual faults are not usually continuous for more than about 200km, two major fault lines controlled the location of the Worcester-Mossel Bay, and Oudtshoorn-Gamtoos series of outliers. Both fracture zones can be traced under the Agulhas Bank (as the Plettenberg and Gamtoos faults, respectively), where they form the northern boundaries of two major offshore sub basins: Pletmos and Gamtoos. Dingle et al., 1983, go on to say that in addition to these two main series of outliers, other basins occur in the Knysna-Plettenberg area and north of Algoa Bay, the former being partially fault-bounded on their southern sides, and rest on top of the main basement high which separates the Oudtshoorn-Gamtoos and Worcester-Pletmos basin lineaments. This high feature continues under the Agulhas Bank as the St Francis Arch. In the Algoa, Oudtshoorn-Gamtoos, and Worcester-Pletmos lineaments, the basins are strongly asymmetric, and sedimentation was controlled by differential subsidence across major boundary faults, so that maximum thicknesses invariably lie adjacent to these main fractures (Dingle et al., 1983).

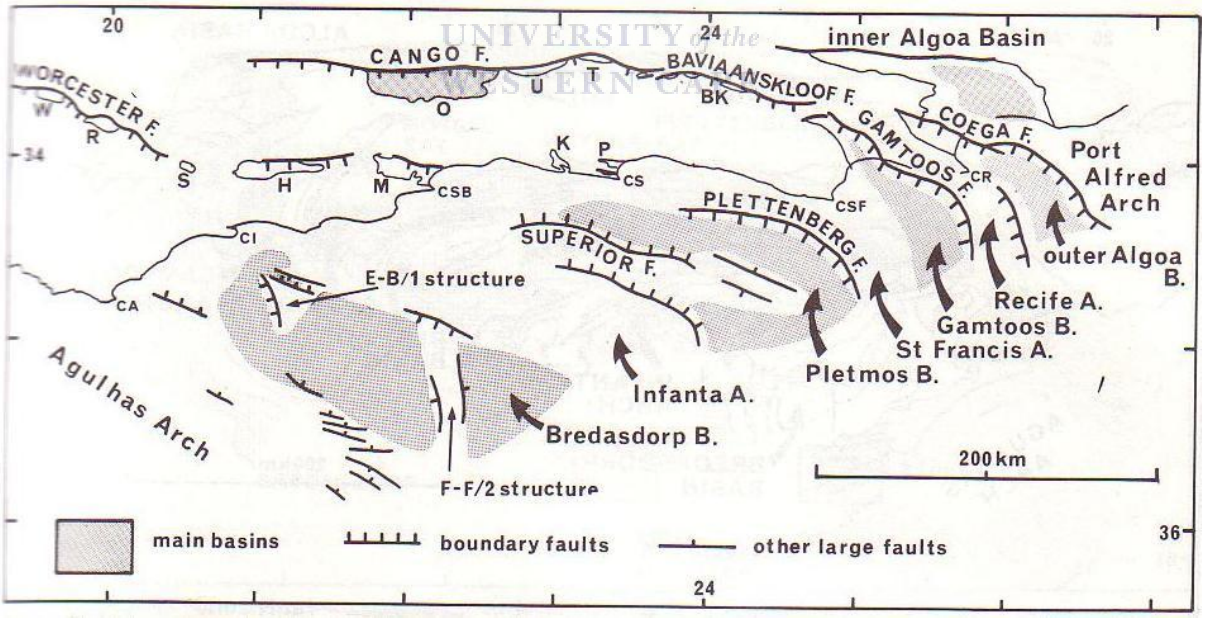


Figure 2.9: Main structural features that controlled sedimentation during the Jurassic to Lower Cretatceous times in the Southern Cape, according to Dingle et al., 1983. Only major faults shown.
Abbreviations: F= Fault; B= basin; A= arch; W= Worcester; R=Robertson; S=Swellendam; H=Heidelberg; M= Mossel Bay; K= Knysna; Plettenberg and Pisang; O= Oudtshoorn; U= Uniondale; T=Toverwater Poort; BK= Baviaans Kloof; CA, CI, CSB, CS, CSF, CR= Cape Agulhas, Infanta, St Blaize, Seal, St Francis, and Recife respectively.

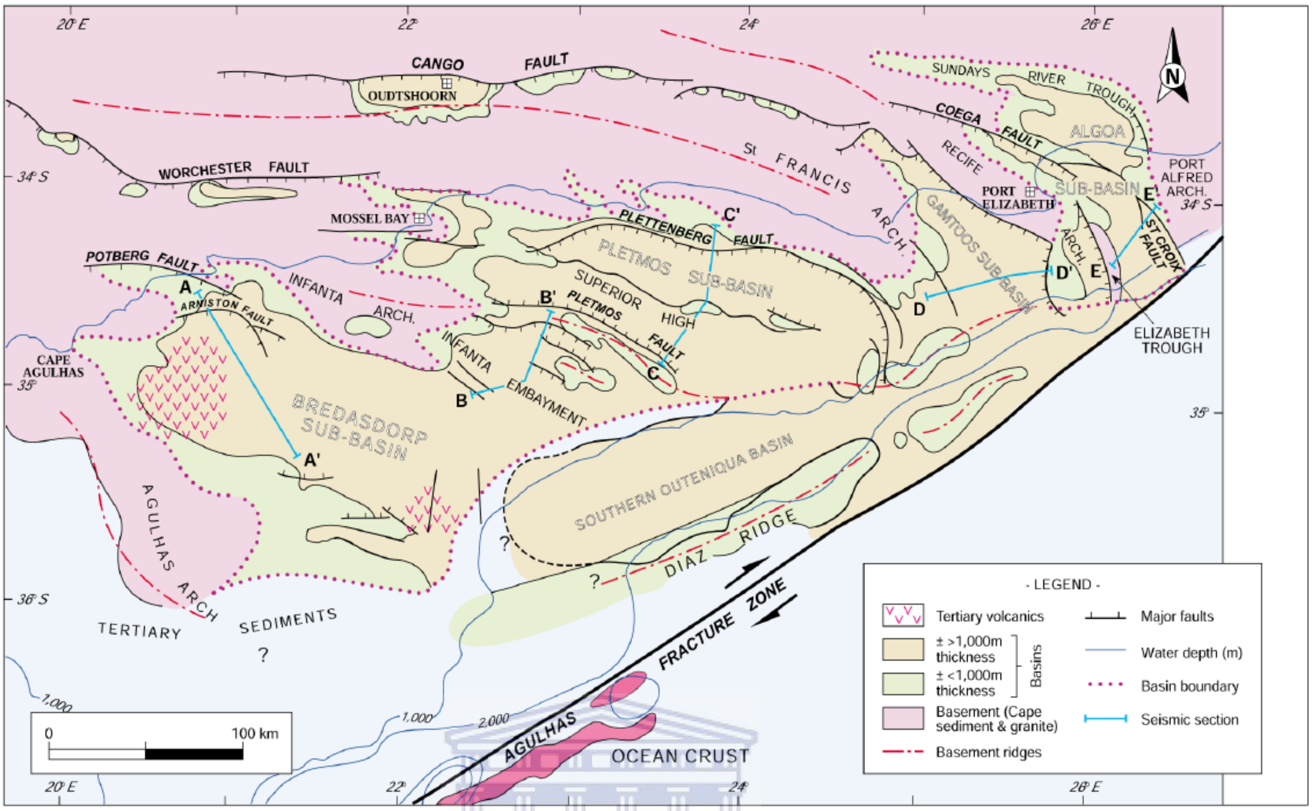


Figure 2.10 Major faults in the Pletmos Basin (Modified after Letullier, 1992 and McMillan et al., 1997.

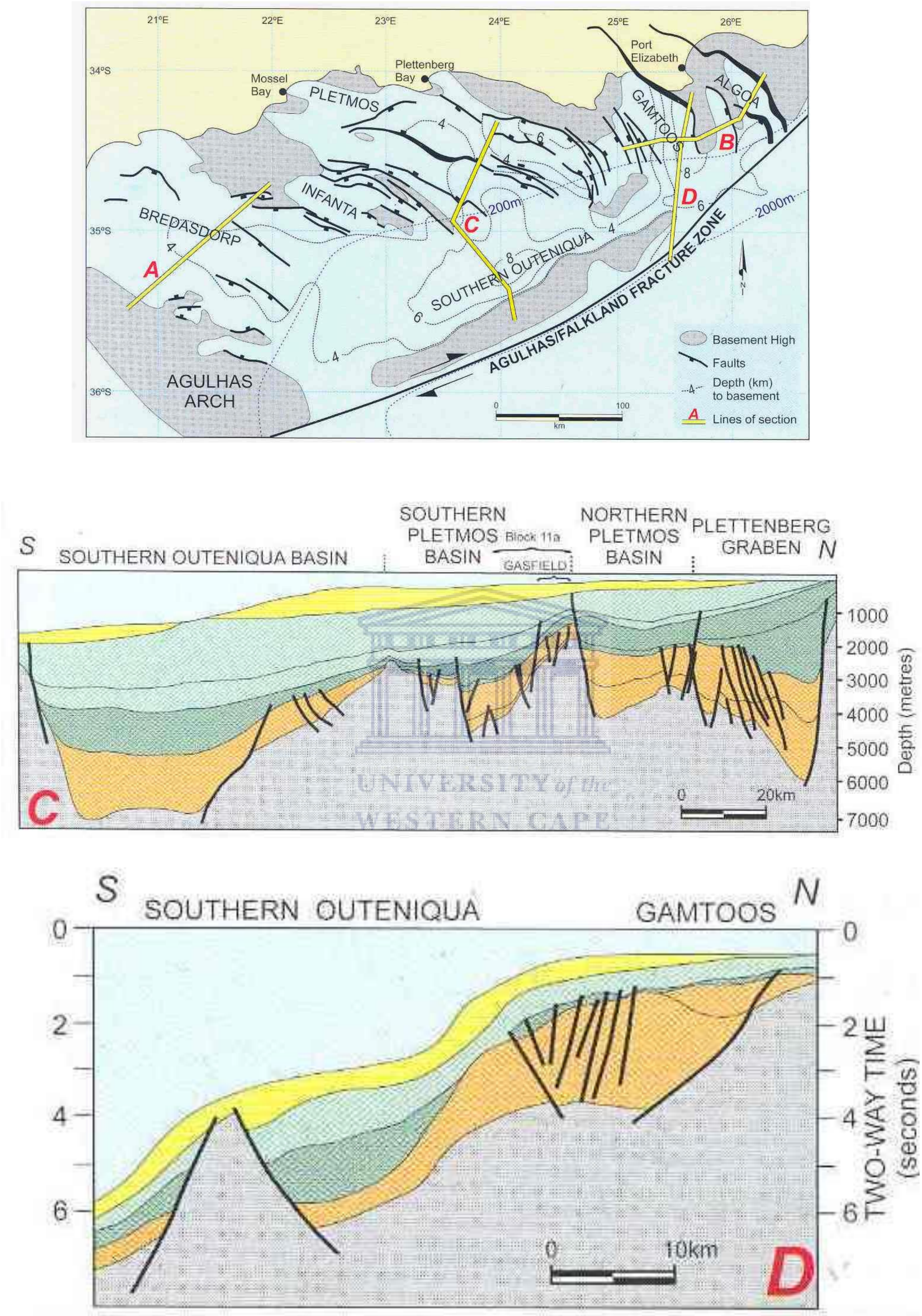


Figure 2.11: Cross sections of the Outeniqua Basin according to PASA, 2008.

Both onshore and offshore basins are floored with less resistant Bokkeveld-like shales. This evidence suggests that the taphrogenic basins developed along the lines of synclines originally formed during the Cape Orogeny, particularly in view of the fact that shale clasts are subordinate in the basin fill, i.e. the high ground adjacent to the Middle Jurassic-Lower Cretaceous basins was already stripped bare of Bokkeveld cover (Dingle et al., 1983).

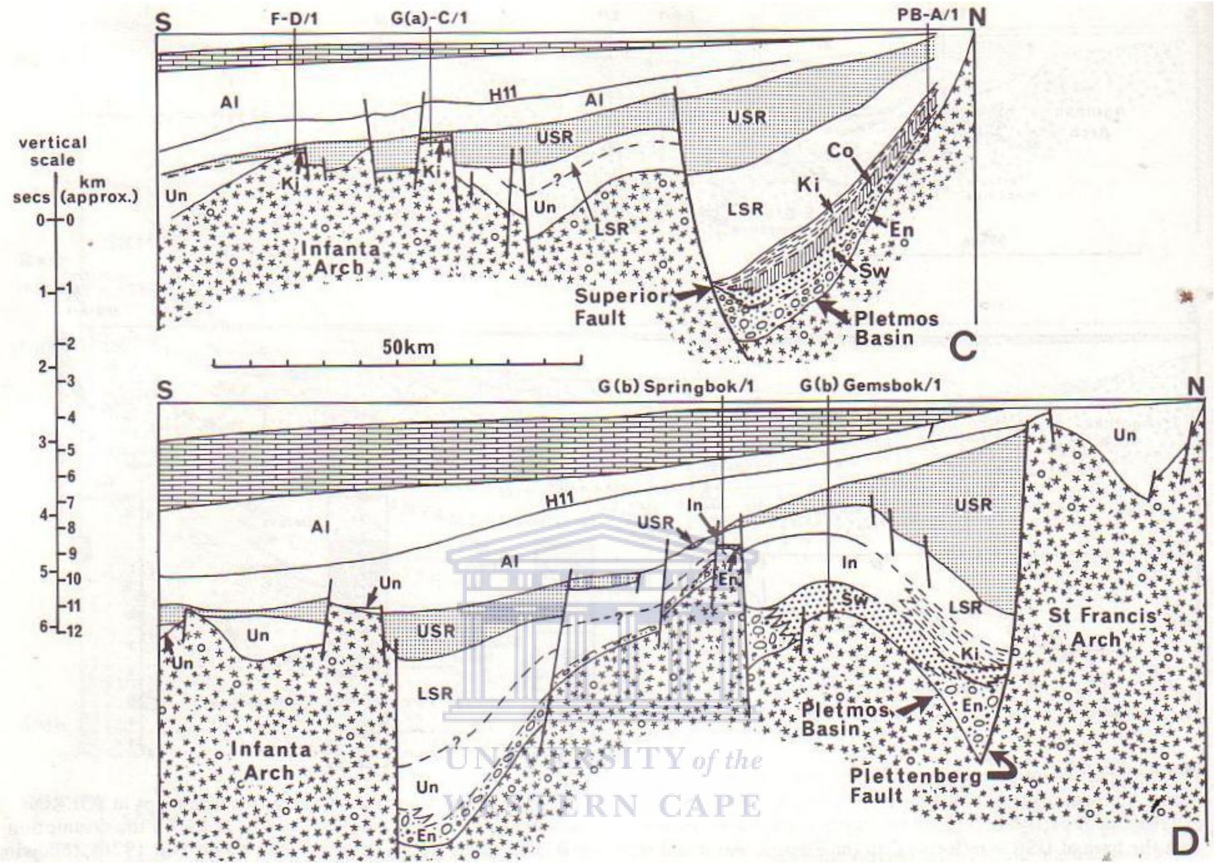


Figure2.12:. Sections across the central Outeniqua basin. C = West Pletmos Basin. D= East Pletmos basin. According Dingle et al., 1983.

Below is an account of the structural evolution of the southern coast from the Palaeozoic to the Tertiary.

2.5.1 Upper Palaeozoic

Subduction of the southwest margin of Gondwana in the Late Carboniferous- Early Permian led to the transformation of an old passive margin into a foreland basin (the Great Karoo Basin). Further convergence in the Permo-triassic led to the development of the Cape Fold Belt which extends from Australia through Antartica and South Africa to South America (PASA, 2008).

2.5.2 Mesozoic and Tertiary

Following erosion and peneplanation there was a phase of widespread volcanism in the Early to Middle Jurassic in Southern Africa, the Falklands and Antartica. This provides the first evidence of the impending breakup of Gondwana.

At this time the Falkland Islands lay off the south or southeast coast of South Africa. Breakup started on the eastern margin of Africa with Madagascar and Antartica beginning to move away in the Middle Jurassic. This initiated the formation of the Durban and Zululand Basins.

During the Early to Mid- Cretaceous a complex series of micro plates including the Falkland Plateau gradually moved west south-westwards past the southern coast of Africa creating important dextral shearing of the South African margin. This created the Outeniqua sub basins as a series of oblique rift half-grabens which may be regarded as failed rifts, oldest in the east and youngest in the west (PASA, 2008).

PASA, 2008, further explain that the rift phase on the south coast ended in the Lower Valanginian (drift-onset unconformity, 1At1) but was followed by at least three phases of inversion related to continue dextral shearing. This ended in the Mid-Albian (14At1) with the final separation of the Falkland Plateau from Africa. This transitional rift-drift phase was followed by development of a true passive margin. The Lower Valanginian drift-onset unconformity on the South coast is contemporaneous with the earliest oceanic crust in the South Atlantic.

2.6 Stratigraphy of the Southern Cape Basins

Renewed interest in the stratigraphy and facies of the sediments of the southern Cape taphrogenic basins has been generated by commercial and academic research on the Agulhas Bank. Although complete consensus does not exist, good agreement has been reached on the main points of lithostratigraphic correlation in the areas, and various classifications proposed by Hill, 1972,; Dingle, 1973a, 1978,; Winter ,1973, 1979,; du Toit, 1976, and McLachlan and McMillan,1976, 1979, illustrate this. This is close to the scheme formally submitted for consideration to the South African Committee for Stratigraphy (du Toit et al., 1975, SACS, 1980).

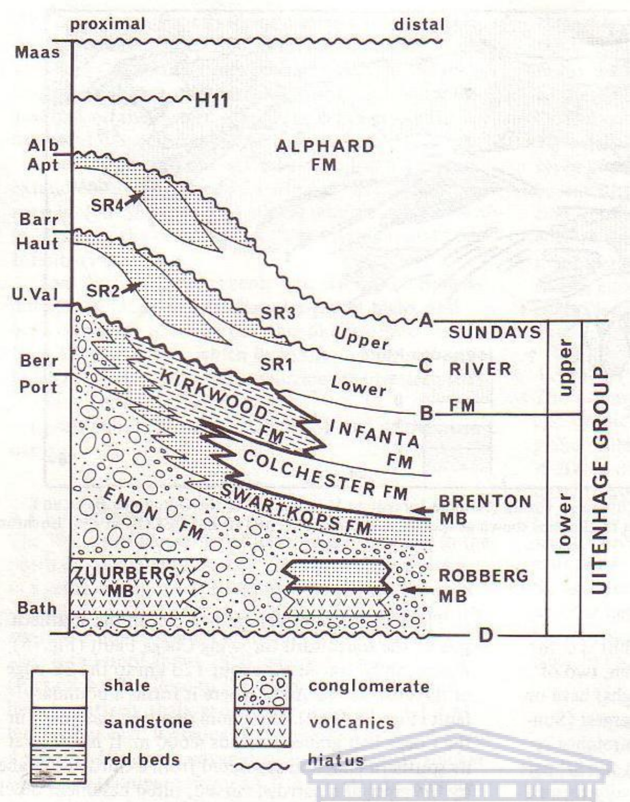


Figure 2.13: Jurassic to Cretaceous lithofacies stratigraphy in the E. Outeniqua and southern Cape basins. This refers specifically to the Pletmos and Algoa basins. A-D are prominent are prominent seismic reflection horizons. Thickened line marks the marine (above)/ non-marine (below) boundary. Based on Dingle (1973a, 1978, 1980a), du Toit (1976), Soekor (1976) and McLachlan and McMillan (1976, 1979)

Plays

From IHS Basin Monitor, 2010 there are two major groups of plays in the Outeniqua Basin.

The Syn-rift group of plays includes the fields and discoveries of the Mossel Bay gas trend. The reservoirs are the top syn-rift shallow marine sandstones in tilted fault blocks, sealed at the rift-drift unconformity by the overlying deepwater mudstones.

The post-rift plays involve stratigraphic traps in deepwater mass flow sandstones of Hauterivian to Albian age, sealed within deepwater mudstones of the same age. Two plays are recognised here: the 14A Stratigraphic Play comprises a fairway of Albian oil, gas and condensate discoveries and prospects, including the producing Oribi field, in the Bredasdorp Sub-basin and the Lower Post-rift Stratigraphic Play arbitrarily groups together a small number of similar discoveries with reservoirs at pre-14A horizons.

The syn-rift plays have mostly been exemplified by onshore basins. Below is an example of an onshore Mesozoic basin.

Case study of an onshore Mesozoic basin: Stratigraphy of the Heidelberg/ Riversdale Mesozoic basin

The Heidelberg/Riversdale basin is one of the onshore Mesozoic taphrogenic basins along the Worcester/Pletmos basin line (Dingle et al., 1983) which forms a discontinuous east/west line of half-grabens for over 400km (Viljoen, 1992).

The Worcester/Pletmos basin line is bounded on its northern side by a series of southward throwing normal megafaults, one of which is the Worcester Fault (Viljoen, 1992).

The strata of the Heidelberg/Riversdale basin form part of the Uitenhage Group (SACS, 1980; Winter, 1979), and have a three-fold subdivision (see also Rigassi and Dixon, 1970).

From the bottom to the top they are the Enon Formation (reddish conglomerate), Kirkwood Formation (varicoloured to grey-green sandstone, mudstone and tuff) and the Buffelskoof Formation (whitish conglomerate and sandstone) (Viljoen, 1992). This subdivision can also be extended to the other onshore basins of the Worcester/Pletmos basin line (Malan et al., 1992). A schematic north/south section through the Heidelberg/Riversdale basin is depicted in Figure 2.14.

2.6.1 Enon Formation

In the Heidelberg/Riversdale basin the Enon Formation is mainly exposed in a narrow strip along the southern and south-western margin of the basin being virtually absent at the northern margin, probably due to faulting and erosion. Only the distal part of this northern Enon conglomerate is preserved (Viljoen, 1992).

The Enon Formation consists of reddish to purplish northward-dipping conglomerates and breccia with a few sandstone interbeds. The conglomerate is clast-supported and has a polymodal, poorly sorted matrix. The conglomerate and breccia probably represent scree slope and alluvial fan deposits. A conglomerate wedge building out from the north overlapping part of the Kirkwood Formation in this basin. Outcrops of this wedge are confined to a small area to the north of Heidelberg and are probably only the distal part of the wedge which crops out (Viljoen, 1992).

2.6.2 Kirkwood Formation

The Kirkwood Formation can be subdivided into two units (Malan and Viljoen, 1990), namely a varicoloured to buff unit consisting of sandstone and mudstone with conglomerate lenses and a more clayey, grey to grey-green unit (“Heidelberg beds” of Hager, 1922) probably representing fluvial flood plain and lacustrine depositional environments respectively (Viljoen, 1992).

A lower and upper tuff zone, consisting of altered tuff and tuffite beds can be recognised in the Kirkwood Formation. There is a marked difference in the sedimentological setting of the lower and upper tuff zones (Viljoen, 1992). The lower zone was probably deposited in the lacustrine environment as indicated by the interbedded grey to grey-green laminated mudstones and sandstones and the occurrence of freshwater crustaceans (Jones, 1901) and Unio, a freshwater bivalve (McLachlan and McMillan, 1976).

The upper tuff zone was probably deposited in a fluvial floodplain environment (Viljoen, 1992).

2.6.3 Buffelskloof Formation

Overlying the northward-dipping (20^o to 30^o) Enon and Kirkwood Formations with and angular unconformity is a whitish conglomerate and pebbly sandstone unit (Brandwag Formation of Malan and Viljoen, 1990). It is provisionally correlated with the Buffelskloof Formation (Theron et al., 1992).

It consists of clasts derived exclusively from the Table Mountain Group. No clasts of the Table Group are found in the lower formations, not even at the northern margin. The Buffelskloof Formation probably represents alluvial fan and braided stream deposits (Viljoen, 1992).

According to Viljoen, 1992, the development of the Heidelberg/Riversdale basin is seen as a series of events starting in the deposition of the Enon Formation close to the margin and the Kirkwood Formation in the central part of erosional (probably syncline- and fault-controlled) valleys. The basin appears to have been approximately symmetrical during its early history with deposition from the north and south. Due to movement on faults along the northern margin the Enon Formation started to onlap the Kirkwood Formation from the north. This followed a period of relative tectonic stability when mainly “Kirkwood-type” sediments were deposited. The situation changed as result of renewed faulting, which produced prominent scarps along the northern boundary. Subsequent erosion and unroofing of the Table Mountain Group initiated the deposition of the Buffelskloof conglomerate.

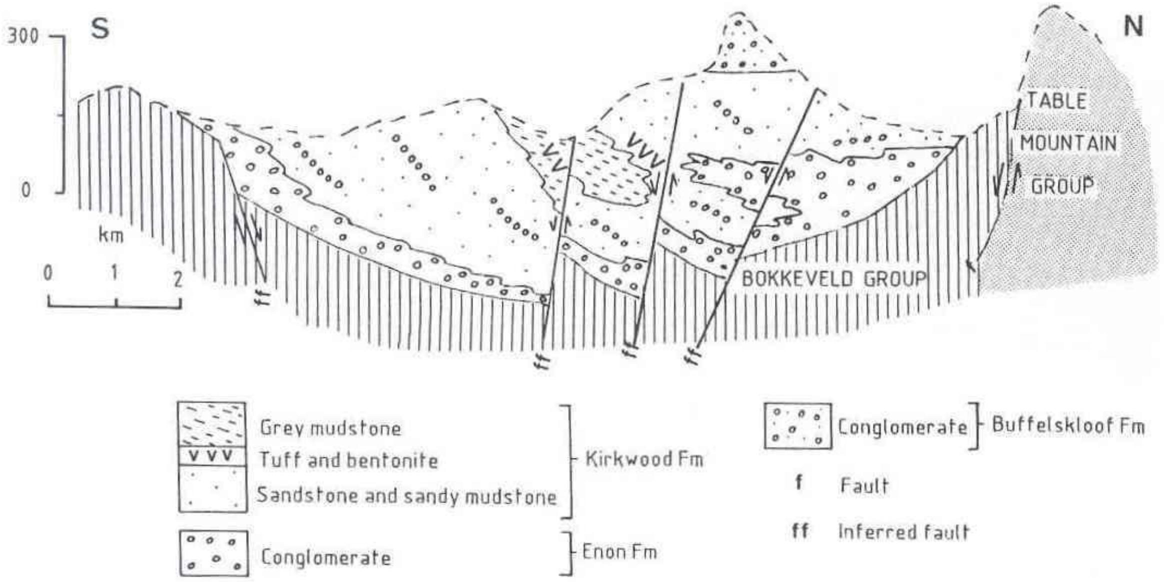


Figure 2.14: Schematic north/south section through the Heidelberg/Riversdale basin (Viljoen, 1992).

2.7 Petroleum Systems

From IHS Basin Monitor Report, 2010 there is essentially only one petroleum system in the Outeniqua Basin, comprising Aptian (sequence 13A) source rocks and predominantly Early Cretaceous reservoirs. Maturation may have occurred first in Cretaceous times, but the periods of generation believed to have charged the observed accumulations took place in Early (60 Ma) and Late (5 Ma) Tertiary. Considerably larger volumes of hydrocarbons have probably been generated than remain in the basin today. Retention is lower risk in the west than in the east, where tectonic control persisted through latest and major faults as they penetrate higher up into the succession.

CHAPTER THREE

LITERATURE REVIEW OF DEEP SEA SEDIMENATION

3.1 Deep-sea fan models

3.1.1 Classical deep-sea fan models

When research on turbidites was blooming in its early days, one of the main concerns of sedimentologists was to find a way to construct better and predictive depositional models through an interpretation of turbidite facies and facies associations. Such an interpretation at first was inspired strongly by 'autogenic' or 'autocyclic' concepts, i.e. processes and mechanisms intrinsic to the depositional systems. In this strictly uniformitarian view, turbidites were related to the slope– canyon–deep sea fan setting that was being explored increasingly in modern deep-sea fans by marine geologists at the same time (Mutti et al., 2009).

Normark, 1970, attempted to develop a depositional model for modern fans essentially based on the detailed analysis of relatively small deep-sea fans from continental borderland basins and from deep-water settings offshore of California and Baja California, Mexico (Figure 3.1 (A)). Independently, Mutti and Ricci Lucchi, 1972, elaborated a fan model on the basis of outcrop studies in the Northern Apennines and the South-central Pyrenees (Figure 3.1(B)). Both models of Normark and Mutti and Ricci Lucchi became very popular: the first model was based mostly on physiography and limited data from surface sediments, the second model was based on *facies and facies associations thought to represent slope, fan and basin-plain sedimentation*. The fan was subdivided further into inner, middle and outer fan facies associations.

Fan models and their derivatives became widely accepted in both the scientific community and industry. Because of their assumed predictive potential, it might be said that these models inspired or were the standard reference for much hydrocarbon exploration in many basins worldwide, both onshore and offshore, for at least two decades (Mutti et al., 2009).

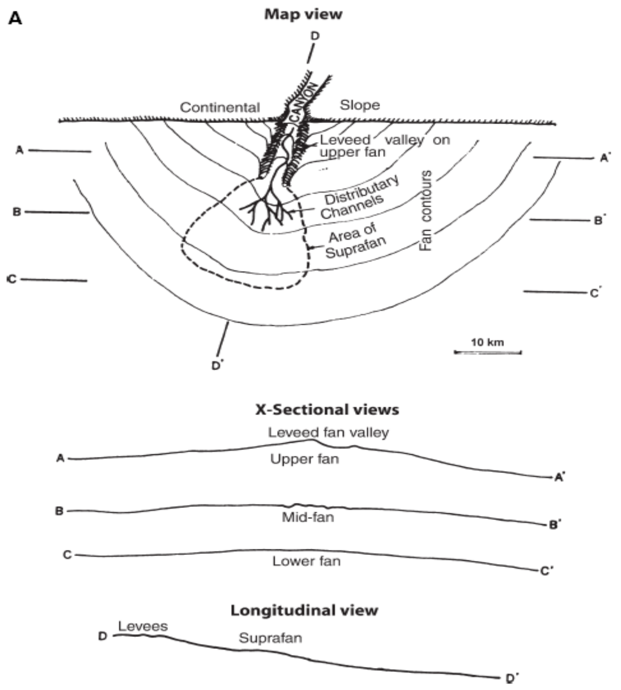


Figure 3.1 (A) Fan model of Normark (1970).

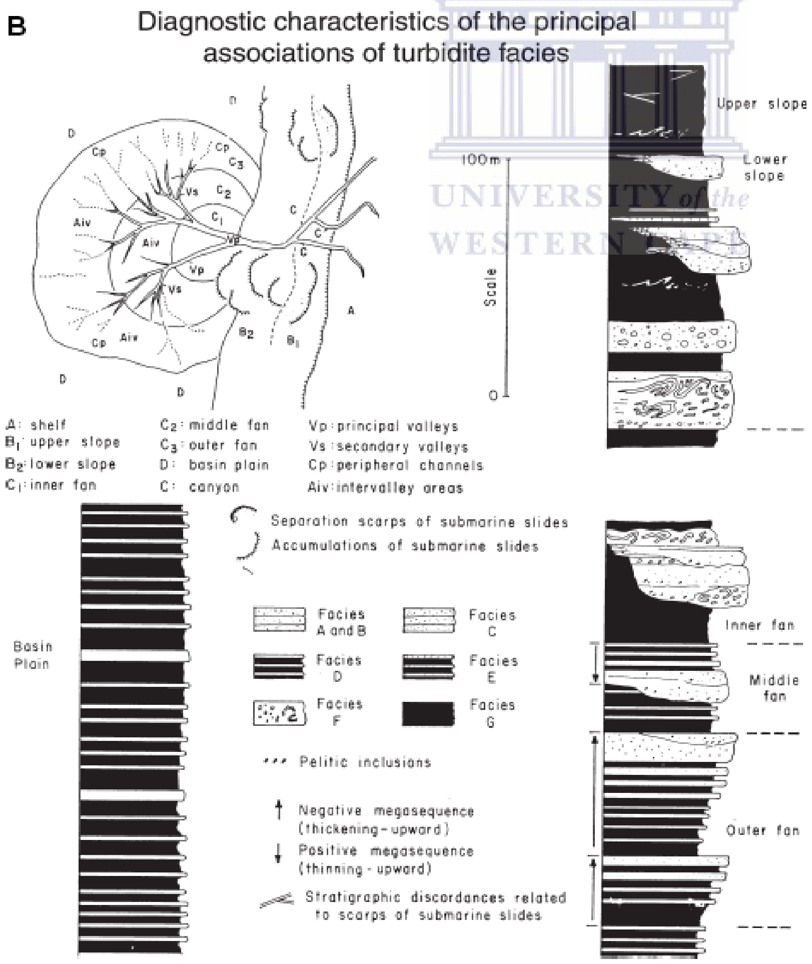


Figure 3.1 (B) Fan model of Mutti and Ricci Lucchi (1972).

3.1.2 The decline of fan models

It was not until COMFAN I (Committee on Submarine Fans), held in Pittsburgh in 1982 and hosted by Arnold H. Bouma, that many sedimentologists fully perceived the extent of the confusion surrounding turbidite sedimentation and, particularly, comparative studies of modern deep-sea fans and ancient turbidite systems; in other words, the meeting cast serious doubt on the general validity of apparently well-established fan models. The main conclusions of COMFAN I were summarized in special volumes (see Normark et al., 1983/1984, 1985; Bouma et al., 1985) and focused in particular on the many problems, primarily differences in scale and type of data sets, that were encountered when comparing modern and ancient fan systems (Mutti et al., 2009).

Mutti et al., 2009, see a somewhat different and more complex view of the relationships between marginal deltaic deposits and basinal turbidite systems that was offered by Mutti, 1985, mostly on the basis of stratigraphic and facies relationships observed in exposed orogenic belt basins.

Turbidite systems can differ greatly from each other primarily in terms of the characteristics of the receiving basin (e.g. type of crust, tectonism and basin configuration), as well as in terms of rate of sediment supply, longevity of sediment sources, eustasy and climate. Moreover, not all turbidite systems develop a plan-view fan morphology; rather, most ancient systems appear to have grown in tectonically confined basins as, for instance, the classical sandy flysch formations of orogenic belts (Mutti et al., 2009).

Authors cautioned stratigraphers and explorationists not to be misled by the application of existing models that did not take into account adequately the complex interaction of the many factors that control turbidite deposition and how these factors may vary with time during the different stages of growth of each system (Mutti et al., 2009).

Despite all the limitations discussed above, there are some fairly well-described and understood features, both erosional and depositional that are common to both recent and ancient turbidite systems. These features, which have been referred to as ‘turbidite elements’ by Mutti and Normark, 1987, (Figure 3.2) are ‘‘the basic mappable components of both modern and ancient turbidite systems and stages that can be recognised in marine, outcrop and subsurface studies’’ (Mutti and Normark, 1991). The correct recognition and mapping of these elements and of their relative stratigraphic importance within each considered system allows the definition of major classes of system, each characterized by specific types of internal architecture, facies distribution patterns and inferred processes. The approach, which is summarized briefly below, has been referred to as the ‘elemental approach’ (see also Normark et al., 1993, for a more extensive discussion of the seismic expression of turbidite elements). Piper and Normark, 2001, have provided an excellent example of application of the elemental analysis to modern fan systems with particular emphasis on the distribution of sandy elements (channel fills and channel-termination lobes).

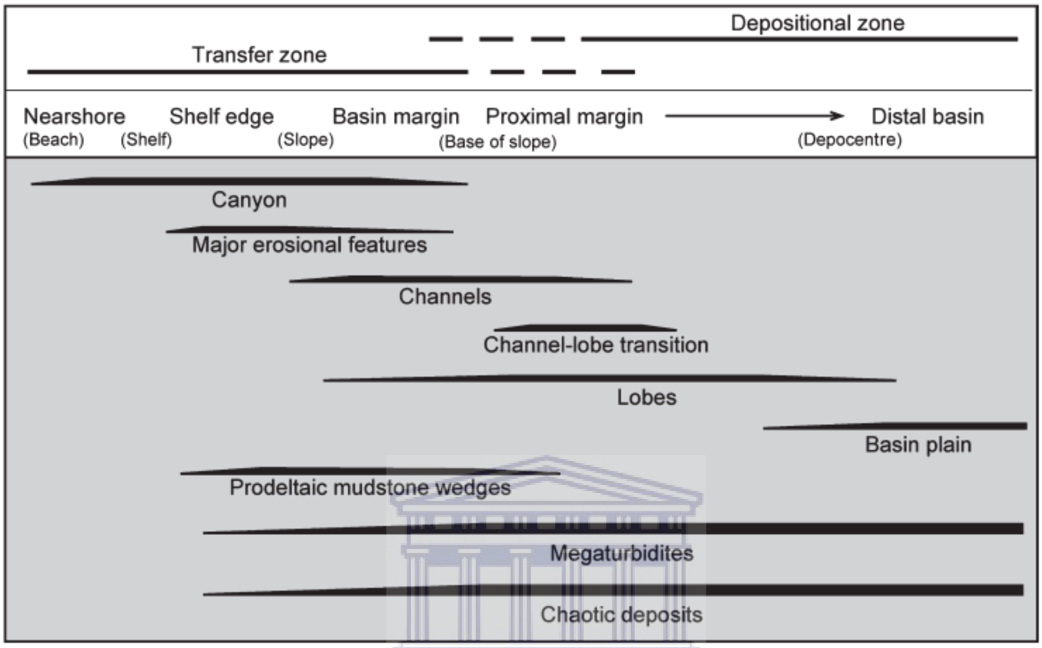


Figure.3.2 Main turbidite depositional elements recognizable in both modern and ancient systems (modified from Mutti and Normark, 1987, 1991; Normark et al., 1993; Piper and Normark, 2001).

With the need to exercise caution on the application of turbidite models to determine and predict facies distribution patterns and relationships Mutti et al., 2009, resorted to the incorporation of the ‘elemental approach’. This was done by looking at the seismic expression of these turbidite elements.

The characteristics of the receiving basin (e.g. type of crust, tectonism and basin configuration), as well as in terms of rate of sediment supply, longevity of sediment sources, eustasy and climate was also incorporated in this research.

Data from marine geological investigations have highlighted recently the importance of slide and slide-related deposits generated by instability processes along many continental margins worldwide and caused primarily by lowering of sea level, high rates of sedimentation, earthquake, and gas hydrate destabilization (see summaries in Hampton et al., 1996; and Canals et al., 2004 with references therein).

Thus, recently the focus of hydrocarbon exploration on divergent continental margins has moved to the so-called ‘mass transport complexes’ (MTCs; see Weimer, 1989, 1990 for a detailed discussion with particular reference to the Mississippi fan), i.e. folded, disrupted and chaotic units of considerable extent and with individual thickness of up to 200 to 300 m, which are displayed spectacularly on many seismic reflection profiles and marine geology imageries particularly in Quaternary deposits (Mutti et al., 2009).

Weimer, 1989, 1990, suggested originally that the use of the term MTCs be limited to those units which have a well-defined sequence-stratigraphic significance, i.e. units occurring at the very base of depositional sequences and that are commonly overlain by mud-dominated channel– levee complexes as in the case of the Pleistocene Mississippi fan; by contrast, the term 'slide' should be used when there is no sequence- stratigraphic context. The sequence-stratigraphic interpretation of most large-scale MTCs as baseof- sequence (early lowstand) deposits was accepted herein but the authors argued with the restriction of these deposits to slide and slump units, as apparently intended by Weimer and Shipp, 2004, when they stated that ''the term MTC be used for sediment that has experienced post depositional deformation and can be resolved at a multi-fold seismic scale''. Actually, an abundant literature, dating back to Dott ,1963, indicated that the term 'mass transport' included a spectrum of processes from isolated slide blocks to low density turbidity currents (e.g. Mutti and Ricci Lucchi, 1972; Nardin et al., 1979; Hampton et al., 1996; Canals et al., 2004). Changing this definition might cause serious confusion unless the reasons for this change are justified and discussed. Therefore, it is preferable to consider the 'mass transport complexes' of Weimer and Shipp, 2004, simply as 'chaotic deposits', i.e. units whose original bedding has been deformed, folded and disrupted during the process of mass transport (Mutti et al., 2009).

The facies of the re-sedimented family can be seen as in Figure 3.3 below.

Basin Plain and lower fan: These topographically smooth, low gradient areas are characterised by slow hemipelagic deposition, interrupted periodically by turbidity currents (Walker, 1978).

According to walker, 1978, five (5) main facies of deep-water clastic rocks basically exist:

The five main facies of deep-water clastic rocks can be defined as below:

- Classic turbidites (monotonously parallel-lnterbedded sandstones and shales without channeling).
- Massive sandstones (thicker, coarser and commonly channelized).
- Pebbly sandstones (tend to be well graded, and can contain parallel stratification and large-scale cross-stratification).

- Conglomerates and (inverse and normal grading, parallel and cross-stratification, and commonly have a preferred clast fabric (imbrication).
- Debris flows (with slumps and slides).

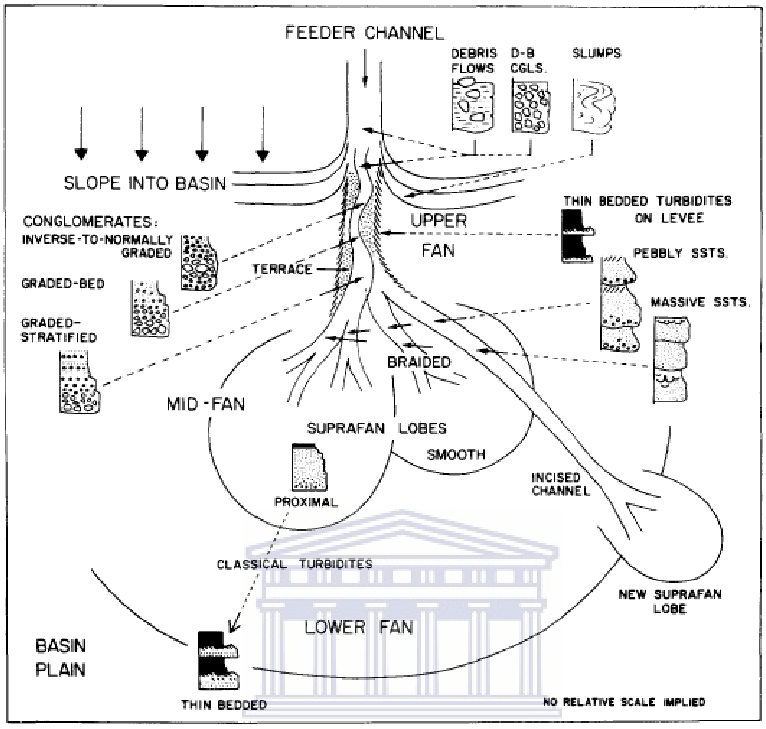


Figure 3.3: Model of submarine-fan deposition, relating facies, fan morphology, and depositional environment-Walker, 1978.

From Walker, 1978, levees of the upper fan channel tend to consist of fine-grained alternations of thin sandstone beds and mudstones. These belong to the thin-bedded turbidite facies and in ancient examples could easily be confused with similar facies on the basin plain.

The lateral facies above can serve to predict vertical stratigraphic sequences under conditions of *active fan progradation*. It is now possible to relate specific facies to specific parts of prograding fan systems (Walker, 1978).

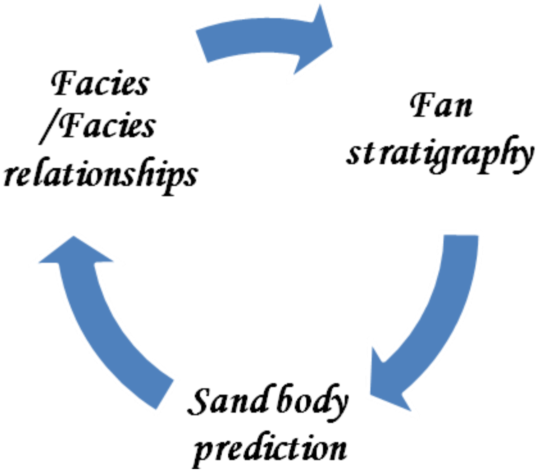


Figure 3.4: Uses of submarine fan model

Sandy turbidite systems can be generated by the resedimentation of deltaic deposits through submarine slides or be derived directly from flood-generated hyperpycnal flows; in the latter case, climatic variations must have played a fundamental role in controlling flood frequency and magnitude with time (Mutti et al., 2009).

Recognizing these two different types of system is not always easy and requires a good understanding of the geological context of the basin under consideration and particularly of the role of marginal fluvio-deltaic systems from which turbidites are ultimately derived.

The concept of ‘turbidite’ has evolved so much from its original definition given by Kuenen and Migliorini,1950, – i.e. the deposits of turbidity currents essentially exemplified by the Oligocene and Miocene sandy flysch successions of the Northern Apennines (Macigno, Cervarola and Marnoso-arenacea Formations) – that it is now used to define a variety of deposits that often have little in common with these sandy flysch in terms of facies, geometry and geological significance.

The concept of resedimentation of shallow marine or river-borne sand in deep-water environments through turbidity currents caused a revolution in the history of sedimentary geology. Because of the-then well established belief that sands were shallow-marine deposits whereas muds were characteristic of a deeper environment, interpreting the depositional environment of alternating sandstone and shale beds was quite problematic (Mutti et al., 2009).

The concept of Prevost, 1845, anticipated by Lavoisier, 1789, of the bathymetric significance of grain-size in clastic rocks whereby gravel and sand are deposited near the coast and mud offshore, was the current belief well into the 20th Century (Walker, 1973; and references therein). The deep sea was thought to be an area of non-deposition except for the rain of pelagic organisms (Maury, 1855). This view seemed to be confirmed by the results of the Challenger Expedition (1872 to 1876) which suggested that only pelagic clays, biogenic oozes and volcanogenic sediments were deposited in the deep sea and that sand and gravel were restricted to shallow-water or terrestrial environments (Murray and Renard, 1891).

However, observations in modern oceans suggested that sand was also transported from continents to the deep sea (Mutti et al., 2009). Well-sorted sands were discovered at abyssal depth by the Gazelle Expedition (1874 to 1876, e.g. Andre´e, 1920) and the now classical turbidite deposits of the Alpine and Carpathian flysch sequences, that defied an easy interpretation from the beginning, were interpreted as deep-sea deposits by several late 19th Century authors (Mutti et al., 2009).

Because of the close association of the flysch deposits of the Apennines with the chaotic complexes of the Argille scagliose, Fuchs, 1877a, b, interpreted the flysch deposits in general as the eruptive products of mud volcanoes but admitted that the sands and muds emplaced on the sea floor by them could be redeposited by currents. Later, in a fundamental review of ‘modern’ deep-sea sediments, Fuchs, 1883, argued for a deep-water origin of the flysch, without, however, mentioning the earlier mud-volcano hypothesis. Fuchs based this new interpretation on:

- The generally fine-grained nature of the sediments and the absence of (large-scale) cross-bedding (that was named ‘false bedding’);
- The absence of traces of birds, mammals or reptiles and mud cracks;
- The exclusively pelagic (ammonites) or deepsea organisms (fishes);
- The occurrence of sponge spicules and radiolarians;
- The ubiquitous trace fossils, particularly fucoids (Chondrites) that, in contrast to most authors of the time, were interpreted by Fuchs as burrows;
- Wrinkles on bed surfaces (load casts on lower bed surfaces).

The excellent preservation of all these biogenic or inorganic structures indicated to Fuchs, 1883, the absence of erosion and, therefore, deep and quiet waters. The mechanisms of transport, however, remained unexplained.

At the 18th International Geological Congress in 1948, Kuenen discussed the mechanics of turbidity currents of high density (already invoked by Johnson, 1939) but failed to recognize their depositional products in the field. Kuenen, 1950, writes: ‘‘The deposit of such a flow is probably inconspicuous in a sedimentary series”.

It was Migliorini who recognized these deposits and ‘‘argued that when a high-density current ceased to move larger blocks, the finer material would pass down gentle slopes to the lowest enclosed depression and there give rise to well graded sediments’’ (Migliorini in Kuenen, 1950). Indeed, it was the casual encounter of Kuenen and Migliorini at the 18th International Geological Congress in London in 1948 which set the stage for the scientific revolution (Walker, 1973) that was going to take place in Italy and Holland (Mutti et al., 2009).

In Italy, Signorini (1936), an eminent Italian geologist, was probably the first to recognize that the graded sandstone beds of the Miocene Marnoso- arenacea Formation were likely to represent a relatively deep-water deposit but failed to explain the possible mechanism of their deposition. The first interpretation of these beds in terms of ‘turbid’ density currents was offered by Migliorini in a historical paper published in 1943 and written in Italian (for an English translation, see Ricci Lucchi, 2003a). In this very short paper, Migliorini interpreted the graded beds of the Macigno Formation as resedimented, i.e. as sand originally deposited in shallow waters and then displaced to deep waters by turbid density currents triggered by slope instability processes.

Although the main scientific contribution of Migliorini will certainly remain that of the interpretation of graded sandstone beds as deep-water deposits produced by dense ‘turbid’ currents, Migliorini also developed the ideas of orogenic ridges, composite wedges and orogenic submarine landslides (frane orogeniche) which formed most of the conceptual background onto which Merla, 1951, 1957, built an interpretation of the Northern Apennines in terms of gravity tectonics and migration of orogenic ridges.

It can be said that the paper of Migliorini published in 1943 should be considered as a milestone in sedimentary geology and sedimentology. However, it was not until 1950 that these concepts were widespread in the scientific community through the famous paper written jointly with Kuenen that appeared in the Journal of Geology with the title ‘Turbidity Currents as a Cause of Graded Bedding’.

The term ‘turbidite’ was introduced only in 1957 by Kuenen (following the suggestion of his student C.P.M. Frijlink; Kuenen, 1957a) and was clearly intended as synonymous with the ‘graded sandstone beds’ of Kuenen and Migliorini, 1950. The 1950s and the early 1960s were a fertile period of research mainly carried out by students of Kuenen through field studies of flysch formations of the Northern Apennines (Ten Haaf, 1959), Maritime Alps (Bouma, 1962; Stanley and Bouma, 1964) and Carpathian mountains (Dzulynski and Slaczka, 1959; Unrug, 1963).

Laboratory experiments on turbidity currents, pioneered by Kuenen (1937, 1950), have been regarded as fundamental to an understanding of the transport and the deposits of these currents which are inherently difficult to observe in the Recent, mainly because of their episodic and catastrophic nature and the water depth at which they fully develop.

3.1 The Bouma sequence

The Bouma sequence (Bouma, 1962; Figure 3.5), the summary of the observations of Bouma in the Tertiary turbidites of the Annot Sandstone and to a lesser extent, the sandy flysch formations of the Northern Apennines, became synonymous with turbidite and the standard model. By using this model and its plane-view expression (the depositional cone, see Figure 3.5), qualitative (Parea, 1965) and quantitative (Walker, 1967) approaches were developed to define ‘proximal’ versus ‘distal’ turbidite deposits, i.e. a means of recognizing the products of a turbidity current implicitly viewed as an unsteady and non-uniform flow decelerating with time and distance.

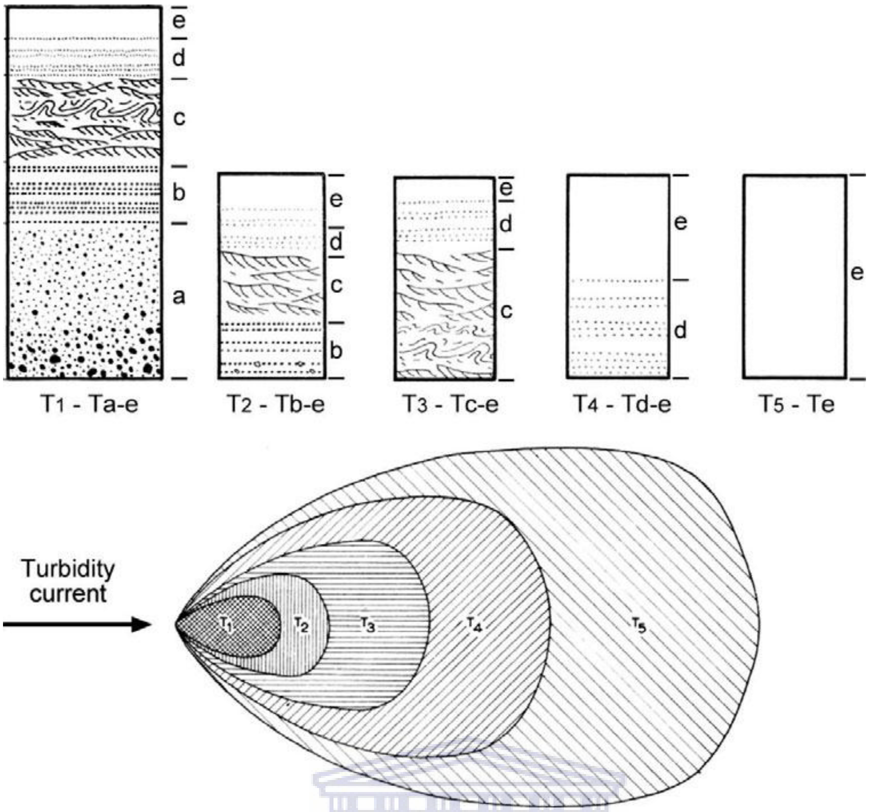


Figure. 3.5. The Bouma sequence and its 'depositional cone' (from Bouma, 1962).

Sediment gravity flows and more complex facies schemes Middleton and Hampton, 1973, 1976, first recognized the complexity of facies and depositional processes of deep-water sediment associated with classical turbidites (those conforming to the Bouma sequence) and attempted to develop the broader concept of 'sediment gravity flows' (commonly abbreviated to 'gravity flows'). Four basic types of flow (and in a more cursory way, their related types of deposit) were identified according to the different mode in which particles can be sustained within each type of flow:

(i) Debris flow (flow strength); (ii) grain flow (grain-to-grain collisions); (iii) fluidized flow (upward water escapement); and (iv) turbidity current (turbulence) (Figure 3.6(A)

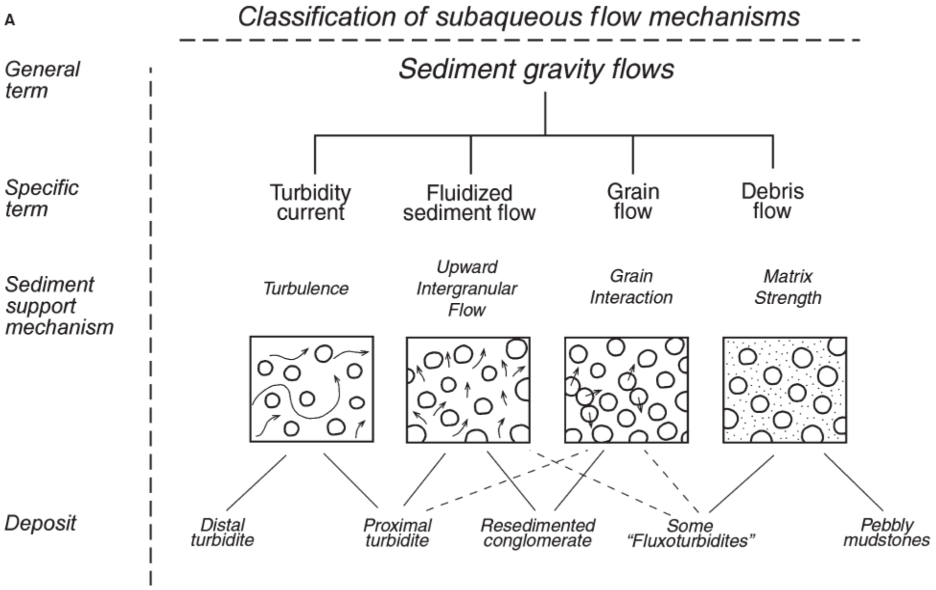


Figure 3.6(A) Classification of subaqueous sediment gravity flows as suggested by Middleton and Hampton (1973)

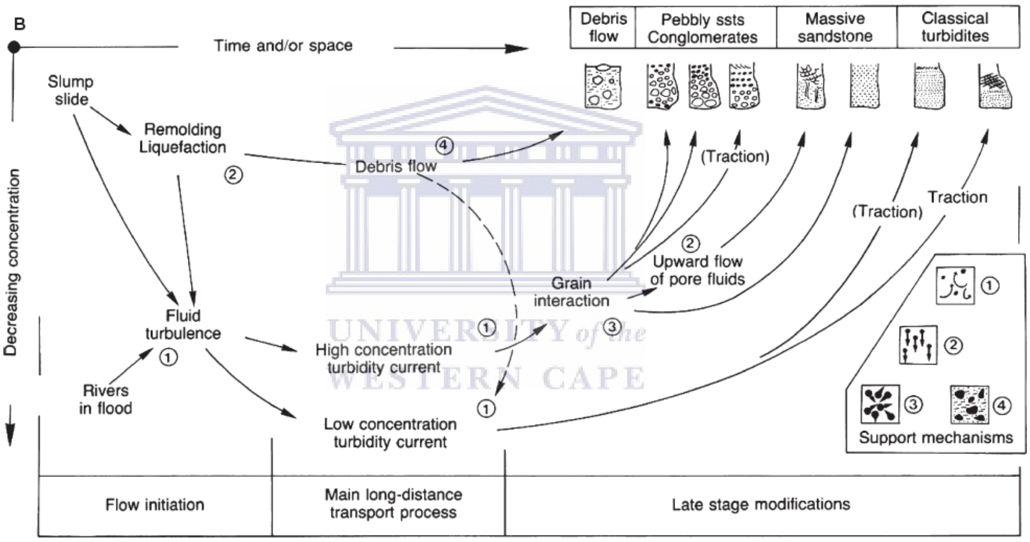


Figure 3.6(B) Genetic facies scheme of Walker (1978) (ssts = sandstone].

The role of inertia-driven dense flows is assumed by Mutti et al., 1999, 2003a, b, to be the fundamental force in carrying sand over considerable distances along the basin floor before the flow loses its excess pore pressure and is thus forced to deposit its load because of frictional freezing.

Mutti et al., 1999, 2003a, b, emphasized the bipartite nature of most turbidity currents, i.e. a basal and faster moving inertia-driven dense flow (the flowing grain layer of Sanders, 1965), with excess pore pressure, and an overlying more dilute turbulent flow (Figure 3.7 below).

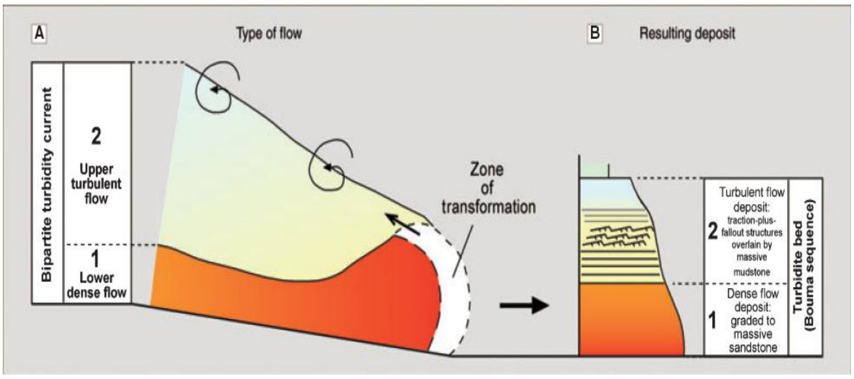


Figure 3.7 Example of a bipartite turbidity current reproduced in laboratory experiments (inspired from Mohrig and Marr, 2003).

Not all turbidity currents are necessarily bipartite, depending upon the origin and the efficiency of each flow and the distribution of grain-sizes available (Mutti, 1992).

Most turbidity currents carrying a significant proportion of coarse grain-size populations as their sediment load can be viewed as bipartite flows. This view not only stresses the importance of previous studies (e.g. Sanders, 1965; Ravenne and Beghin, 1983; Norem et al., 1990) but also suggests that part of the deposits of such bipartite flows forms a variety of *quite different but genetically linked facies*. Laboratory experiments strongly support this conclusion by showing how, for instance, the head of sandy coherent debris flows transforms into a fully turbulent flow (turbidity currents) during their downslope motion (e.g. Mohrig and Marr, 2003).

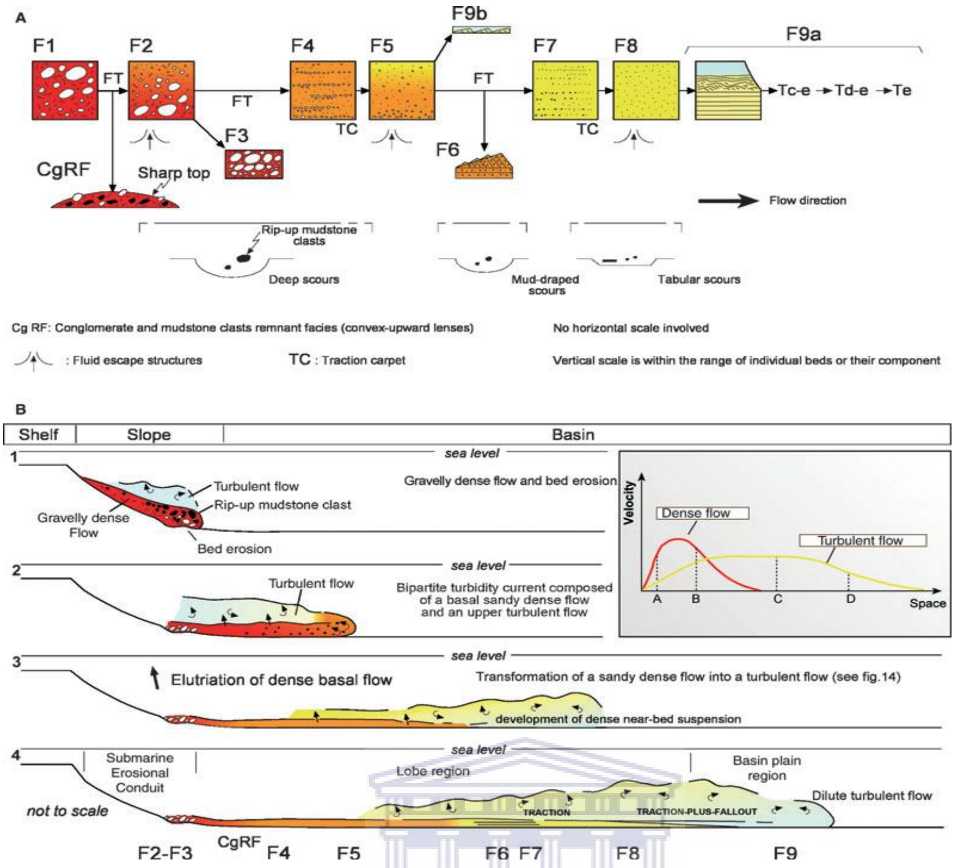


Figure 3.8 (A) Framework for a predictive classification scheme of turbidite facies (slightly modified from Mutti, 1992; for a more updated version, see Mutti et al., 2003b). (B) Main erosional and depositional processes associated with the downslope evolution of a turbidity current (from Mutti et al., 2003b).

Obviously, it would certainly be confusing and inappropriate to define all the above spectrum of deposits as ‘turbidites’ therefore restricting the term to denote the part of the spectrum deposited by plastic and fluidal flows (in the sense of Lowe, 1979; see also Lowe, 1982) might be a reasonable and wise choice. Basically, such a definition of ‘turbidites’ would include resedimented conglomerates, pebbly sandstones, massive sandstones and ‘classic’ turbidite sandstones as implicitly suggested – although with some variations among different authors – by Mutti and Ricci Lucchi, 1972, 1975; Walker and Mutti, 1973; Walker, 1978; Mutti ,1979; Lowe ,1982 and Mutti,1992.

3.2 Sequence-stratigraphic framework of turbidite deposition

Sequence-stratigraphic concepts – a natural evolution of earlier seismic–stratigraphic concepts (see above- Chapter 1) and the way in which turbidite systems would fit these new schemes – were introduced in the late 1980s by Wilgus et al.,1988, and in numerous subsequent volumes (e.g. Van Wagoner et al., 1990; Weimer and Link, 1991a; Weimer and Posamentier, 1993; Weimer et al., 1994). Most of this work was devoted largely to assessing the exploration potential and the seismic expression of turbidite systems around the world (e.g. Weimer and Link, 1991b).

Sequence-stratigraphic concepts for an interpretation of turbidite systems are shown in Figure 3.9 describing basin-floor and slope-fan depositional systems as lowstand system tracts during the development of a cycle of relative sea level variation. The basin-floor fan is thought to be coeval with the basal unconformity of the depositional sequence to which it belongs (and therefore the early lowstand basin-floor fan has no stratigraphic equivalence on the shelf) and the slope fan would form immediately after, during the rapid progradation of a lowstand delta under conditions of much reduced accommodation space.

In general, the basin-floor fan is a sand rich feature, commonly with a mounded geometry (e.g. Mitchum, 1985), whereas the slope fan is mud-prone, locally containing ‘shingled’ sandy turbidites deposited in a mudstone-dominated delta-slope environment (Mutti et al., 2009). Basin floor fans are typically isolated massive mounds or well-sorted grain flows or turbidite sands derived from alluvial valleys or nearshore sands (Neal et al., 1993).

As long as turbidite sedimentation is restricted to divergent continental margins, eustasy should exert a dominant control on sea-level variations, as assumed by Posamentier and Vail, 1988, and Vail et al., 1991.

However, tectonism in such settings, associated with salt and mud mobility and growth faults, might produce locally more or less substantial departures from predictable eustasy-controlled cycles. Eustasy-dominated cycles of relative sea-level variations are not equally important in thrust-and-fold belt basins. In such basins, tectonism may play a major role in generating relative sea-level variations and therefore substantial basinward shifts of marginal-marine facies belts when rates of tectonic uplift (relative sea-level fall) and subsidence (relative sea-level rise) exceed those of eustatic variations (e.g. Mutti, 1985, 1990).

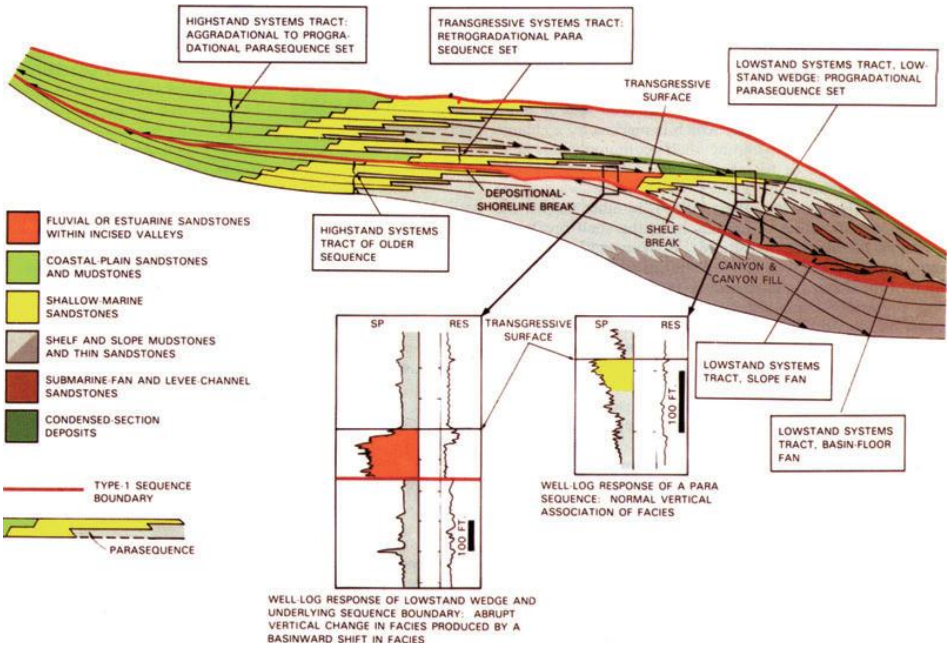


Figure 3.9 Sequence-stratigraphic model for lowstand deep-water siliciclastic systems (from Van Wagoner et al., 1988). Note the basal sand-rich basin-floor fan with a pronounced mounded external geometry overlain and downlapped by the mud-rich slope fan.

According to Mutti et al., 2009, it appears that in the study of turbidite systems, sequence-stratigraphic models need to be integrated not only with more information on the tectonic history of the basin under consideration but also with sufficient sedimentological data to be able to adequately describe and interpret the turbidite systems considered.

3.3 Sequence Stratigraphic analysis and interpretation

Classic sequence stratigraphy begins with the subdivision of seismic data into genetic reflection packages, also referred to as seismic sequences and systems tracts (Hoek et al, 2010). They explain it as being done by identifying discontinuities on the basis of seismic reflection terminations (onlap, downlap, truncation, toplap, and apparent truncation).

Subsequent subdivision of the sequences and systems tracts into seismic facies units using seismic facies analysis (description and geological interpretation of seismic reflection parameters such as configuration, continuity, amplitude, frequency, and interval velocity) facilitates the interpretation of environmental settings, depositional processes and lithology predictions (Vail, 1987).

The definition of facies analysis is given by Anderton, 1985, as the description and characterization of sediment bodies, which can be interpreted in terms of depositional process and depositional environment. For this purpose, sedimentary rocks can be classified by their specific characteristics such as lithology, composition, colour, geometry, sedimentary structures, and fossil contents (Pirrie, 1998). Thus, seismic facies analysis can be defined as the study of the description and classification of seismic data into different seismic packages, which are distinguished by specified characteristics from adjacent reflectors. In seismic data, parameters like reflection configurations and various seismic parameters including amplitude, continuity, phase, frequency, and interval velocity are frequently used to describe and characterize these seismic units (Vail et al., 1987). These parameters can be used to infer the geological information on lithology and depositional process and environment, which is one of the main purposes of seismic facies analysis. Even though there is no unique relationship between specific seismic parameters and litho-facies, reasonable geological information such as depositional environment and lithology can be extracted from seismic facies analysis when combined with well logs, cuttings descriptions and paleo-data (Whittaker, 1998).

3.3.1 Seismic attributes

Seismic attributes measuring seismic continuity, frequency, amplitude and interval velocity characteristics have been in existence for decades, but these traditional derivatives do not address the large-scale building blocks common to sequence stratigraphy. They instead address seismic data on local scales (single trace to 3-9 traces, making computation fairly straightforward) (Hoek et al., 2010).

In contrast, seismic geometries associated with sequence stratigraphy, consisting of both external form and reflection configuration, (e.g. Mitchum et al., 1977) have been much harder to derive as seismic attributes (Hoek et al., 2010). The critical challenge here has been the need to capture *relevant seismic geometries* at scales in the range of hundreds to thousands of seismic traces.

To illustrate the methodology underpinning these geometric attributes and their application, Hoek et al., 2010, created a simple synthetic seismic section (1D convolution), using Vail’s systems tract schematic as the basis for analysis (Figure 3.10 a).

A fundamental element to our approach was also the analysis of the seismic dip field (Figure 3.10b). There are several ways to characterize the dip, the least ambiguous of which is to define the normal vector field which is everywhere perpendicular to seismic reflections.

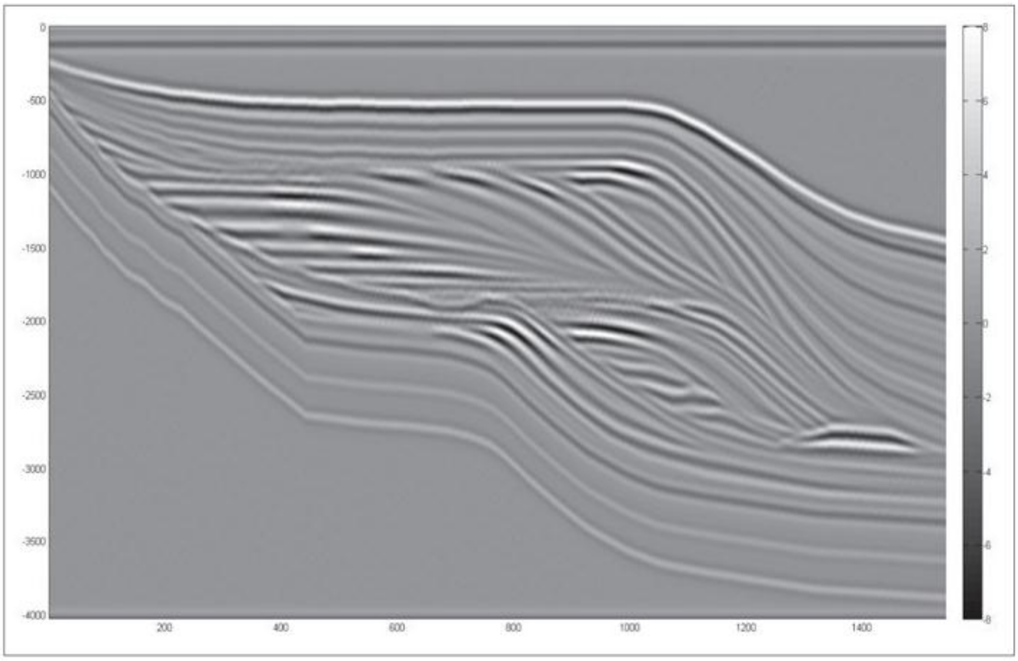


Figure 3.10 a.: Synthetic version of Vail's seminal systems tract schematic used to illustrate the geometric attributes and pseudo-Wheeler display. (After Vail, 1987). Vertical axis = ms and horizontal axis= traces.

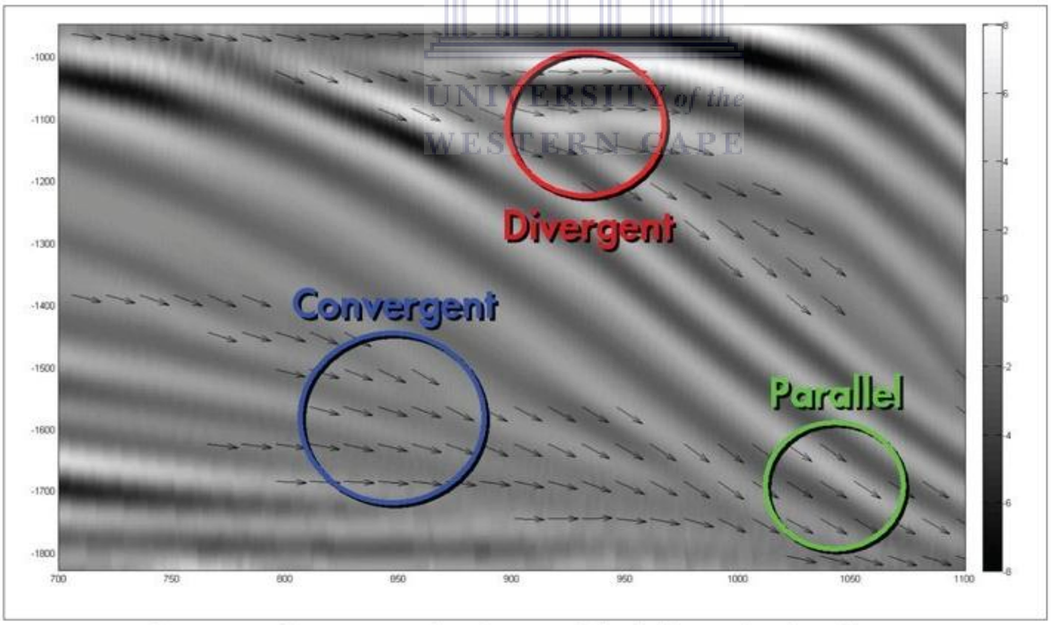


Figure 3.10b: Enlargement of Figure 3.10a above with a decimated dip field visualised on the section. Geometric information is contained within the dip field as illustrated by the divergent, convergent, and parallel regions. (After Hoek et al., 2010).

In this research we were basically looking at three (3) basic geometric attributes out of the four that Hoek et al., 2010 discuss. They are as below:

3.3.1.1 Thinning attribute

The "thinning" attribute quantifies the degree of seismic reflection convergence (or divergence) of a seismic package over a moderate to large scale (typically 100 – 500 seismic traces; Figure 3.11). In contrast to other attributes that highlight local features such as channels or faults, the thinning attribute enhances reflection packages defined by different external geometries (i.e., parallel versus thinning). The latter, combined with their associated reflection terminations (i.e., onlap, downlap, toplap, etc), aid the interpreter in recognising significant stratigraphic packages such as parasequences, sequences and groupings of stratigraphic elements in general.

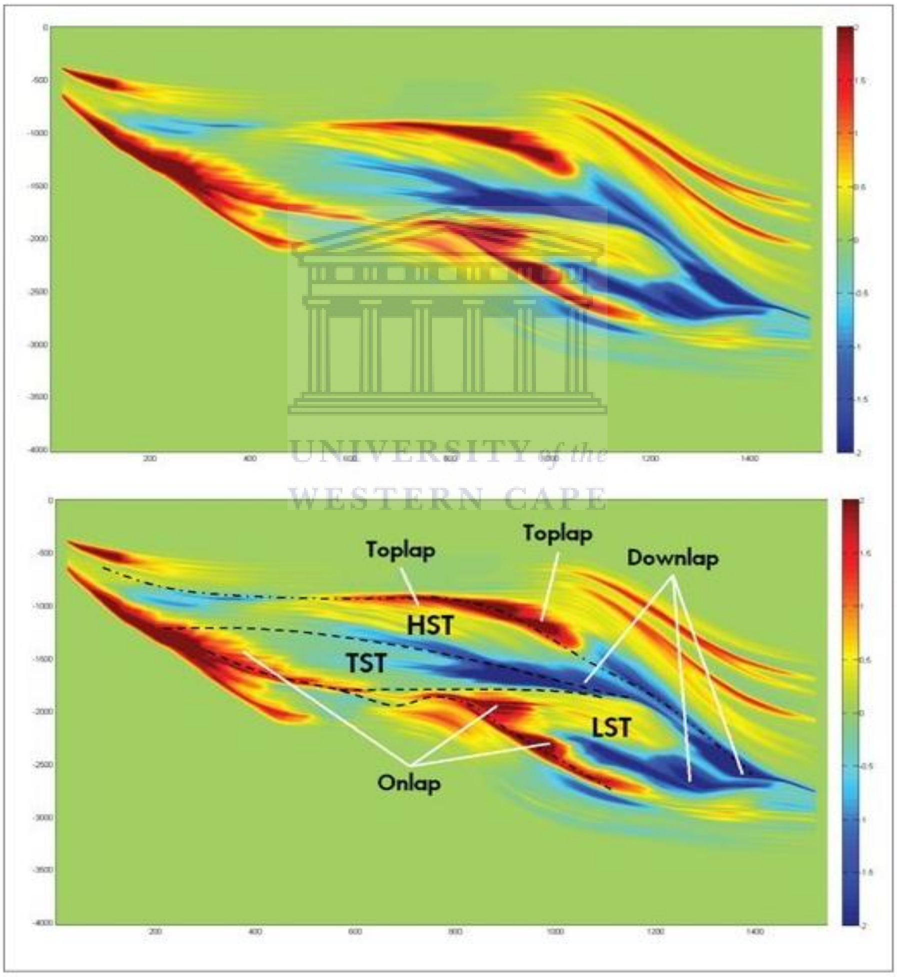


Figure 3.11.: Thinning attribute highlights reflection terminations (i.e., onlap, downlap), thereby indirectly delineating reflection packages in space and time. Both systems tract as well systems tract elements can be interpreted. HST= highstand systems tract. TST= Transgressive systems tract. LST= Lowstand systems tract.

3.3.1.2 Unconformity attribute

The "unconformity" attribute computes the degree of conformability (or inversely the degree of unconformabilty) of seismic reflections over a large scale (typically > 1000 traces Figure 3.12)

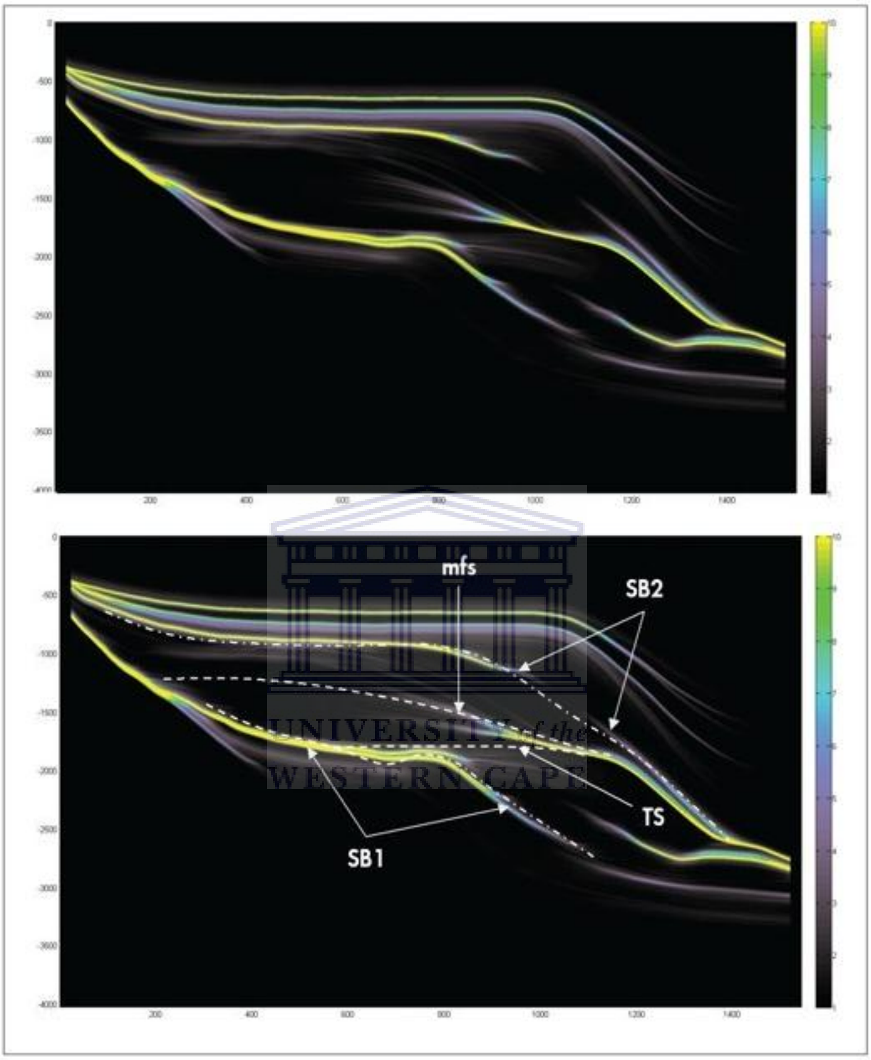


Figure 3.12: The unconformity attribute highlights sequence boundaries, but also downlap surfaces and transgressive surfaces. SB1= type 1 sequence boundary. SB2= type 2 sequence boundary. Mfs= maximum flooding surface.

The unconformity attribute reduces seismic data to a set of key horizons, allowing the interpreter to build a framework of regional correlative markers. The latter, combined with results of the thinning attribute and Wheeler analysis, provide the basis for system tracts delineation and sequence stratigraphic analysis at a range of scales (first to higher order, depending on need) (Hoek et al., 2010).

3.3.1.3 Seismic facies attribute

The “seismic facies” attribute provides a measure of the degree of parallelism of seismic reflections on a moderate scale (typically 10 – 50 traces; Figure 3.13). In 2D seismic data, it maps data across a spectrum with two end members: “layer cake” and “chaotic”. Within a sequence stratigraphic framework, this attribute (unlike the thinning and unconformity attributes) works on a sub-systems tract scale and can be used to unravel depositional environments within systems tracts, based on their seismic facies.

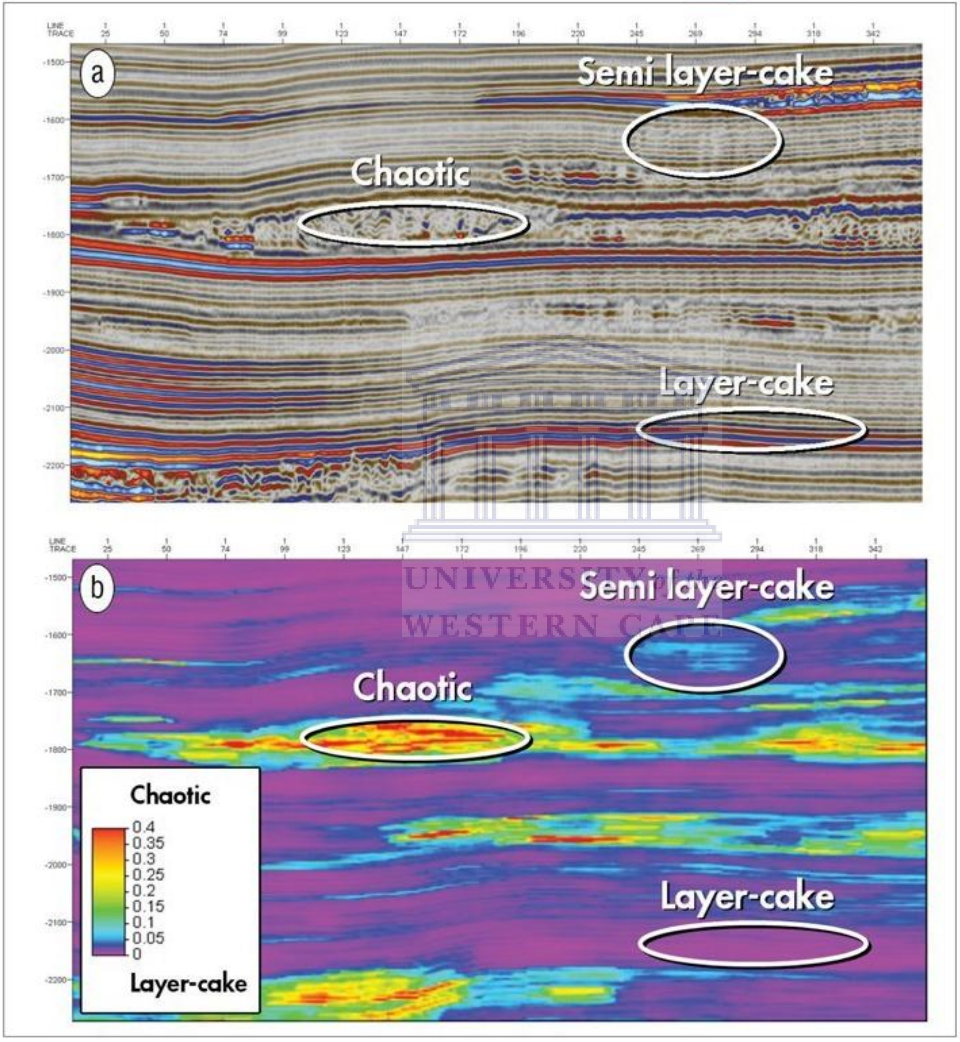


Figure 3.13.: The facies attribute. (a) Seismic section with a spectrum of layer-cake to chaotic seismic signatures. (b) The facies attribute; high values = chaotic, low values = parallel. The attribute distinguishes chaotic. The attribute distinguishes chaotic and layer-cake “facies”, and identifies semi layer cake signatures corresponding to wavy or parallel but “broken-up” reflectors. Vertical axis = ms. Horizontal axis= traces.

3.3.2 Wireline log attributes

Each systems tract exhibits a characteristic log response, seismic signature and paleontologic fingerprint (Neal et al., 1993). It is common knowledge that gamma ray (GR) and spontaneous potential (SP) logs read low in sands and high in shales.

Neal et al., 1993, further affirm that log responses in basin floor fans are blocky, with a sharp top and bottom bracketing clean sand while log responses of slope fans are commonly crescent shaped. The sharp base within the crescent bell shape indicating fining upward as the channel is abandoned while slumps from shelf edge deltas create a chaotic or jumbled pattern- "hummocky" in interpreter's vernacular.

The top of the transgressive systems tract is the limit of marine invasion and is called the maximum flooding surface. This clay rich layer shows low resistivity and high gamma ray readings (Neal et al., 1993).

Part of the upper lowstand, the prograding wedge complex derives its name from shallowing upward deltas that build basinward from the shelf edge and pinch out landward at the preceding shoreline. Log response shows more sand higher in the section and less basinward (Neal et al., 1993).

3.3.3 Biostratigraphy

Fossils of planktonic (floating) organisms are more widespread than those of benthic (bottom-dwelling) organisms and are therefore more useful in establishing regional time correlations (Neal et al., 1993). They further affirm that fossils are indicators of relative sea level (high fossil counts or peaks associated with shales deposited during low sedimentation) and that biostratigraphy holds the key to paleobathymetry (a measure of topography of ancient ocean floor) needed to interpret the depositional environment.

The surface of maximum sediment starvation and the maximum flooding surface are commonly marked by a concentration of microfossils, authigenic glauconite, phosphatic and sideritic fossil molds (steinkern), and encrusted and bored fossils (Baum and Vail, 1988; Loutit et al., 1988).

3.3.4 Cores

Each geological characterisation needs a framework for comparison of the subsurface data set with outcrop-based data set (Fugelli and Olsen, 2005). They further assert that the framework includes qualitative geological information on basin characteristics, tectonic history, stratigraphy, depositional system and lithofacies.

In this study cores proved to be very crucial and vital not only for calibrating the detailed seismic and log interpretations but in revealing the distinct facies peculiar to turbidites as well as their structures.

CHAPTER FOUR

Case Study: Reservoir Characterisation (Searching for Sand) in the Southern Outeniqua Basin.

RESULTS and DISCUSSION

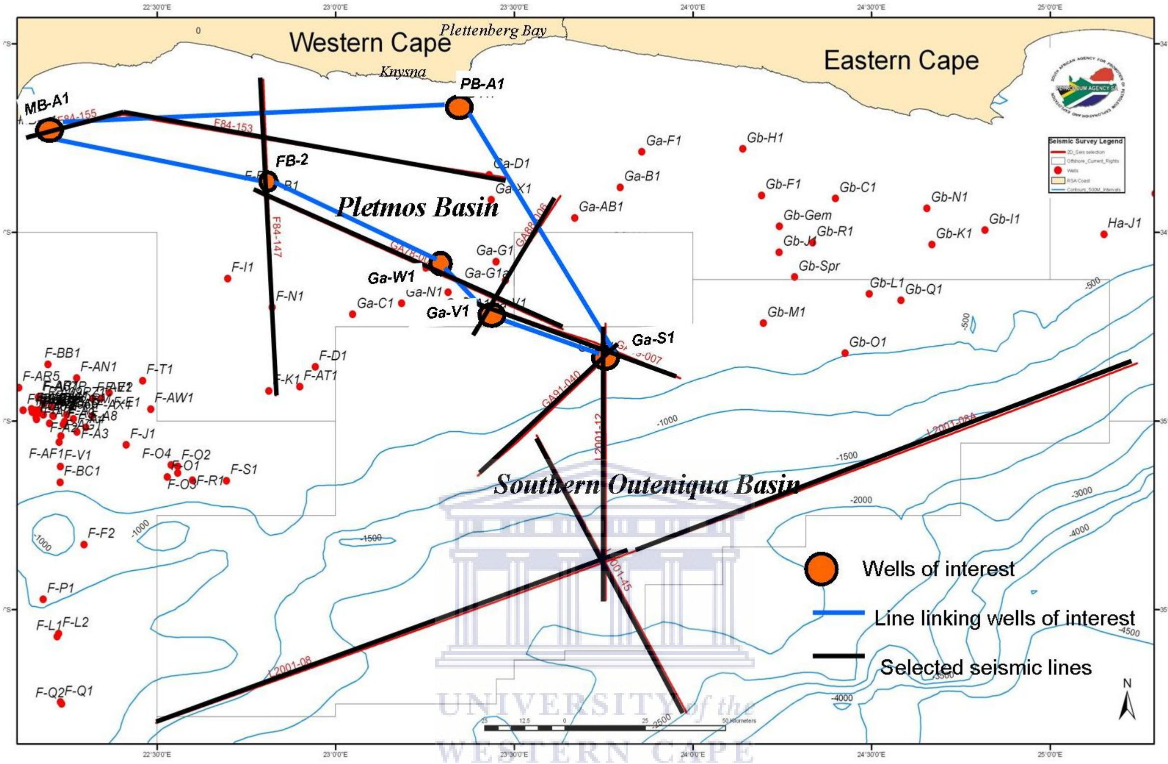


Figure 4.1: Study area: Pletmos and Southern Outeniqua Basin (Modified from Petroleum Agency of South Africa, 2010).

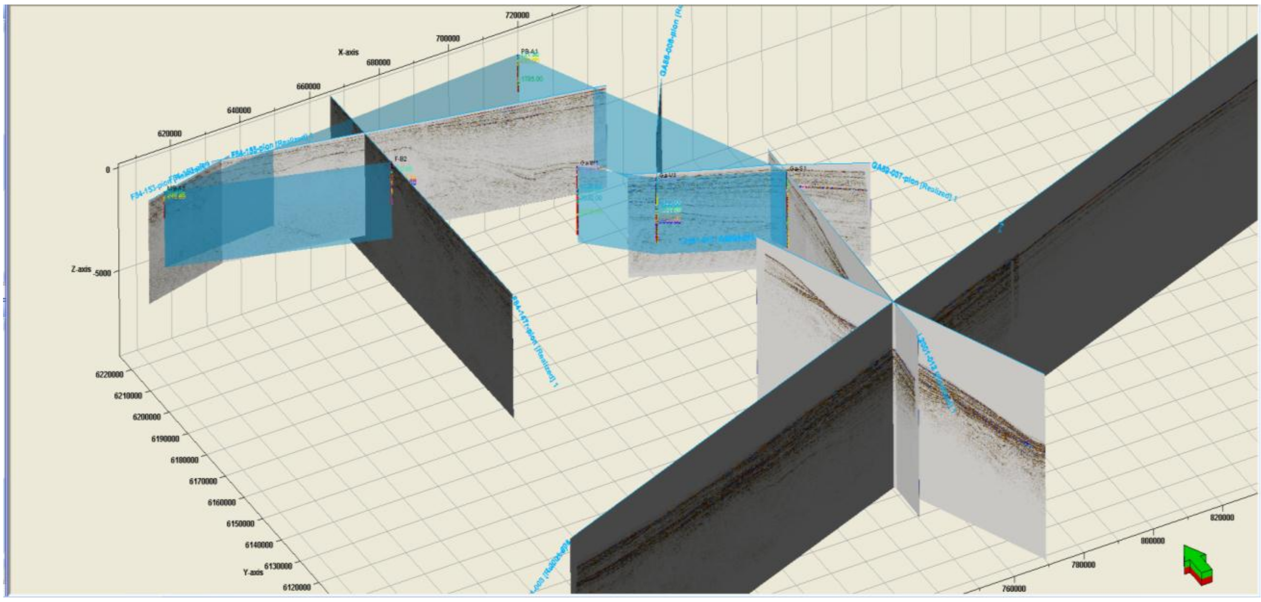


Figure 4.2: Study area: Pletmos and Southern Outeniqua Basin in display cube in Petrel

4.1 Structural Interpretation

Stratigraphic study is always preceded by structural interpretation (Neal et al., 1993). Structural analysis and interpretation cannot be overlooked as it is an essential component as tectonics and faults in particular tend to influence depositional trends. It is in this light that some structural interpretation of the study area was carried out using Schlumberger Petrel software. This entailed identification of faults and fault modelling.

In the southern Cape, the elongate asymmetric anticlines and synclines of the Cape Fold Belt trend approximately E-W between about 20 and 24°E, before swinging sharply SE in the vicinity of Port Elizabeth (Figure 2.8 Dingle et al., 1983). The arcuate trend of the basin-bounding fault system is most likely inherited from the underlying orogenic Cape Fold Belt (De Swardt and McLachlan, 1982).

During a relative fall in sea level, sediments were deposited as slope and basin fans following the structural trend imposed by the basin-bounding faults in these basins (Pletmos and Southern Outeniqua basins). Progradational sequences mostly were found on seismic lines which trended NW-SE. As can be seen on seismic lines (e.g. L2001-45), more progradational sequences trended NNW-SSE.

Seismic expressions on line F84-155 (Figure 4.3) below indicate a broad channel with not well developed levees as well as large scale slumps with jumbled seismic character.

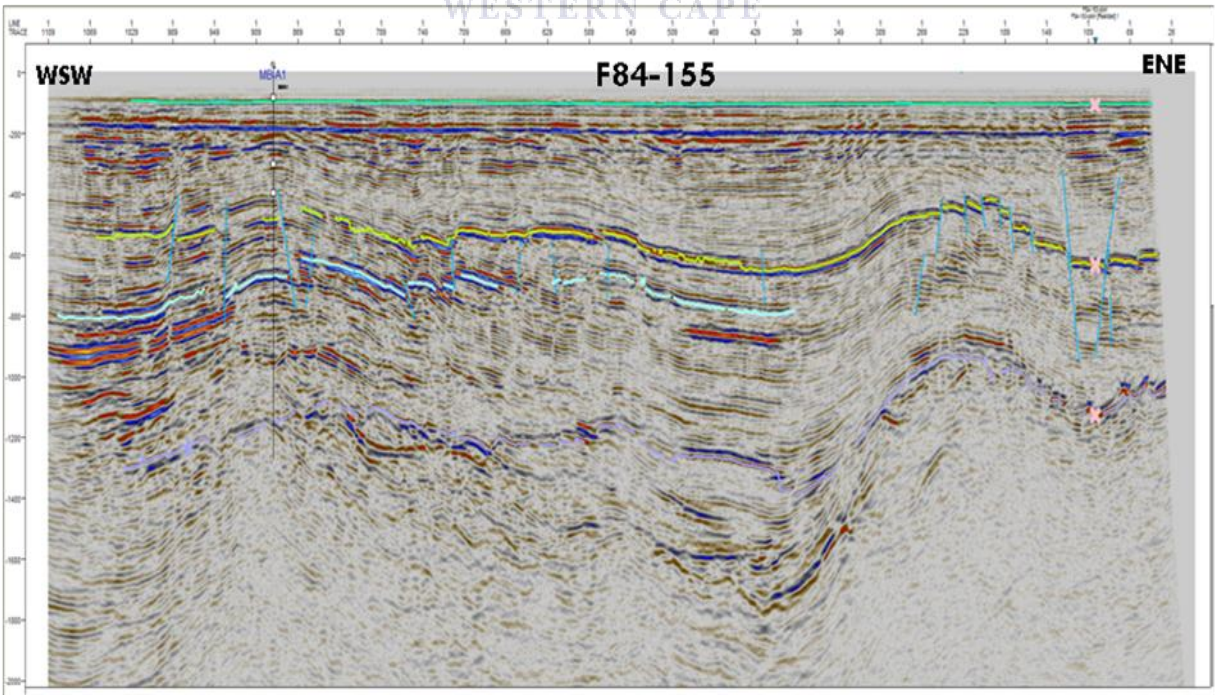


Figure 4.3: Seismic section displaying faults trending NW-SE.

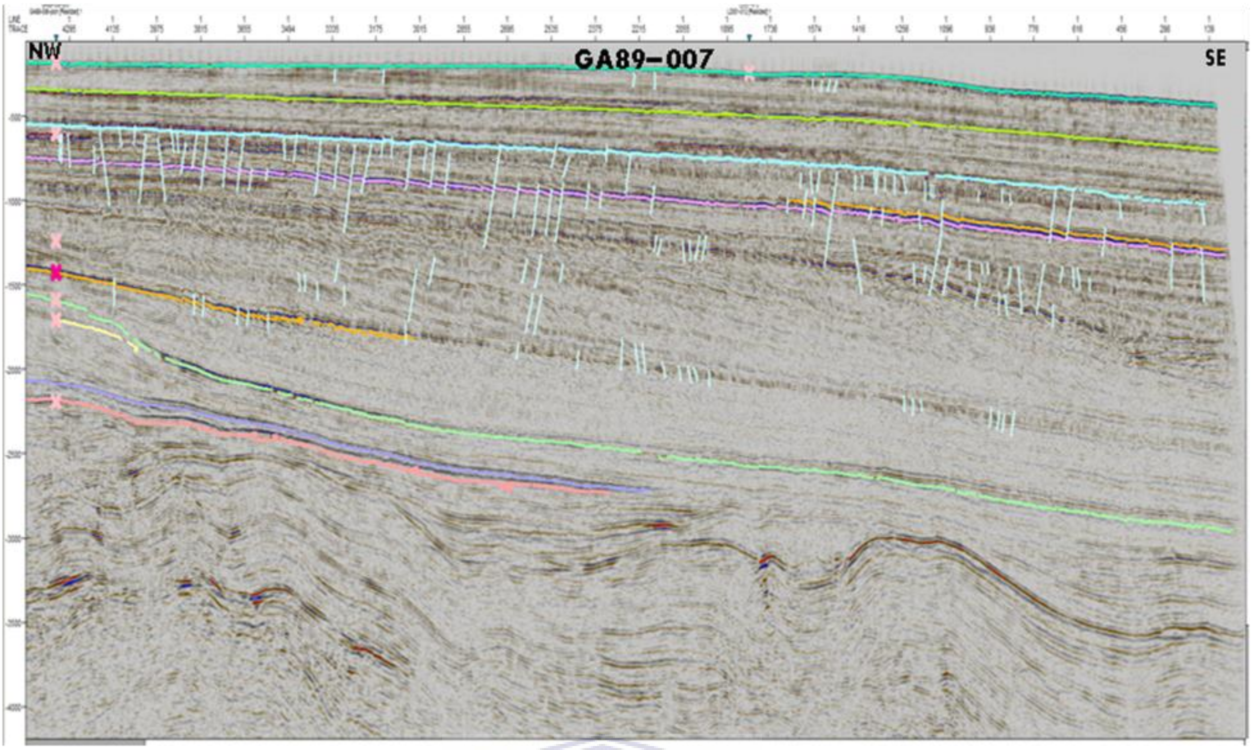


Figure 4.4: Seismic section displaying faults trending almost N-S.

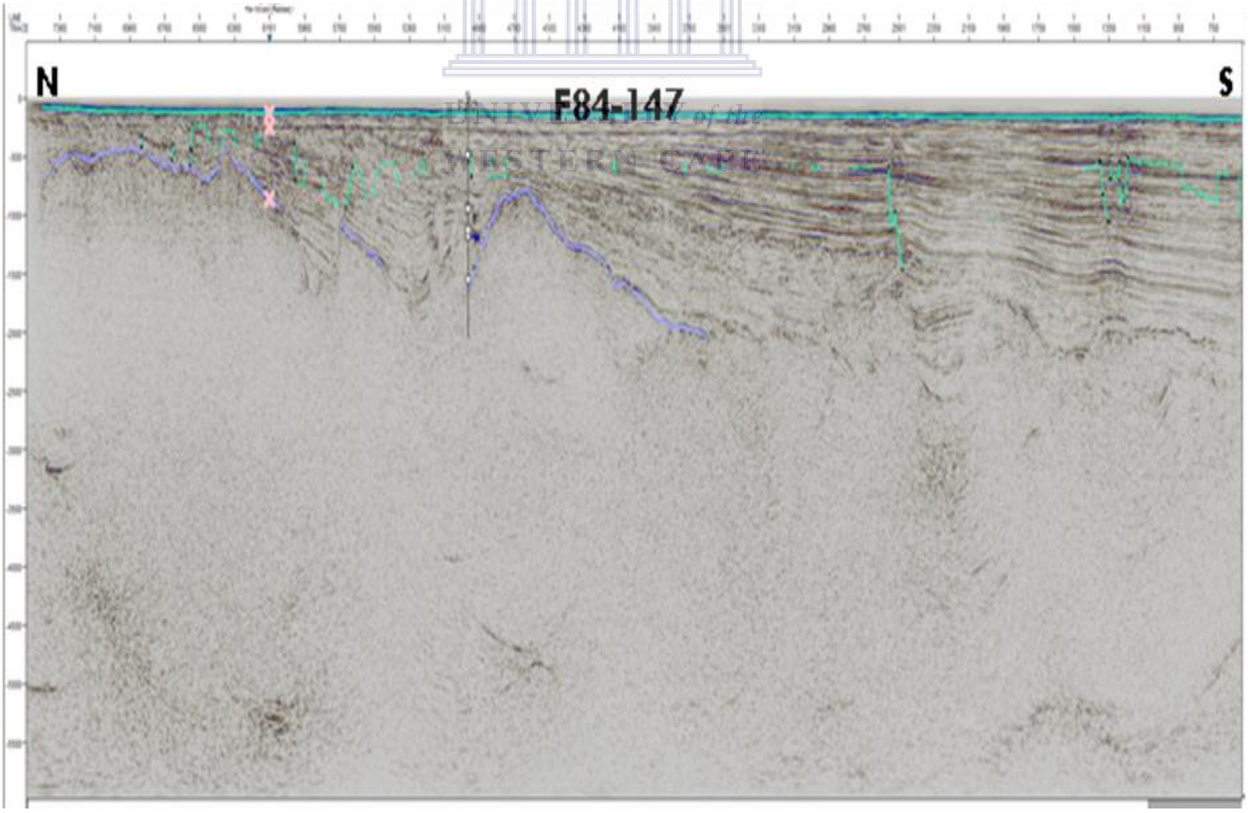


Figure 4.5: Very slightly faulted N-S seismic section.

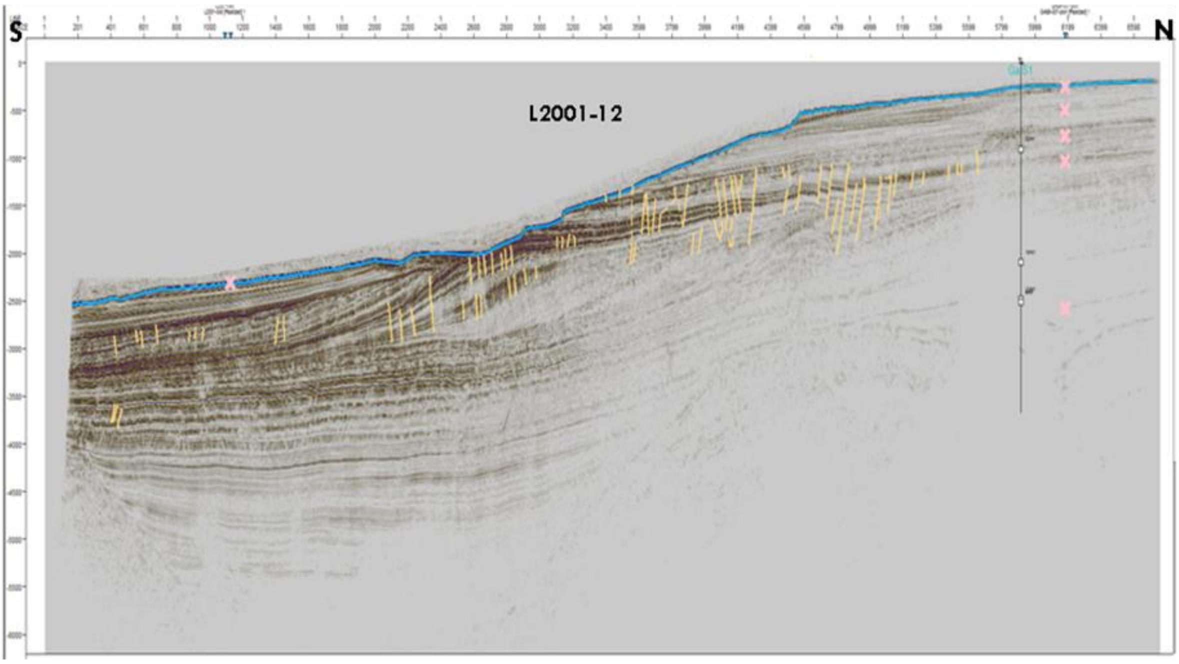


Figure 4.6: Seismic section displaying E-W trending faults.

4.2 Seismic Stratigraphy

Classic sequence stratigraphy begins with the subdivision of seismic data into genetic reflection packages, also referred to as seismic sequences and systems tracts (Hoek et al, 2010).

Seismic geometries associated with sequence stratigraphy, consisting of both external form and reflection configuration, (e.g. Mitchum et al., 1977) have been much hard to derive as seismic attributes (Hoek et al., 2010). The critical challenge here has been the need to capture *relevant seismic geometries* at scales in the range of hundreds to thousands of seismic traces. Here we present a three moderate-to-large scale seismic geometric attributes that blend classical sequence stratigraphy with modern seismic attribute generation. This method was proposed by Hoek et al., 2010.

Pletmos sub-basin, covers approximately 18 000 km^2 (Visser, 1998) and has sediment thickness up to 11 000 m in local depocentres (Broad et al., 2006) of passive margin shallow- and deepwater marine sediments., This provides an excellent opportunity to demonstrate the geometric seismic attributes since the seismic lines are regional in coverage.

Within the area of study, large scale seismic attributes to small scale seismic attributes were observed with tectonics (e.g. faults) sometimes offsetting feeder systems.

Thinning geometries, unconformity attributes as well as seismic facies attributes were all observed on the 2D seismic lines. The analysed and interpreted seismic sections consist of numerous traces with location given along the x-axis and two-way travel time along the y-axis. They are exemplified in the following figures.

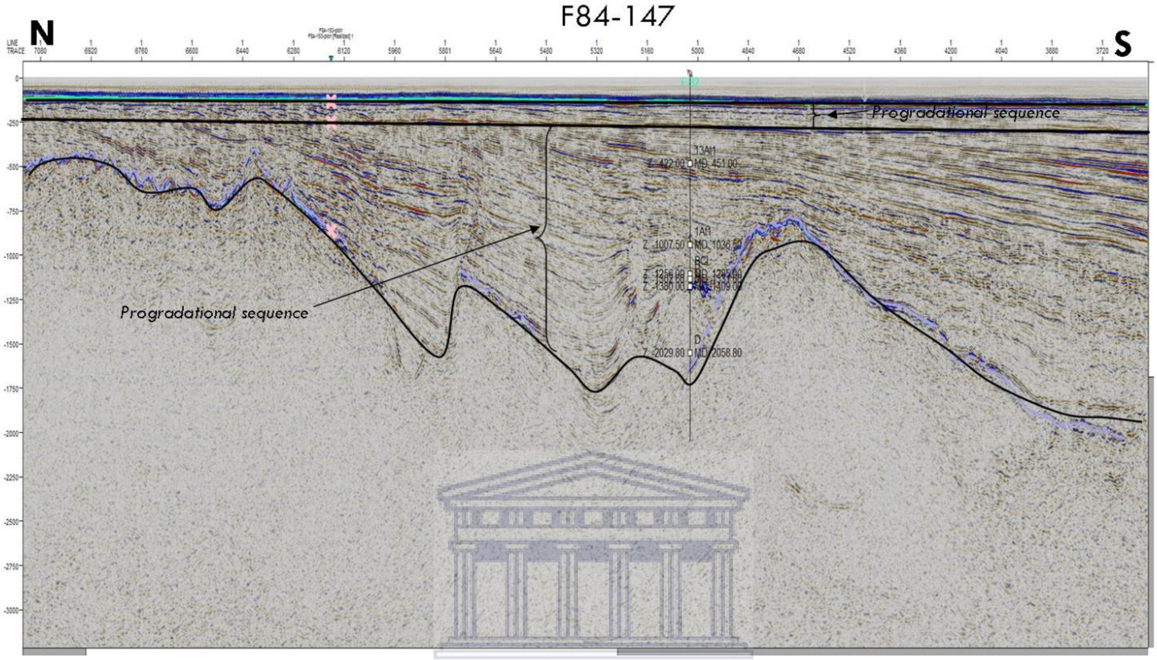


Figure 4.7: Seismic section intersecting well FB-2 displaying progradational sequences.

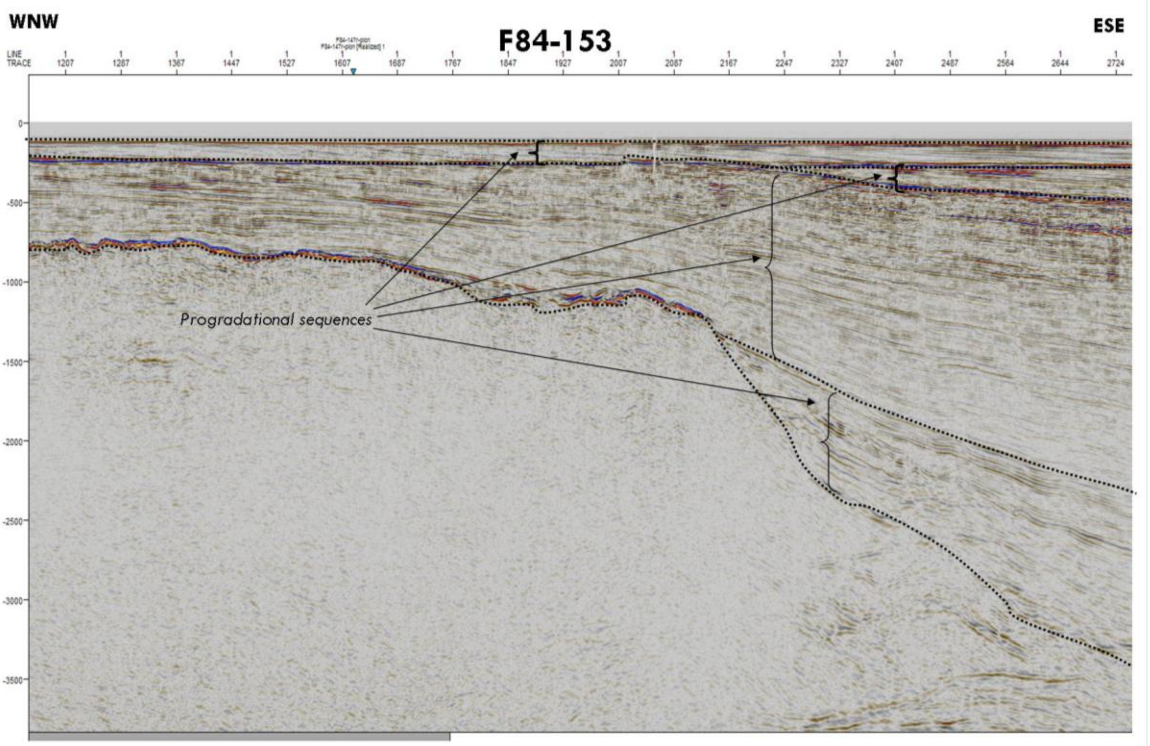


Figure 4.8: Progradational sequences on F84-153

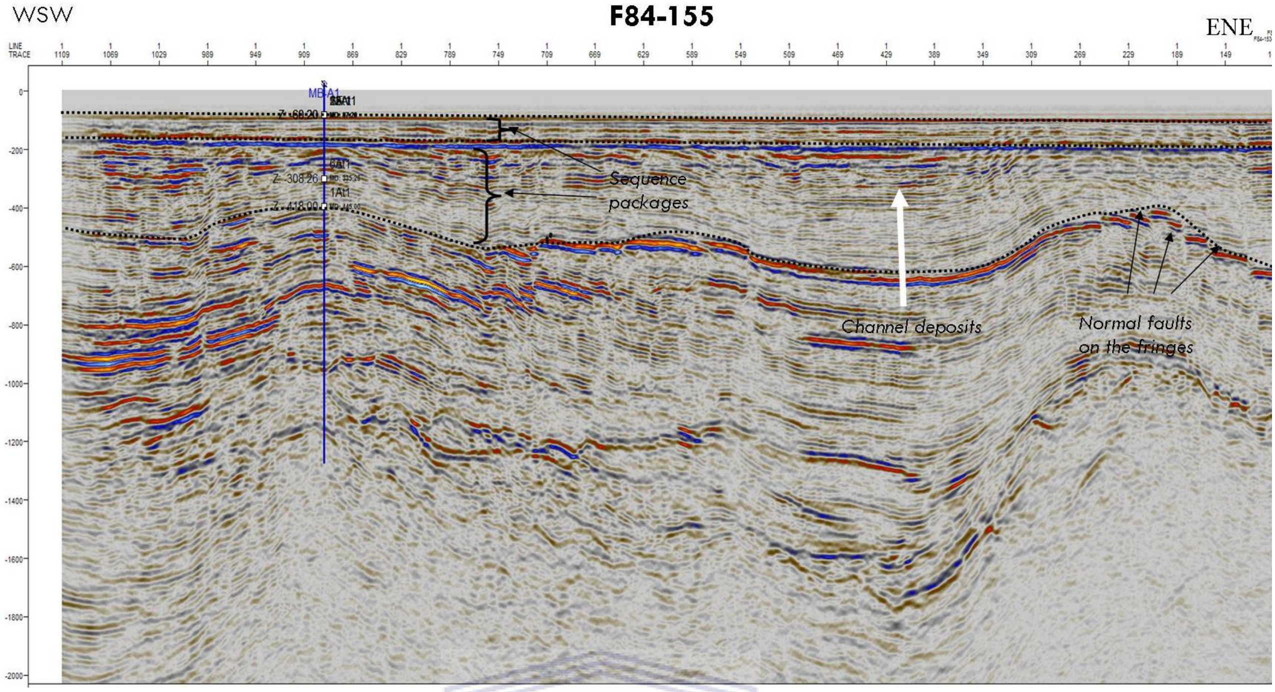


Figure 4.9: Channel deposits and faults.

As observed from the seismic line F84-155 the study area tends to be a sand-rich system since the channel is broad and doesn't possess well developed levees. These sand-rich systems tend to have broad, low-sinuosity channels that do not have well developed levees (Bacon et al., 2003).

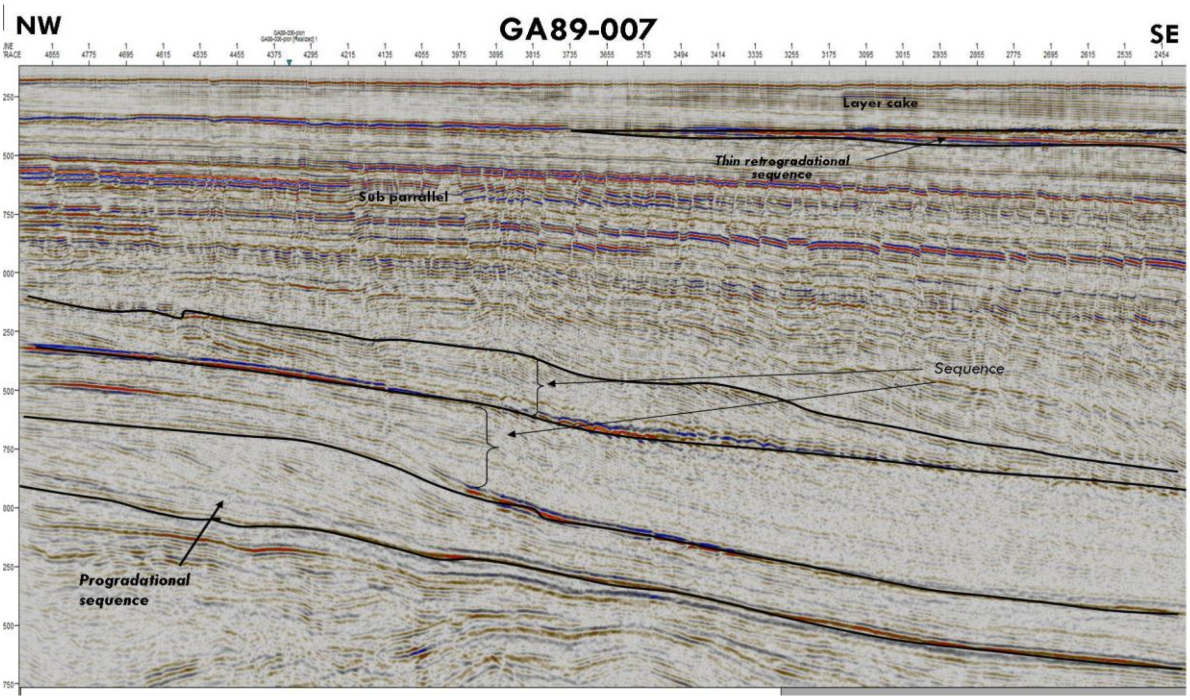


Figure 4.10: Sub parallel, progradational, layer cake and retrogradational deposition.

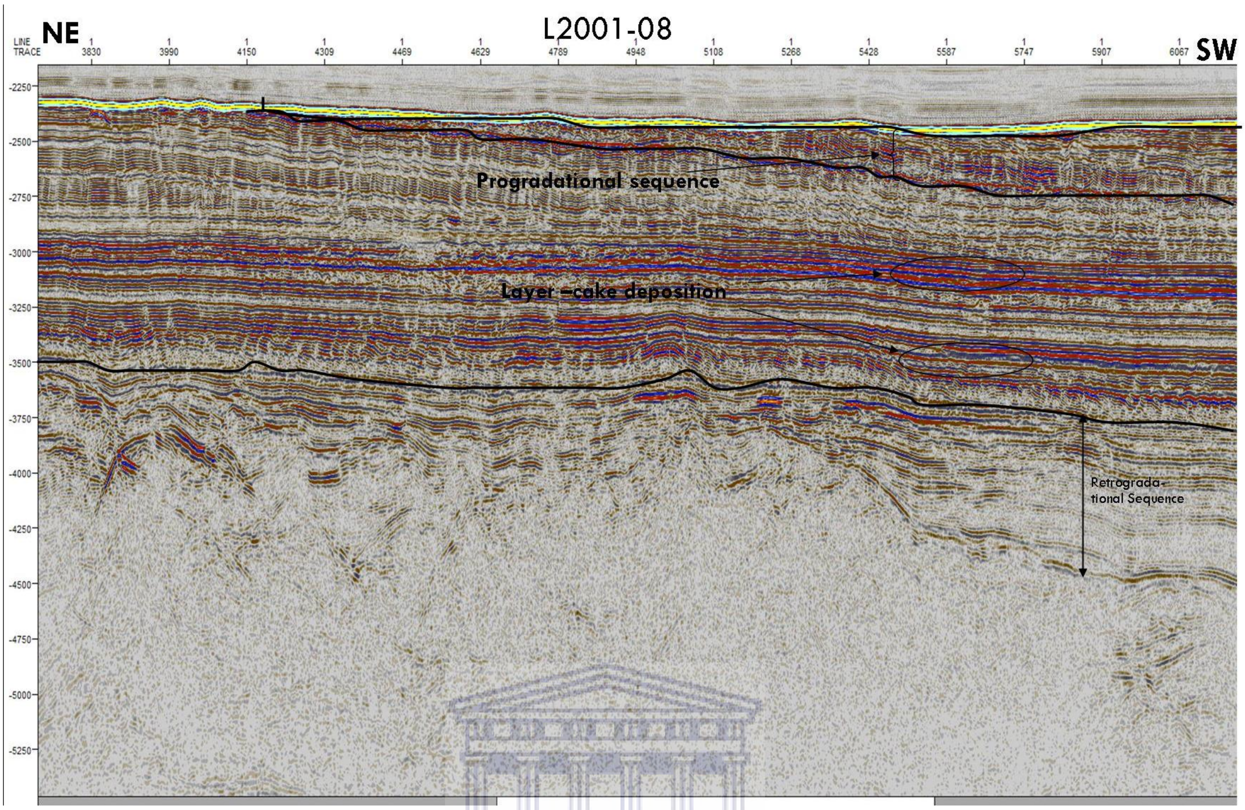


Figure 4.11: Layer cake and progradational deposition on line L2001-08.

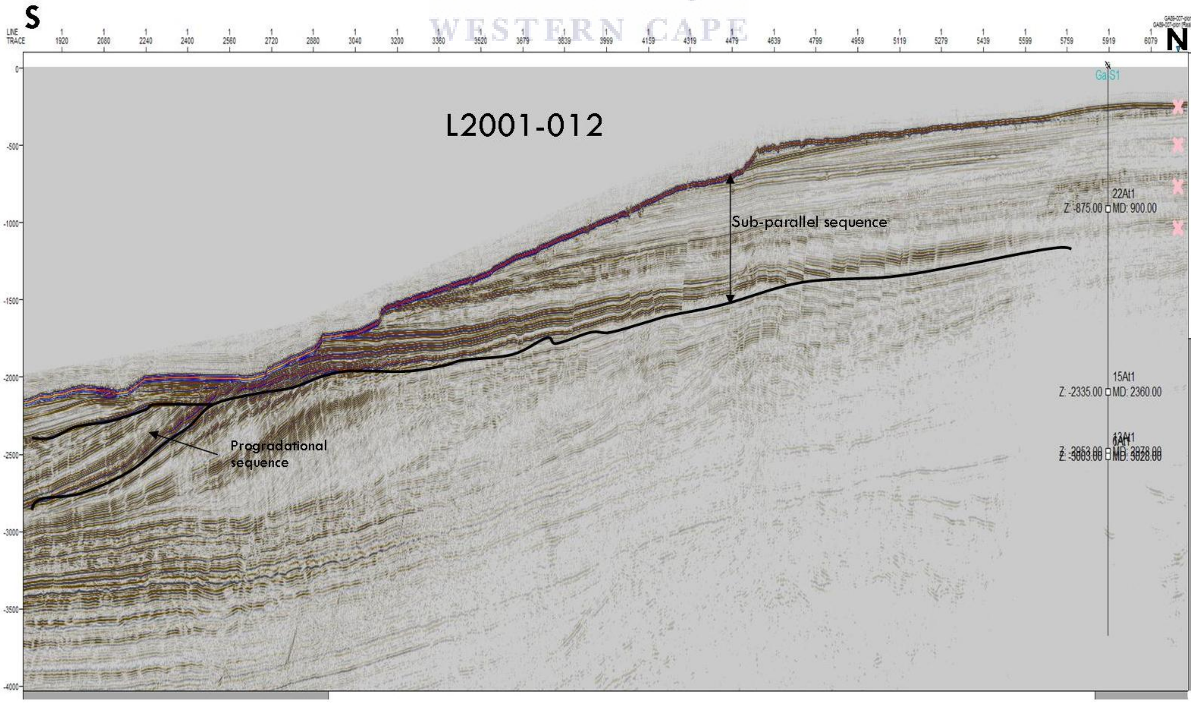


Figure 4.12: Progradational and sub-parallel drift sequence into the Southern Outeniqua Basin.

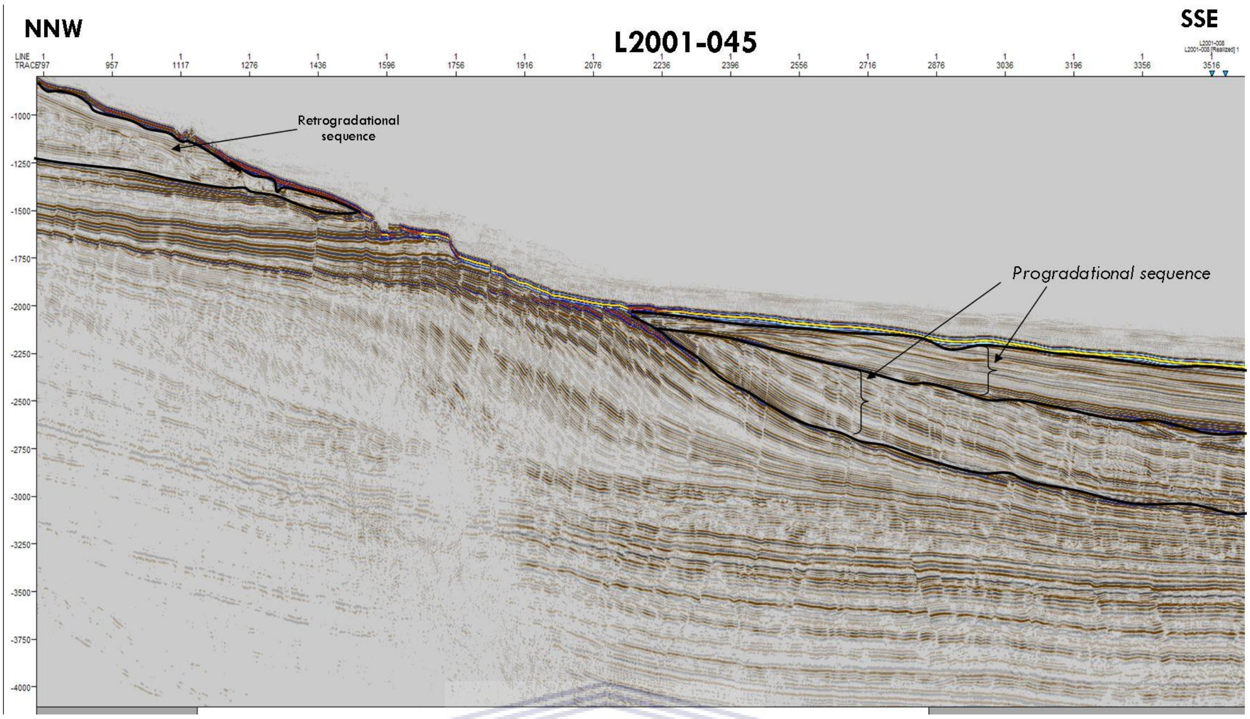


Figure 4.13: Progradational sequences seen in what is almost the southernmost section of the study area in the Southern Outeniqua Basin.

4.3 Well correlation and log analyses/ interpretation.

The principal geological application of logs has always been subsurface stratigraphic correlation (Doveton and Prensky, 1992).

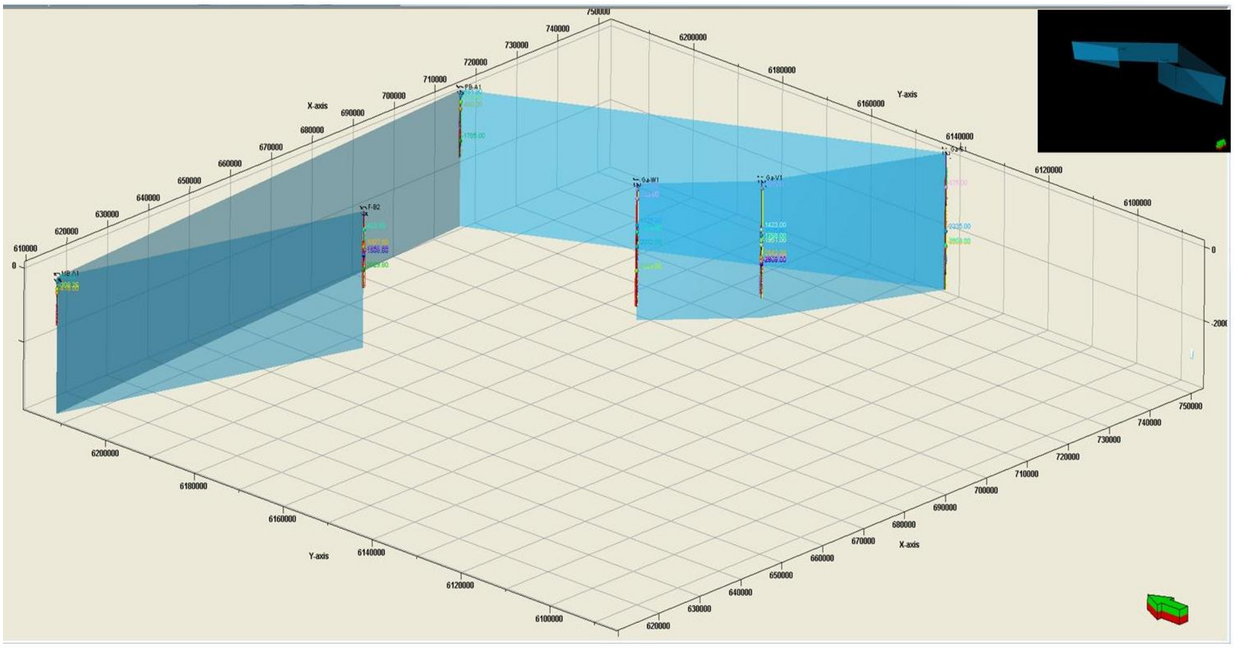


Figure 4.14: Well section window linking all the six (6) wells of interest from made from Petrel software.

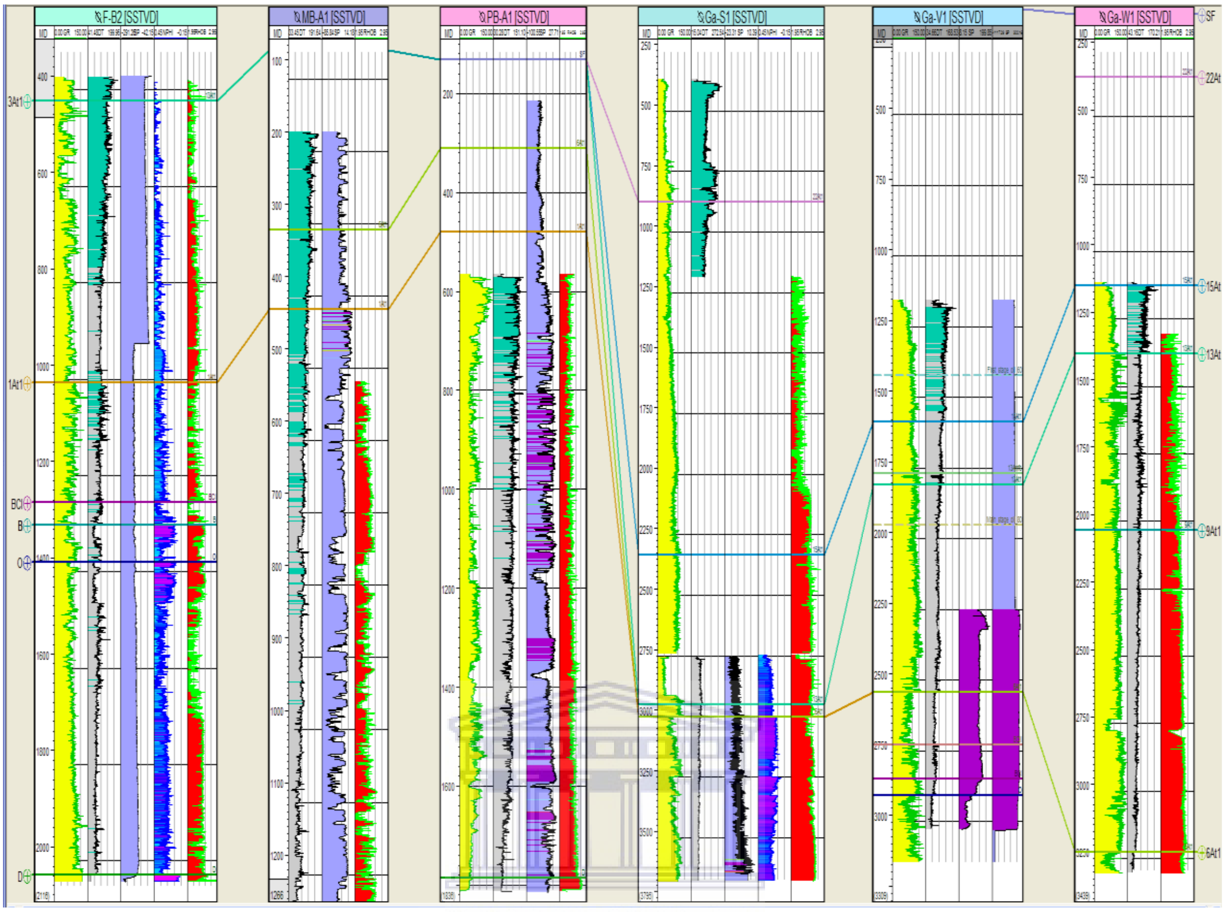


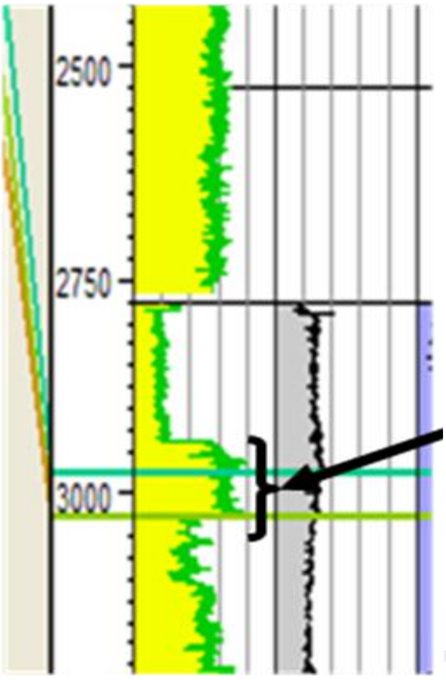
Figure 4.15: Well correlation indicating signatures of four (4) different log types. Also showing the variation with depth of the different stratigraphic surfaces (well tops).

Ga-S1 is the southernmost and most distal well in the area of study while well MB-A1 and PB-A1 are the most proximal being found in the basin margin. As seen above in Figure 4.15, the stratigraphic surfaces show a huge difference in depth, occurring at greater depth in Ga-V1 and Ga-S1. Tectonic subsidence or uplift most probably was the cause of this gap. Tectonic subsidence hereby created a relative sea level change orchestrating the deposition of lowstand prograding sequences that were observed in Ga-V1 and Ga-S1 wells.

Displaying this lowstand prograding sequences isolated massive mound and a bell and crescent shape well log signatures were observed in these two wells.

At least one isolated massive mound of well-sorted sands was observed at depth of between 2925 m to 3050m in well Ga-S1. This type of massive mound structure is characteristic of basin floor fans. This can be seen in Figure 4.16 below. This depicts an episode and event of sand deposition transported into the deep see intermittent to the quiescence that generally characterises pelagic environments.

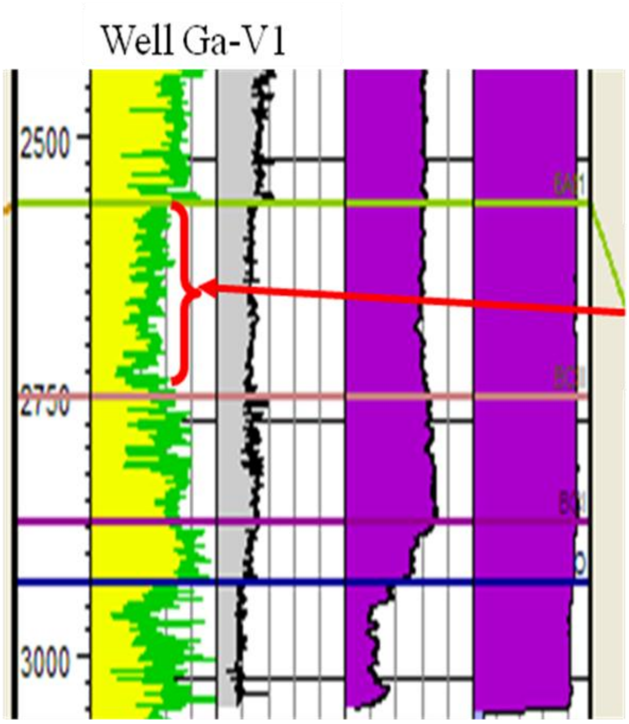
Well Ga-S1



Sand mound shape gamma ray log signature at depths of between 2925 m to 3050m.Over 80m thick of clean sand layer. Sharp termination at the base and top.

Figure 4.16: Sand mound shape gamma ray log signature.

A bell and crescent shape log signature is observed in well Ga-V1 at depth between 2500m and 2750m. It indicates a fining up sequence of more than 150m thick and depicts abandonement of the channel.



Bell and crescent shape gamma ray log signature observed at depths between 2500m and 2750m- approximately 150m thick. This indicates a fining upward sequence as the channel is abandoned

Figure 4.17: Bell and crescent shape gamma ray log signature .

4.4 Core analyses and Interpretation

Apart from wireline logs that come close to revealing the actual subsurface geology displayed by seismic lines, cores reveal this ground truth to a much greater detail. It was therefore important to test the usefulness of spectral gamma ray logs in subsurface correlation, lithofacies identification/ description and the interpretation of depositional environments. Lithofacies and depositional environments were identified from core description of two wells and compared with gamma ray logs from these 2 boreholes.

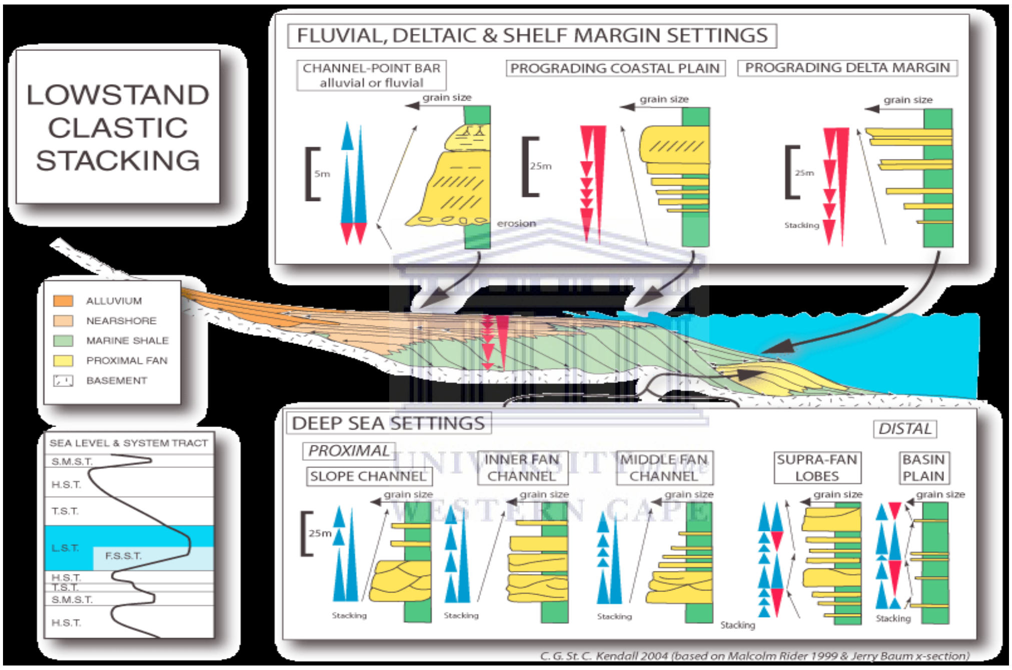


Figure 4.18: Lowstand Clastic stacking-From Kendall, 2004

The cores studied thus far were from 2 wells Ga-V1 and Ga-S1- out of the 6 wells worked on. These wells were chosen because their huge areal coverage from basin margin towards to the deepwater setting of the Southern Outeniqua basin (Figure 4.1.).

The various cores were observed for the various depositional facies. SedLog 2.1.4 software was used to illustrate the various depositional facies as well as the various observed changes in the cores.

Four main facies were defined in this study among which three (3) were observed. These facies were defined using the five main facies of deep-water clastic rocks can be defined by Walker, 1978: classic turbidites, massive sandstones, pebbly sandstones, conglomerates, and debris flows (with slumps and slides).

The four facies defined were as below:

Facies 1: Conglomerates

Facies 2: Sandstones

Facies 3: Sand/Shale

Facies 4: Shales.

4.4.1 Ga-S1: Pletmos Basin

Three (3) cores were cut. All the cores were cut from horizon B-to-1At1 and were prognosed to be marginal to shallow marine sandstones. These are stacked upward coarsening inner shelf sandstones (Geological Well Completion Report, 1990). The cored depth is within 3028m to 3371m (343 m) with 44m effectively cored. The cores are as below at various depth ranges:

Core#1: 3028 – 3048= 18m

Core#2: 3237 – 3244= 7m

Core#3: 3353 – 3371 = 18 m

The various core descriptions could be seen as below.

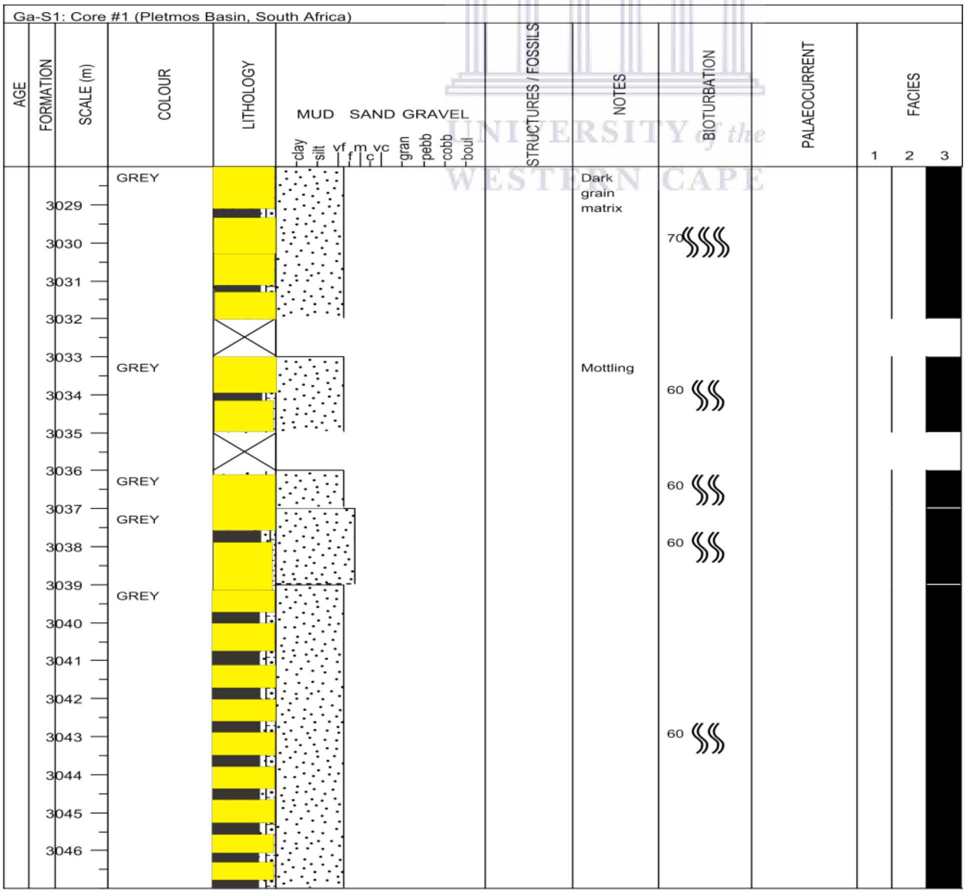


Figure 4.19: GA S1 Core#1= 3028 – 3048= 18m

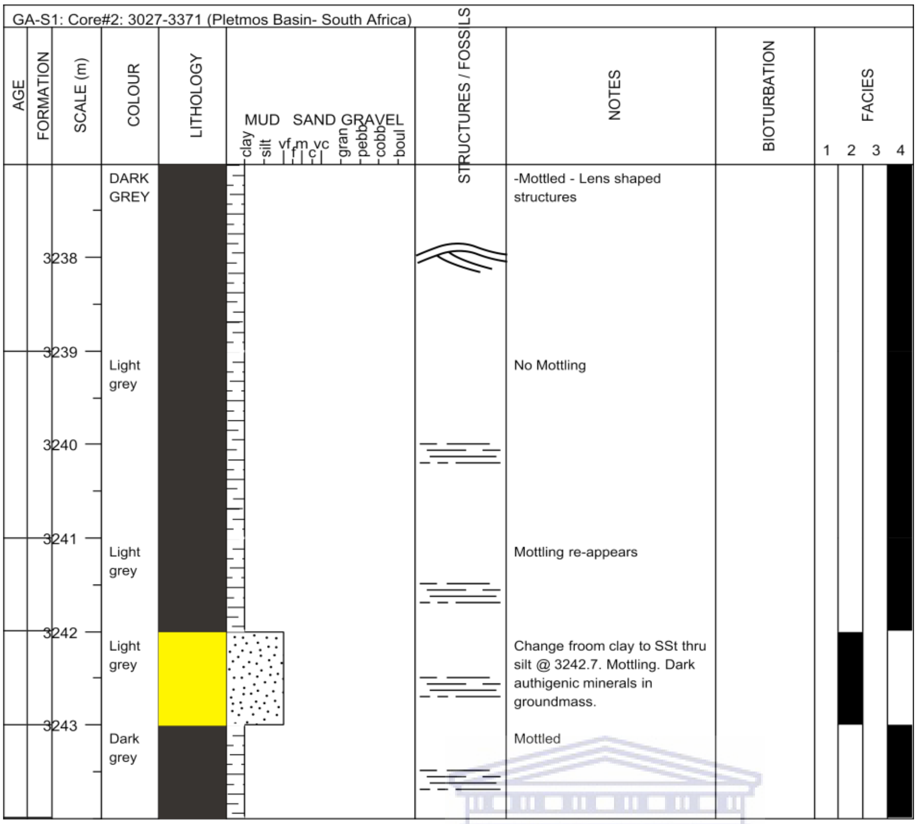


Figure 4.20: GA S1 Core#2= 3237 – 3244= 7m

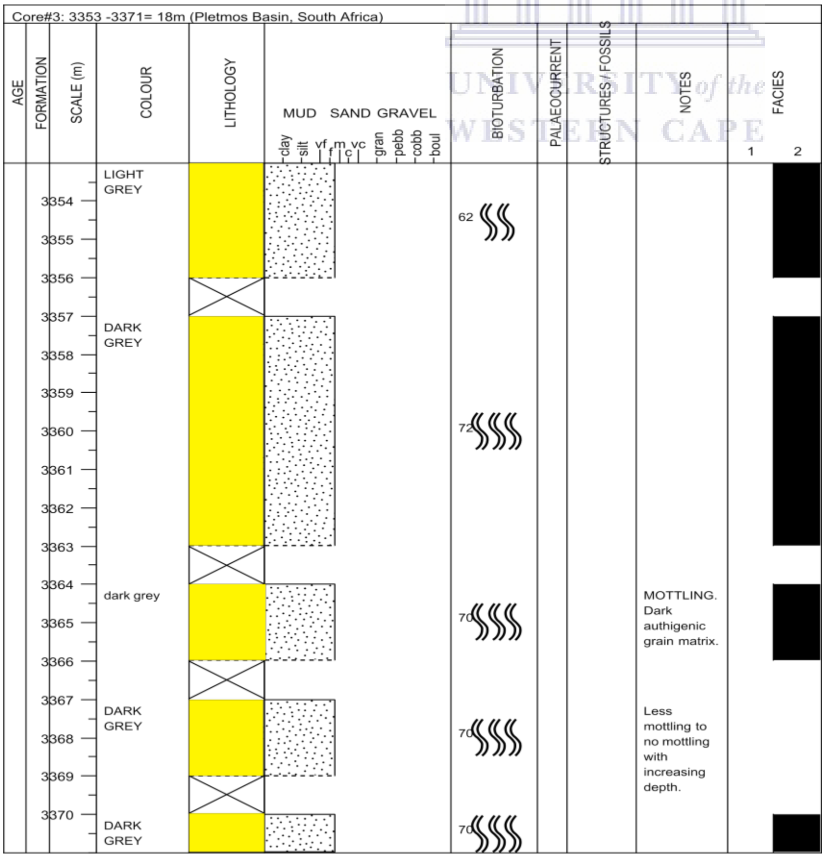


Figure 4.21: GA S1 Core#3= 3353 – 3371 = 18 m

Well Ga-S1 which is much deeper than Ga-V1 shows good sand sections of up to 187m (e.g. Core # 3). This is charateristic of basin floor fans which are typically isolated massive mounds of well-sorted grains flows or tybidite sands derived from alluvial valleys or neashore sands as described by Neal et al., 1993. No conglomerate facies were observed. Observed facies ranged from sand, shale/sand and shale facies.

4.4.2 Ga-V1: Pletmos Basin

Eight (8) cores were cut. Six (6) of them were cut into pre-C sandstones with the following range of porosity and permeability values: 6-14 % and 0.1 - .2.2md (Geological Well Completion Report, 1990). The cored depth ranges from 2519m to 2815m in depth covering a total interval of 296 m. The cores are as below at various depth ranges:

Core#1 : 2519- 2537 = 18 m

Core #2 : 2553 – 258= 5m

Core #3 : 2600- 2611= 11m
Core #4 : 2640- 2658= 18 m
Core #5 : 2658 – 2677= 19m
Core #6 : 2677 – 2695 = 18
Core #7: 2695.5 2714 = 18.5
Core # 8: 2867 – 2815 = 8m
The various core descriptions could be seen as below.

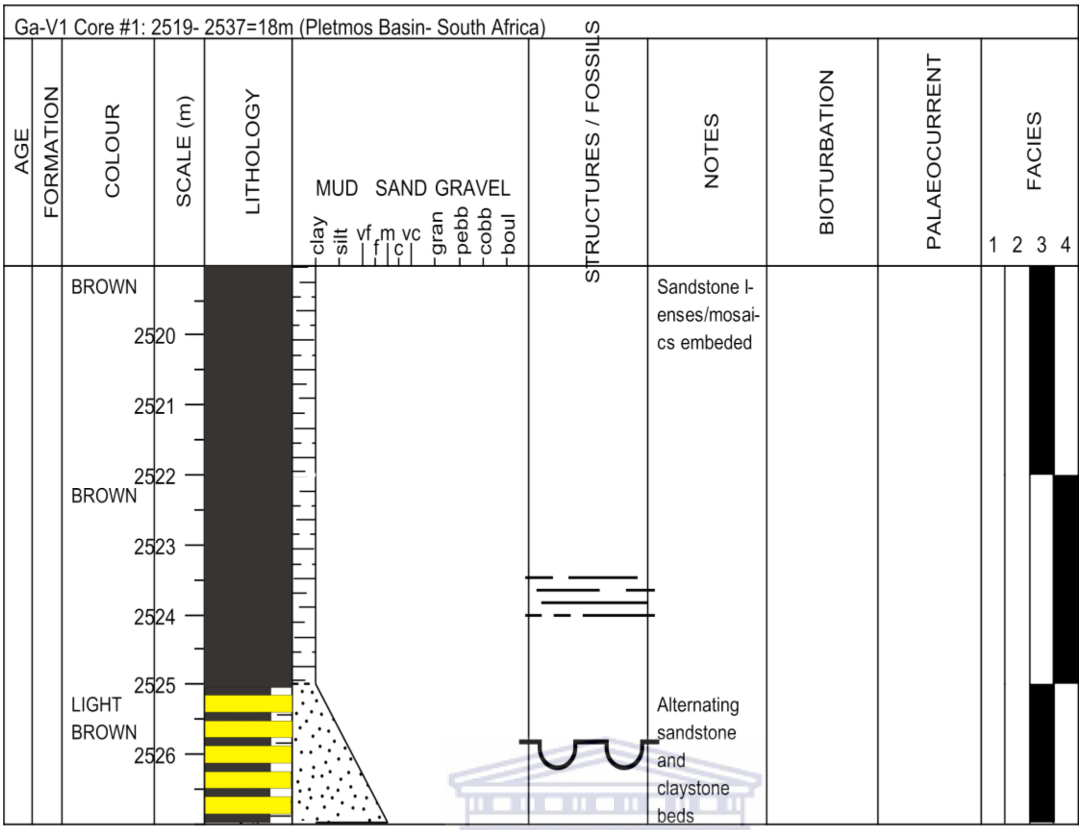


Figure 4.22: *GA V1 Core#1= 2519m- 2537m = 18 m*

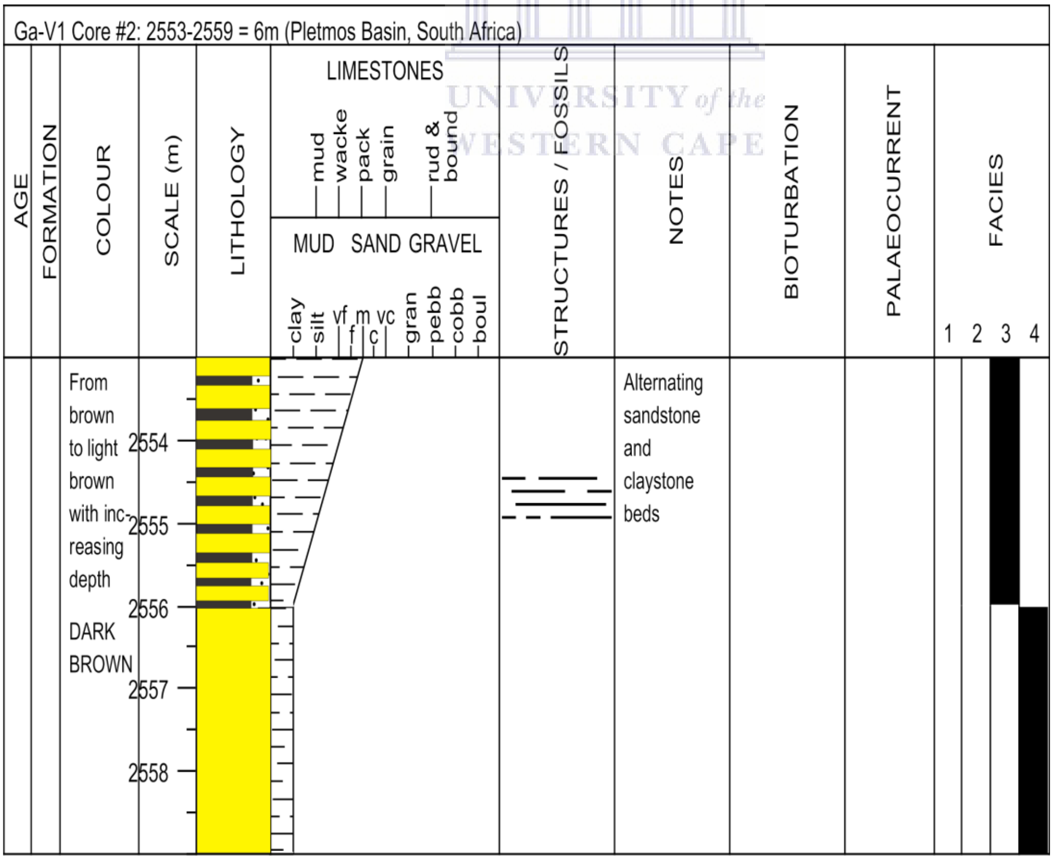


Figure 4.23: GA V1 Core #2= 2553 – 258= 5m

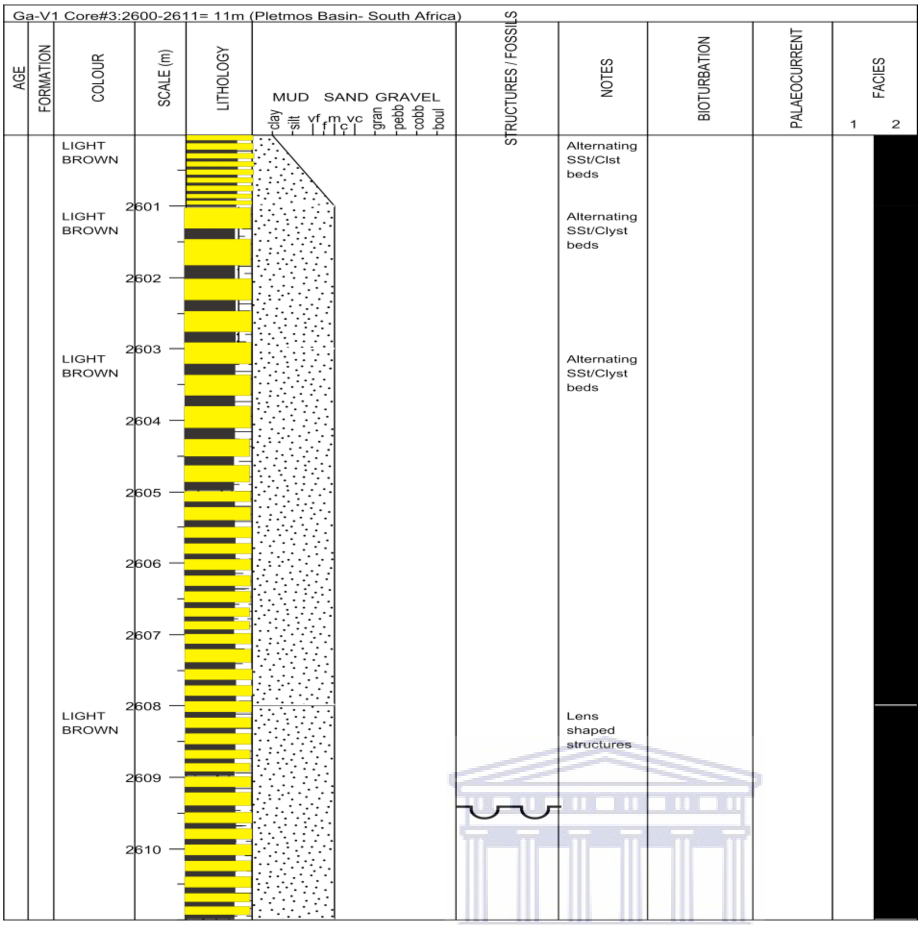


Figure 4.24: GA V1 Core #3= 2600- 2611= 11m

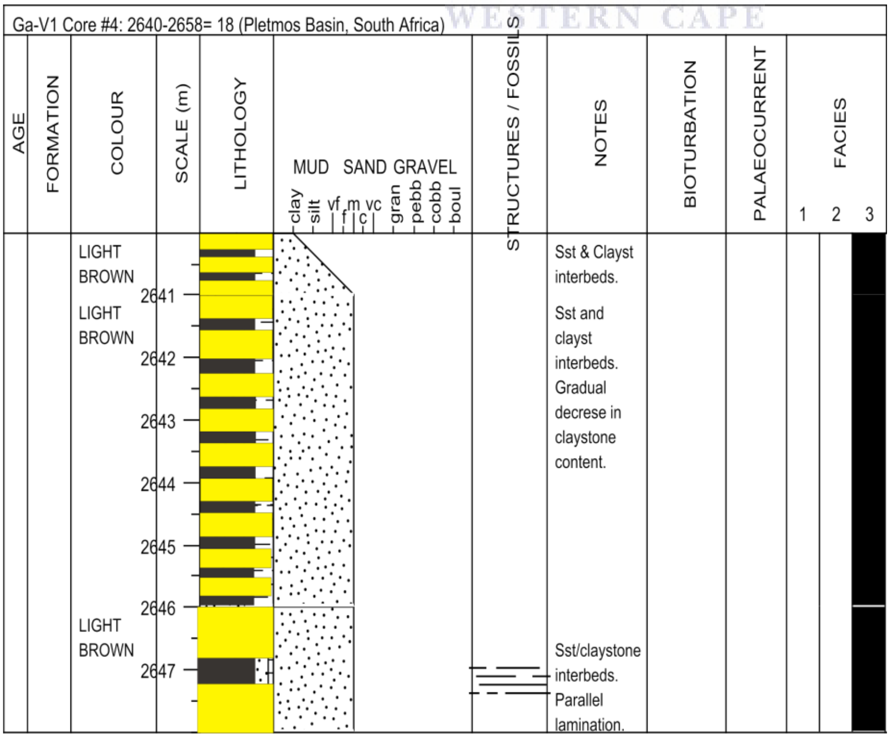


Figure 4.25: GA V1 Core #4= 2640- 2658= 18 m

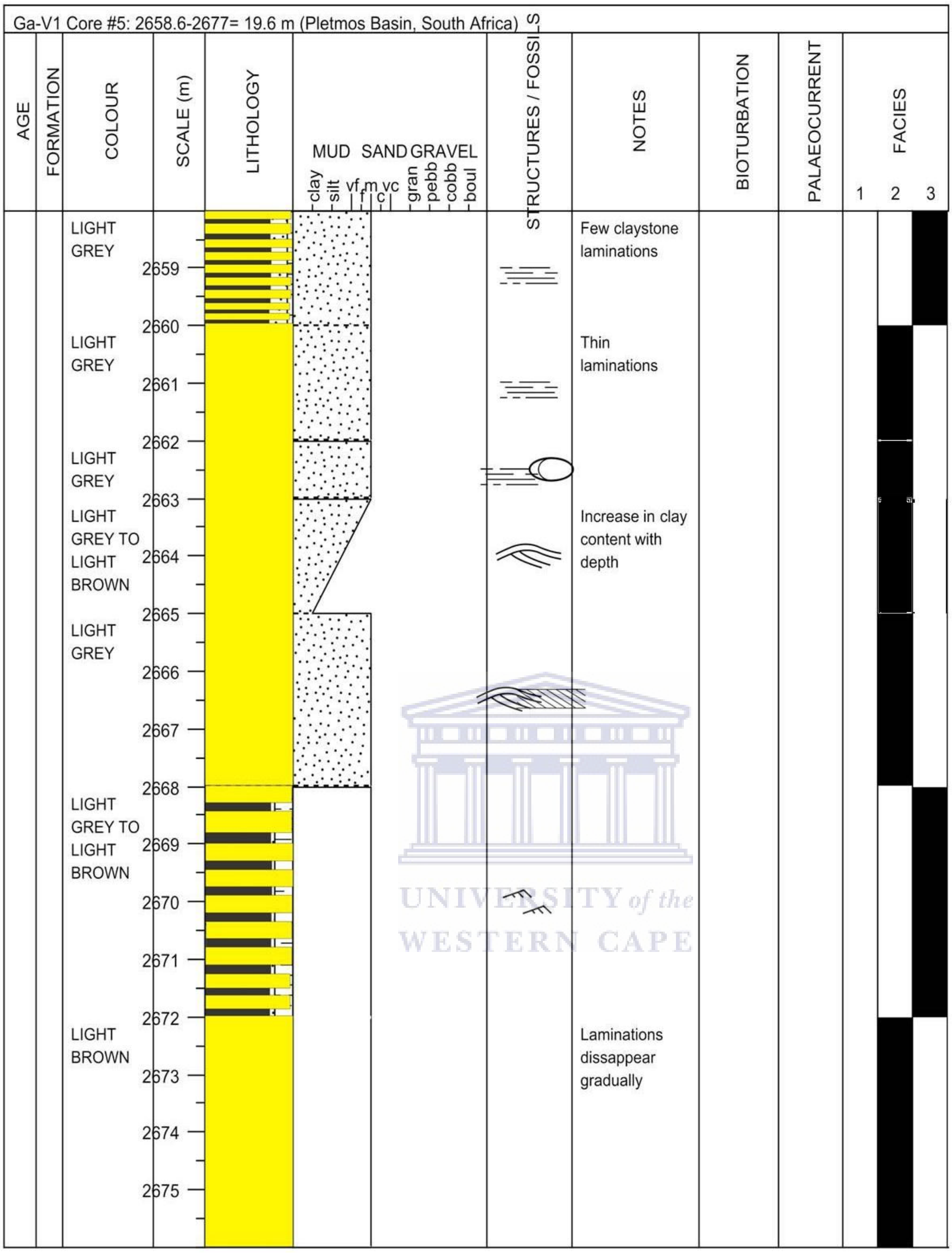


Figure 4.26: GA V1 Core #5= 2658 – 2677= 19m

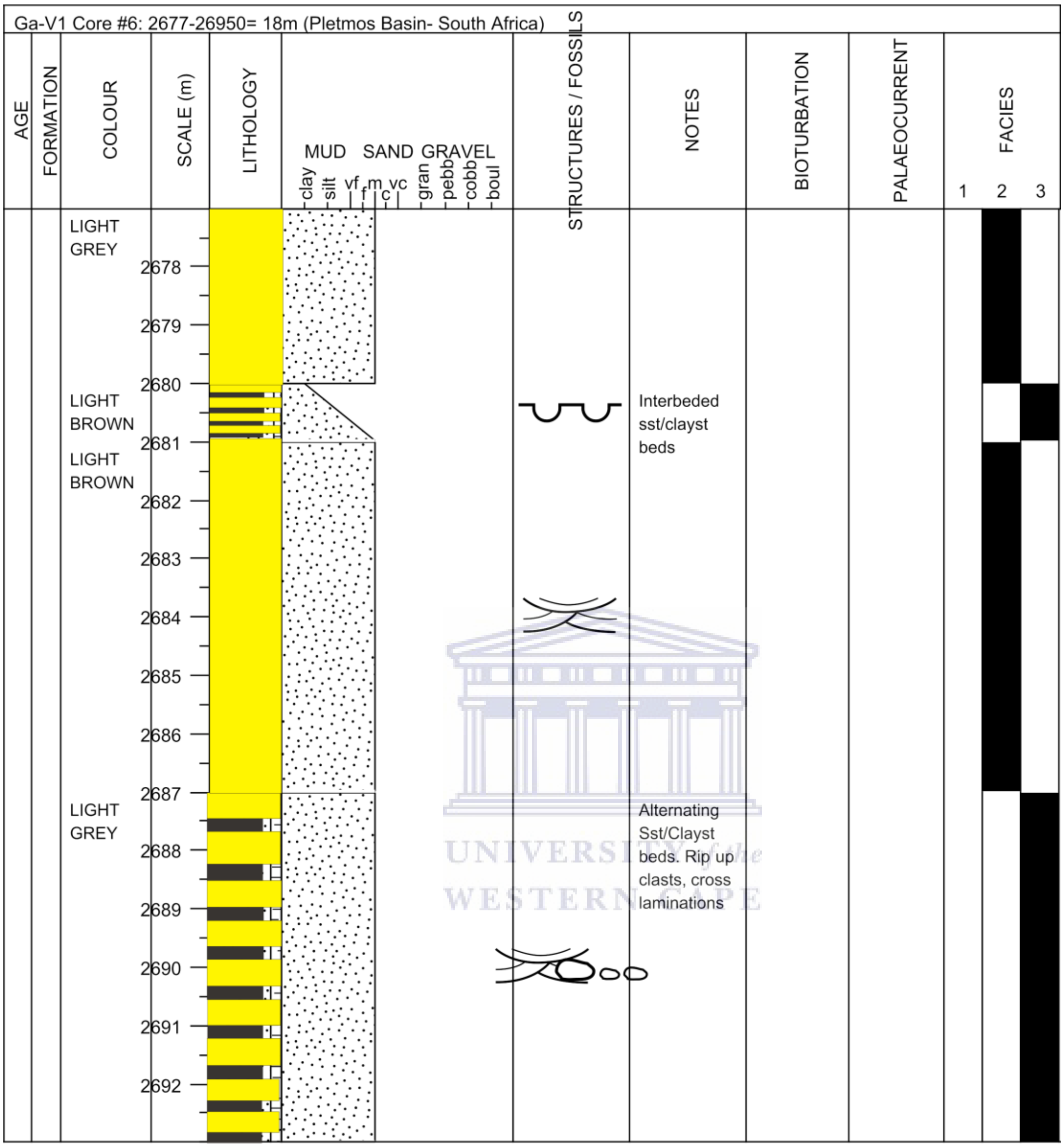


Figure 4.27: GA V1 Core #6 = 2677 – 2695 = 18

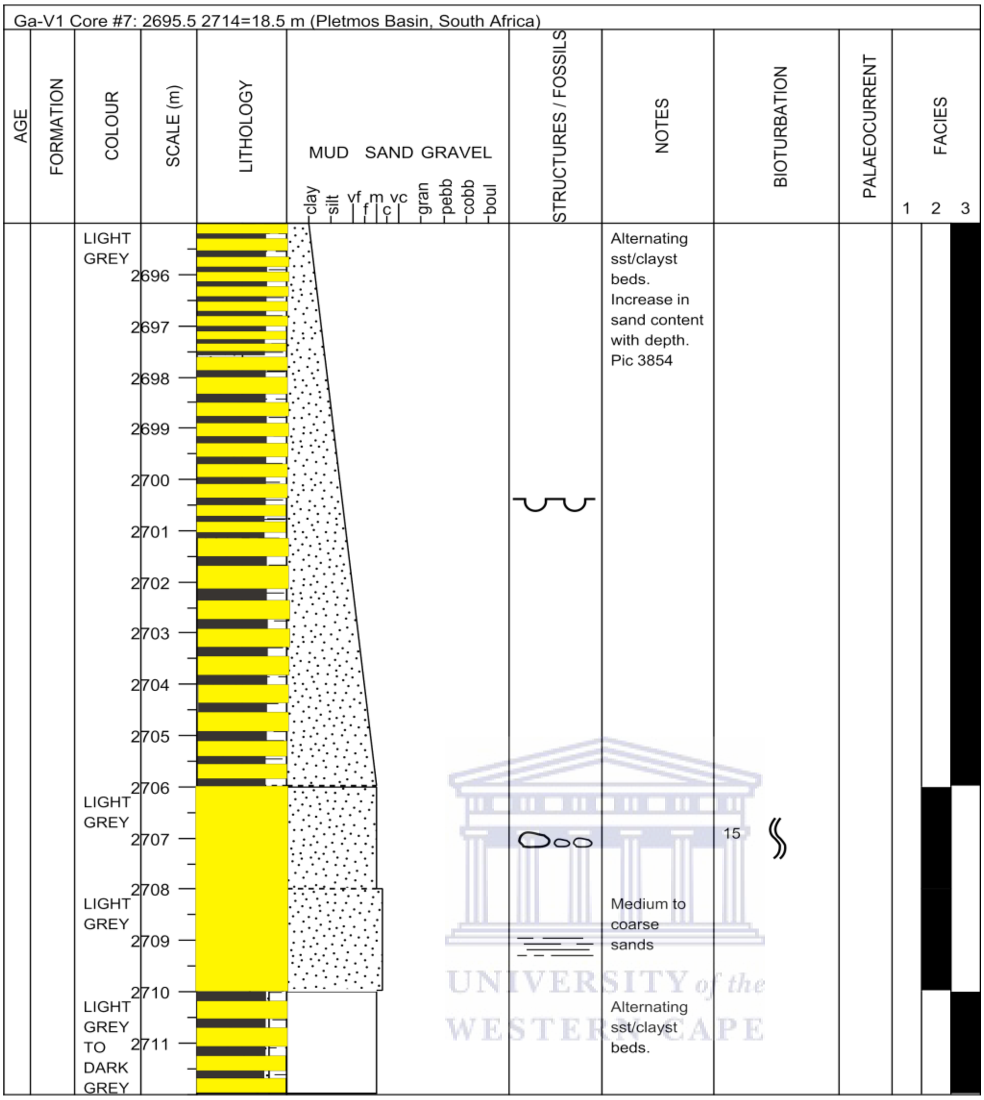


Figure 4.28: GA V1 Core #7= 2695.5 2714 = 18.5

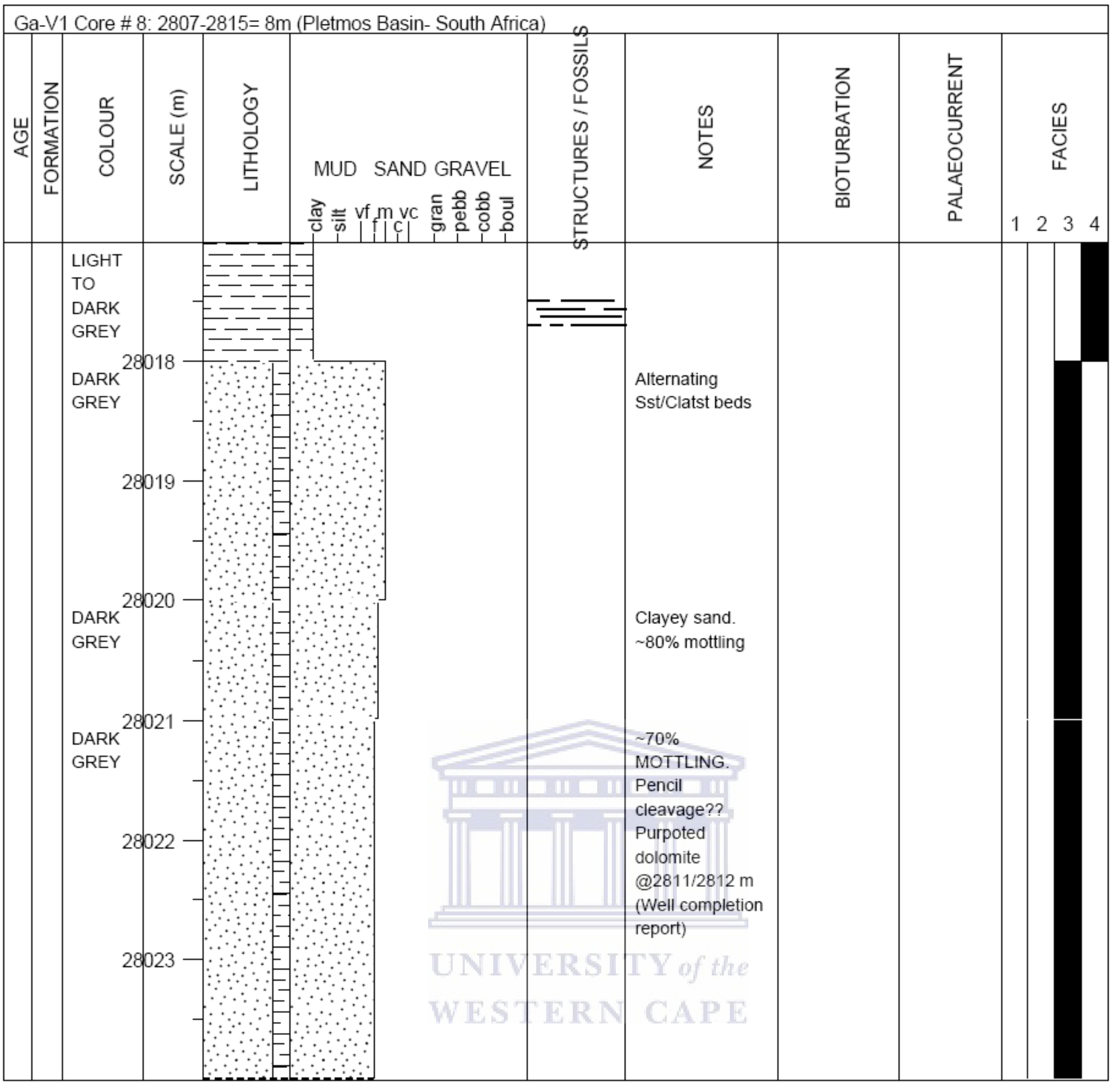
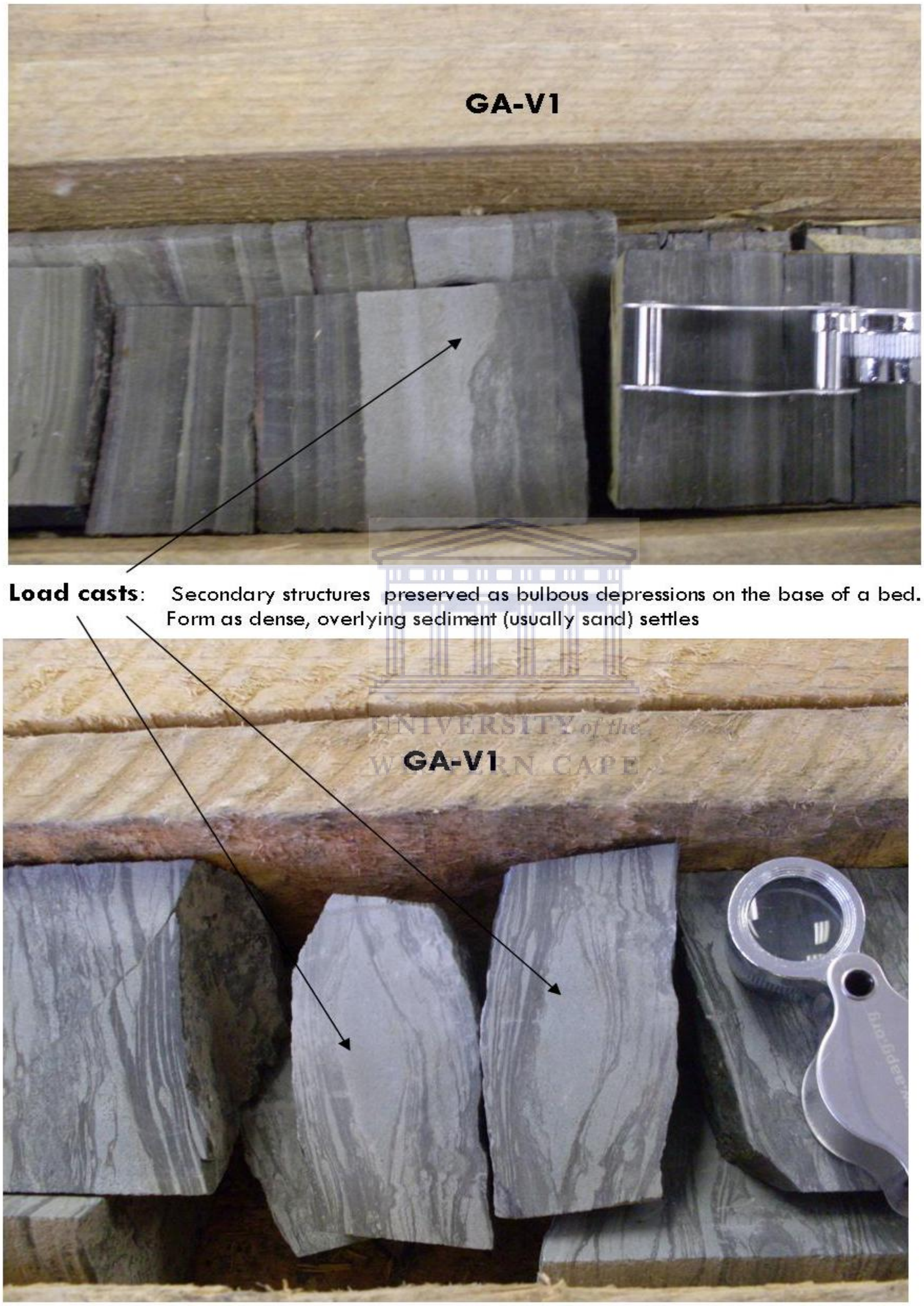


Figure 4.29: GA V1 Core # 8= 2867 – 2815 = 8m

In well Ga-V1, no conglomerate facies were observed. Observed facies ranged from sand, shale/sand and shale facies.

These observed facies are charateristic of inner fan, middle fan and outer fan (basin plain) facies as can be described by the clastic stacking patterns of Kendal, 2004.

4.4.3 Sedimentary structures/textures in cores (Wells Ga-V1 and Ga-S1)



Load casts: Secondary structures preserved as bulbous depressions on the base of a bed. Form as dense, overlying sediment (usually sand) settles

Figure 4.30: Load cast structures- structures peculiar to turbidites (gravity mass transport/ re-sedimented deposits)

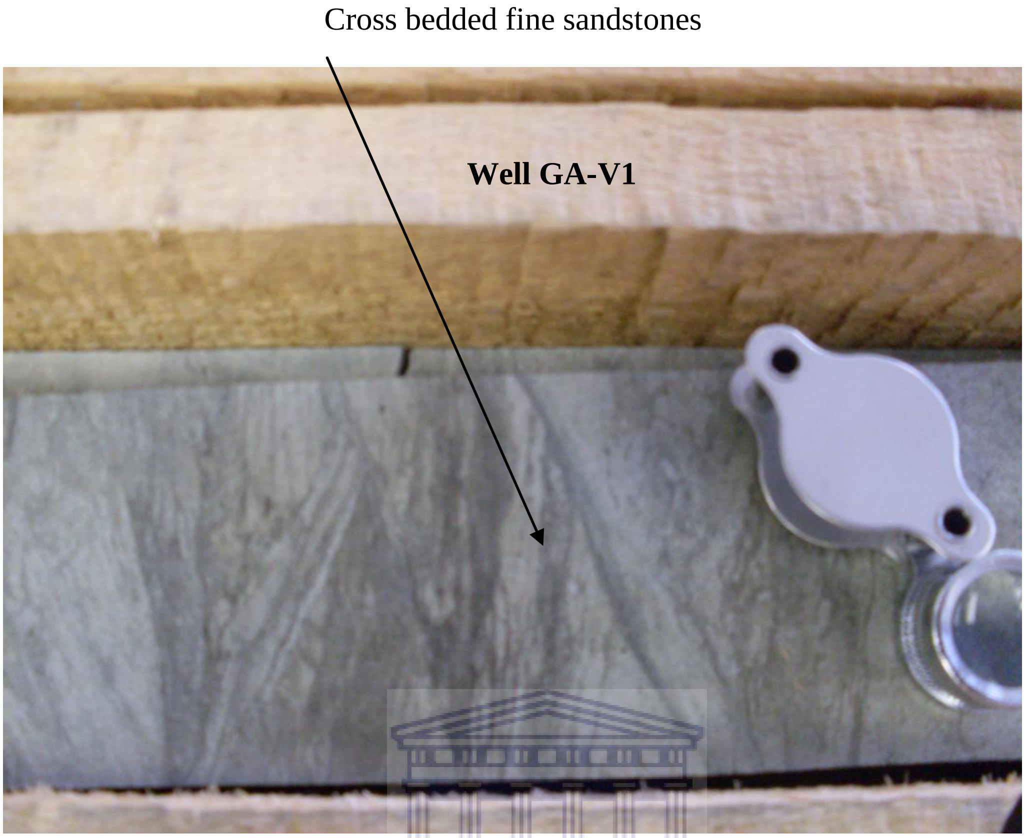


Figure 4.31: Cross stratification: structure characteristic of type C- sequence of the Bouma sequence and typical of slope deposits are exemplified from his depositional cone.

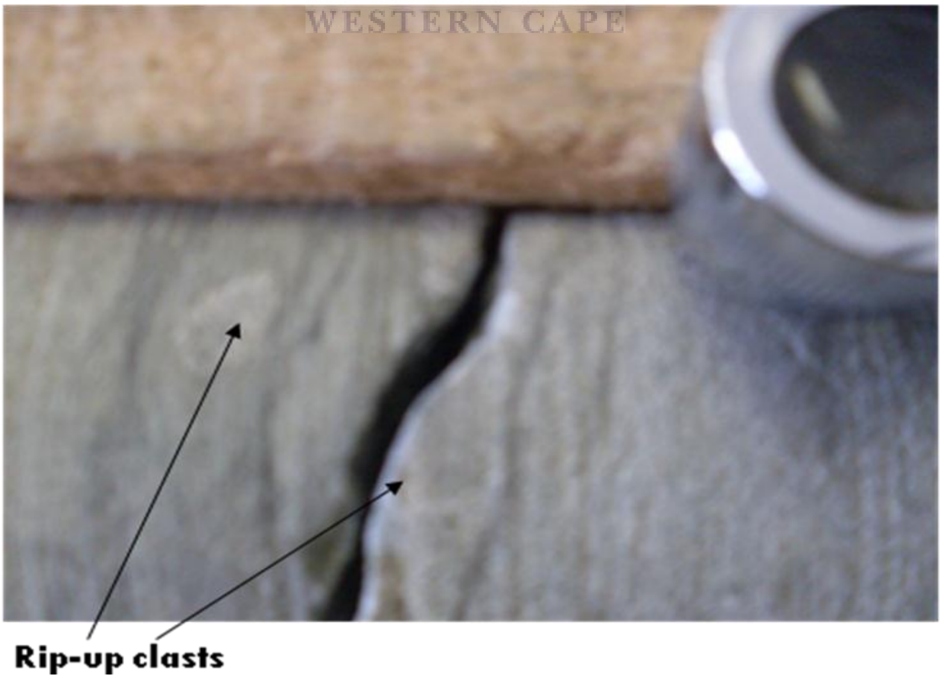


Figure 4.32: Rip-up clasts the exemplify turbidite/mass transport structures.

Fine to medium size sandstones of well **GA-S1**

Figure 4.33: Clean, medium to fine sands as shown by cores of well Ga-V1.

4.5 Biostratigraphic Analyses and Interpretation

Well Ga-V1

Amongst the 6 wells, bisotratigraphic data could only be gotten for one well: Ga-V1.

From biostratigraphic analyses gotten from the very limited paleaodata that was provided of well Ga-V1 (located in the slope/basin plain area of this basin) limited information was extracted giving us information about the age of the sediments, the environment of deposition and the rate of deposition of the sediments.

As we would have desired, we could not get biostratigraphic data which depicts fossil abundance on one axis and depth on the other. This would have indicated fossil abundance with depth. This would have gone a long way to tying this data to our observed turbidite facies observed in the cores and predict the location of other facies in the undrilled parts of the Southern Outeniqua basin once integrated into results from seismic/log analyses and interpretation.

Below is an illustration of the biostratigraphic information of well Ga-V1 that could be extracted from palaeodata.

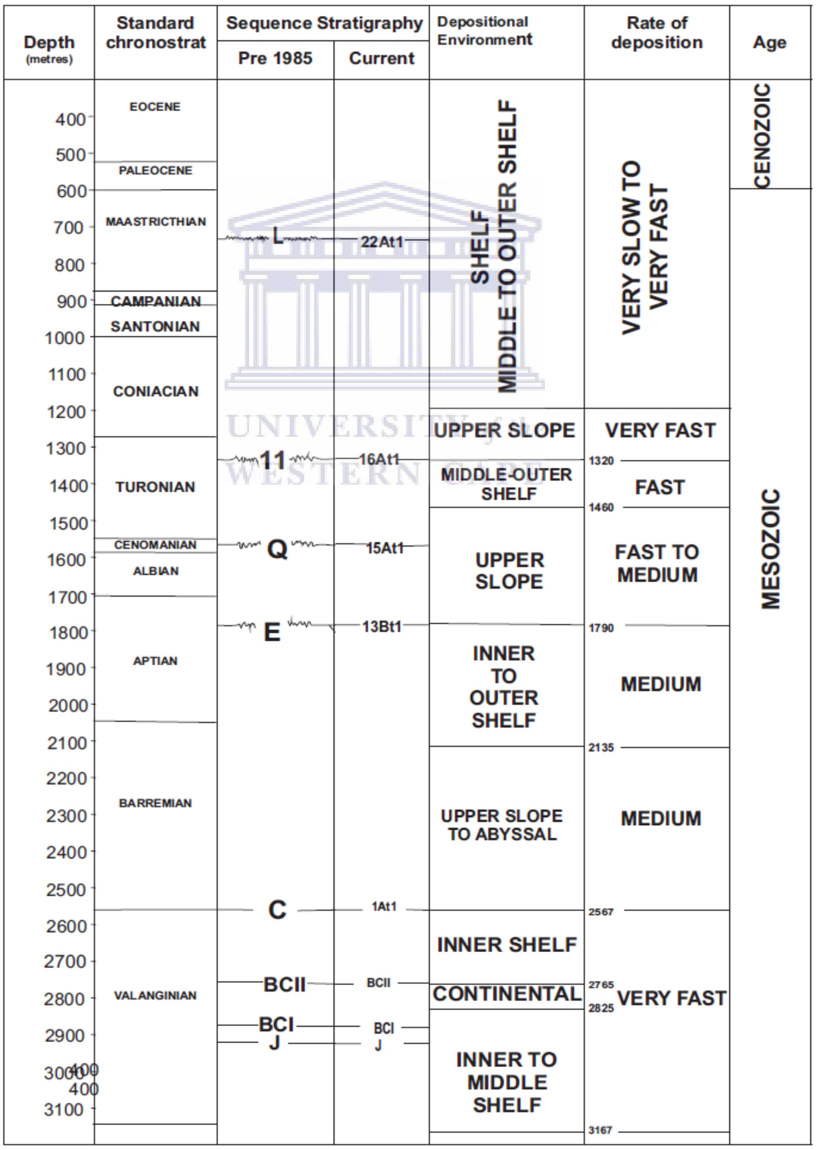


Figure 4.34: .Sequence Stratigraphy, depositional environment and depositional rate from biostratigraphic data. Adapted from geological well completion reports.

From observation of biostratigraphic data in well GA-V1, there were basically 3 (three) phases of slope to basin conditions sandwiched by continental and shelf conditions. The observed conditions at various depths and stratigraphic ages can be seen as below.

Table 2: Depositional rate and, age of slope and basin deposits cut by well Ga-V1.

Environment **(Depositional system)**	**Depth range (metres)**	**Rate of deposition**	**Age**
Upper slope	1320m – 1200m	Very fast	Late Turronian to Coniacian
Upper slope	1790m – 1460	Fast to medium	Late Aptian to Early Turonian
Upper slope to abyssal	2567m – 2135m	Medium	Barremian

Biostratigraphic data clearly marks out Ga-V1 well as one cutting predominantly through slope sediments and at some point through basin plain sediments. Our focus on such environments is because they are the major "habitats" for lowstand/progradational sequences which host turbidites.

Medium to fast depositional rates generally mark sand deposition. This is characteristic of turbidites which are usually deposited at very fast rates.

CHAPTER FIVE

DISCUSSION, CONCLUSION AND RECOMMENDATION

5.1 Discussion

Seismic analysis and interpretation have clearly so far shown prograding sedimentary sequences. These sequences tend to follow the structural grain and trend of the Pletmos basin into the Southern Outeniqua basin. This trend runs more or less in the NW-SE direction in the proximal Plemos Basin and NNW-SSE direction as it gets more distal into the Southern Outeniqua basin.

Wireline log correlation displays tectonic subsidence as we observe in well Ga-S1 in the southernmost and most distal area of study showing stratigraphic surfaces at great depths while well MB-A1 and PB-A1 which are the most proximal to the basin margin show the same surfaces at much shallower depths. The stratigraphic surfaces show a huge difference in depth, occurring at greater depth in Ga-V1 and Ga-S1. Tectonic subsidence hereby creates a relative sea level change orchestrating the deposition of lowstand prograding sequences in the distal and deeper areas of the basin.

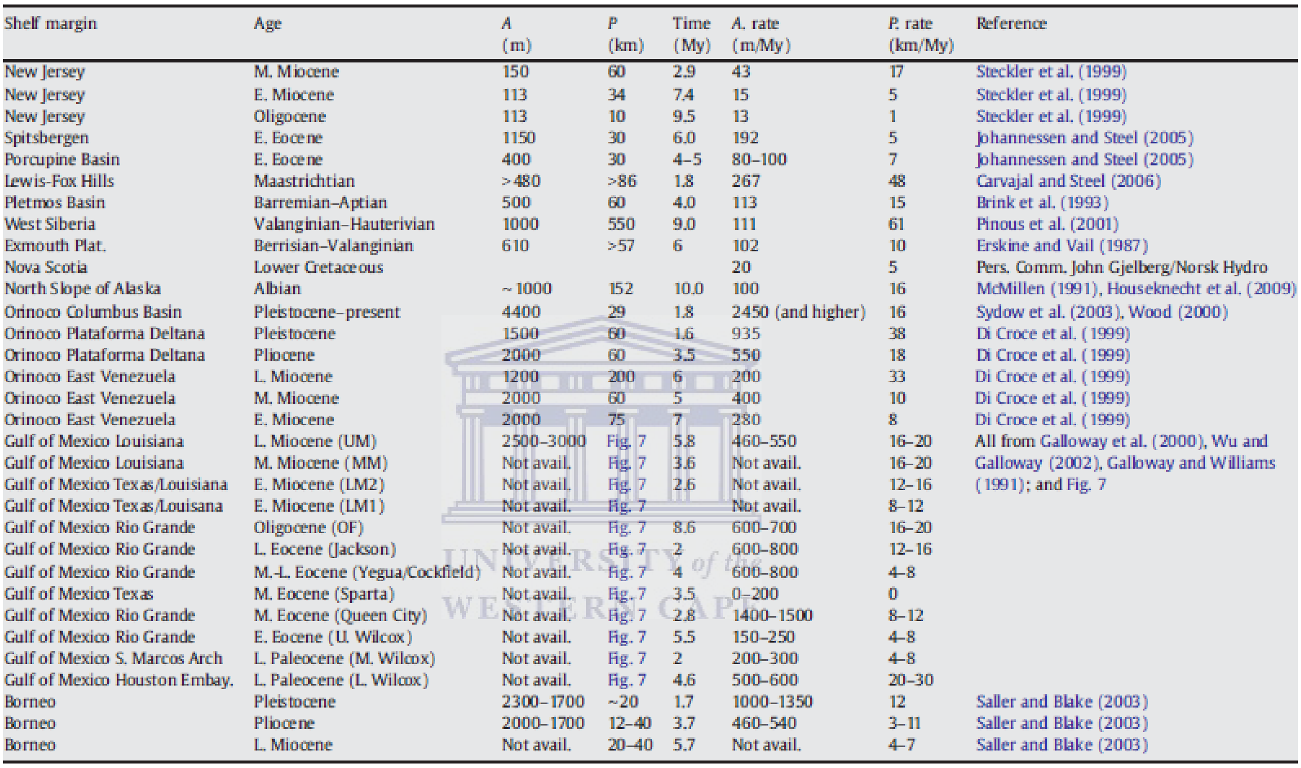
Well Ga-S1 displays an isolated massive mound of well-sorted sands as seen at depth of between 2750m and 3000m. This type of massive mound structure is characteristic to basin floor fans. A bell and crescent shape log signature is observed in well Ga-V1 at depth between 2500m and 2750m. This indicates a fining up sequence as the channel is abandoned

Cores of well Ga-V1 display fine-grained alternations of thin sandstone beds and shales. These belong to the thin-bedded turbidite facies. Levees of the upper fan channel display these facies but this could easily be confused with similar facies on the basin plain. According to Walker, 1978, such facies form under conditions of active fan progradation. From the observed facies on cores, well Ga-V1 therefore cuts across a levee of the upper fan channel.

Ga-S1 cores display not only classic turbidite facies where there are alternating sand and shale sections but show long uninterrupted sections of clean sand overlain by shales. These shales could serve as good seals.

Biostratigraphic data clearly marks out Ga-V1 well as one cutting predominantly through slope sediments and at some point through basin plain sediments and also displays very fast to medium rate of deposition in these environments.

From a complimentary study done by Carvajal et al., 2009, the Pletmos basin among other shelf margins is seen as a rapidly prograding margin. This can be seen in Figure 5.1 below.



Shelf margin	Age	*A* (m)	*P* (km)	Time (My)	*A.* rate (m/My)	*P.* rate (km/My)	Reference
New Jersey	M. Miocene	150	60	2.9	43	17	Steckler et al. (1999)
New Jersey	E. Miocene	113	34	7.4	15	5	Steckler et al. (1999)
New Jersey	Oligocene	113	10	9.5	13	1	Steckler et al. (1999)
Spitsbergen	E. Eocene	1150	30	6.0	192	5	Johannessen and Steel (2005)
Porcupine Basin	E. Eocene	400	30	4–5	80–100	7	Johannessen and Steel (2005)
Lewis-Fox Hills	Maastrichtian	>480	>86	1.8	267	48	Carvajal and Steel (2006)
Pletmos Basin	Barremian–Aptian	500	60	4.0	113	15	Brink et al. (1993)
West Siberia	Valanginian–Hauterivian	1000	550	9.0	111	61	Pinous et al. (2001)
Exmouth Plat.	Berrisian–Valanginian	610	>57	6	102	10	Erskine and Vail (1987)
Nova Scotia	Lower Cretaceous				20	5	Pers. Comm. John Gjelberg/Norsk Hydro
North Slope of Alaska	Albian	~1000	152	10.0	100	16	McMillen (1991), Houseknecht et al. (2009)
Orinoco Columbus Basin	Pleistocene–present	4400	29	1.8	2450 (and higher)	16	Sydow et al. (2003), Wood (2000)
Orinoco Plataforma Deltana	Pleistocene	1500	60	1.6	935	38	Di Croce et al. (1999)
Orinoco Plataforma Deltana	Pliocene	2000	60	3.5	550	18	Di Croce et al. (1999)
Orinoco East Venezuela	L. Miocene	1200	200	6	200	33	Di Croce et al. (1999)
Orinoco East Venezuela	M. Miocene	2000	60	5	400	10	Di Croce et al. (1999)
Orinoco East Venezuela	E. Miocene	2000	75	7	280	8	Di Croce et al. (1999)
Gulf of Mexico Louisiana	L. Miocene (UM)	2500–3000	Fig. 7	5.8	460–550	16–20	All from Galloway et al. (2000), Wu and Galloway (2002), Galloway and Williams (1991); and Fig. 7
Gulf of Mexico Louisiana	M. Miocene (MM)	Not avail.	Fig. 7	3.6	Not avail.	16–20	
Gulf of Mexico Texas/Louisiana	E. Miocene (LM2)	Not avail.	Fig. 7	2.6	Not avail.	12–16	
Gulf of Mexico Texas/Louisana	E. Miocene (LM1)	Not avail.	Fig. 7		Not avail.	8–12	
Gulf of Mexico Rio Grande	Oligocene (OF)	Not avail.	Fig. 7	8.6	600–700	16–20	
Gulf of Mexico Rio Grande	L. Eocene (Jackson)	Not avail.	Fig. 7	2	600–800	12–16	
Gulf of Mexico Rio Grande	M.-L. Eocene (Yegua/Cockfield)	Not avail.	Fig. 7	4	600–800	4–8	
Gulf of Mexico Texas	M. Eocene (Sparta)	Not avail.	Fig. 7	3.5	0–200	0	
Gulf of Mexico Rio Grande	M. Eocene (Queen City)	Not avail.	Fig. 7	2.8	1400–1500	8–12	
Gulf of Mexico Rio Grande	E. Eocene (U. Wilcox)	Not avail.	Fig. 7	5.5	150–250	4–8	
Gulf of Mexico S. Marcos Arch	L. Paleocene (M. Wilcox)	Not avail.	Fig. 7	2	200–300	4–8	
Gulf of Mexico Houston Embay.	L. Paleocene (L. Wilcox)	Not avail.	Fig. 7	4.6	500–600	20–30	
Borneo	Pleistocene	2300–1700	~20	1.7	1000–1350	12	Saller and Blake (2003)
Borneo	Pliocene	2000–1700	12–40	3.7	460–540	3–11	Saller and Blake (2003)
Borneo	L. Miocene	Not avail.	20–40	5.7	Not avail.	4–7	Saller and Blake (2003)

Figure 5.1: Accretion distance and aggradation measured in shelf-edge maps and cross-sections. From Carvajal et al., 2009. All measures un-decompacted except for New Jersey Margin, and Gulf of Mexico in the Paleocene, Eocene and Oligocene whose decompacted aggradation rates are directly provided in Galloway and Williams (1991). Some uncertainties may arise from cross-sections orientations, lack of depth-converted seismic data and limited aerial coverage. Therefore, rates are approximate. Dating is reasonably good for all margins except for the North Slope of Alaska (which may lead to errors in progradation and aggradation rates). In some margins rates were calculated for more than one period to represent variability.

As seen above, the Pletmos basin amongst other moderately deep-water margins infill their basins relatively rapidly, and develop more progradational architectures with morphologically smooth and relatively undeformed slopes. Both moderately deep and very deep-water margins display progradation of several tens of km/My tend to be linked to the delivery of relatively large volumes of sand into the deep-water basin.

The study by Carvajal et al., 2009 of moderately deep-water margins such as the Pletmos basin reveals a couple of interesting views about our study area which compliment our above findings. Such views are as below:

- Sediment supply is the primary variable driving the growth and deep-water sand content of the selected margins. Increased sediment supply leads to increased rates of margin progradation and larger volumes of deep-water sediment. In the moderately deep-water margins, the larger supply also caused increased frequency of sand delivery to deep-water areas and an enhanced potential to generate both highstand and lowstand fans.
- Despite the obvious importance of sediment supply to shelf-margin architecture and to the potential of margins to contain and bypass deep-water sands, the role of supply in shelf-margin growth has received limited attention. High cross-shelf sediment flux is critically important for the occurrence of deep-water sands, not least on Greenhouse or rapidly subsiding margins where the impact of eustatic sea-level fall may be insufficient to drive sediment delivery out across the shelf into deep-water areas.
- This rapidly prograding margin with its linked high supply will tend to reduce the basin-floor fan occurrence risk. In addition, when the supply is high, the greater area of such reservoirs will make them easier to target. In contrast, low supply shelf margins are likely to generate smaller fan reservoirs which are more difficult to target.
- Sediment supply (and not sea level) is likely to be the key limiting factor on the growth of this shelf margin and that sediment supply, as interpreted through progradation rate, can therefore be used to make a first-order prediction of relative amounts of sand passed to deep-water areas.

Not only are large volumes of sand most likely to be found in this deepwater basin, but study byVan der Spuy, 2003 reveal that Early Aptian source rocks have also been intersected in the Pletmos Basin, where the organic-rich interval is over 80 m thick in places. There is strong seismic evidence that this source interval should be well developed in the greater Southern Outeniqua Basin to the south of the Pletmos basin. Burial history studies in this large basin show that the Early Aptian interval is sufficiently mature over large areas to have generated and expelled oil.

5.2 Conclusion

Seismic analyses and interpretation as well as structural, core, log and biostratigraphic analyses and interpretation suggest to high degrees that the Pletmos/Southern Outeniqua Basin is a sand-rich system (being broad and not possessing well developed levees as can be seen on the F84-155 seismic line). Such systems tend to have broad, low-sinuosity channels that do not have well developed levees (Bacon et al., 2003).

This study as well as that of others (e.g. Carvajal et al., 2009) also confirm that depositional rate especially along the slope was very fast to moderate suggesting that there must have been great sediment-bypass into the deepwater Southern Outeniqua basin.

It is also worth noting that tectonics has played a very major role in the development of this basin margin and in the deposition of the many progradational sequences in the deepwater Southern Outeniqua. This goes a long way to also emphasize the concept that eustatic sea level changes is not the only main factor in the deposition of sequences. Tectonics and sediment supply rate have been significant factors (amongst others such as sea level change) in the formation of these deepwater sequences.

Results of this study shows the Southern Outeniqua to be a sand rich deepwater clastic system while Van der Spuy, 2003, shows that that the source rock interval should be well developed in the greater Southern Outeniqua basin. This hereby suggests that a viable and unexplored petroleum system exists in this untested world class frontier basin of the Southern Outeniqua basin.

As Rose, 1996, puts it “the most difficult and critical decision in petroleum exploration is not which prospect to drill, but instead, which new play to enter”. We would think this is the dilema in which exploration in this unexplored frontier basin is caught.

5.3 Recommendations

In order to improve the way we would make exploration risk decisions in a new play such as the Southern Outeniqua, the data base quality needs to be improved as well as the strength of the geological model. We hereby will recommend the following:

- All the seismic lines studied have been in 2D. The study of isolated 2-D seismic sections may miss significant features because they ignore the map view and do not see lateral changes parallel to the coast (Bacon et al., 2003). The distinctive contribution of 3-D seismic is that mapping of the individual seismic units will be much more reliable than can be achieved in a 2-D grid, and so inferences based on the shape of bodies (e.g. channel sinuosity) will be much more reliable. It is therefore recommended that 3D seismic be shot from the margins of the Pletmos basin into the deepwater Southern Outeniqua basin. Focused seismic acquisition and exploratory drilling is recommended in this deepwater basin.

- In the case of any exploratory drilling and/or coring, directional cores are recommended. Data from these cores is important in paleocurrents analyses and interpretation.
- Much more biostratigraphic work and data would be conducted in strategic boreholes where fossil abundance is depicted varying with depth.
- Although dipmeters are of limited use in palaeocurrent analysis of turbidite systems, they nevertheless can provide an important means of distinguishing between organised and disorganised facies by assessment of the consistency, quality and direction of measured dips throughout zones of interest.
- For a more comprehensive insight of the synrift rocks, a detail study through field work to exposed outcrops such as those of Heidelberg/ Riversdale (Western Cape) is highly recommended.

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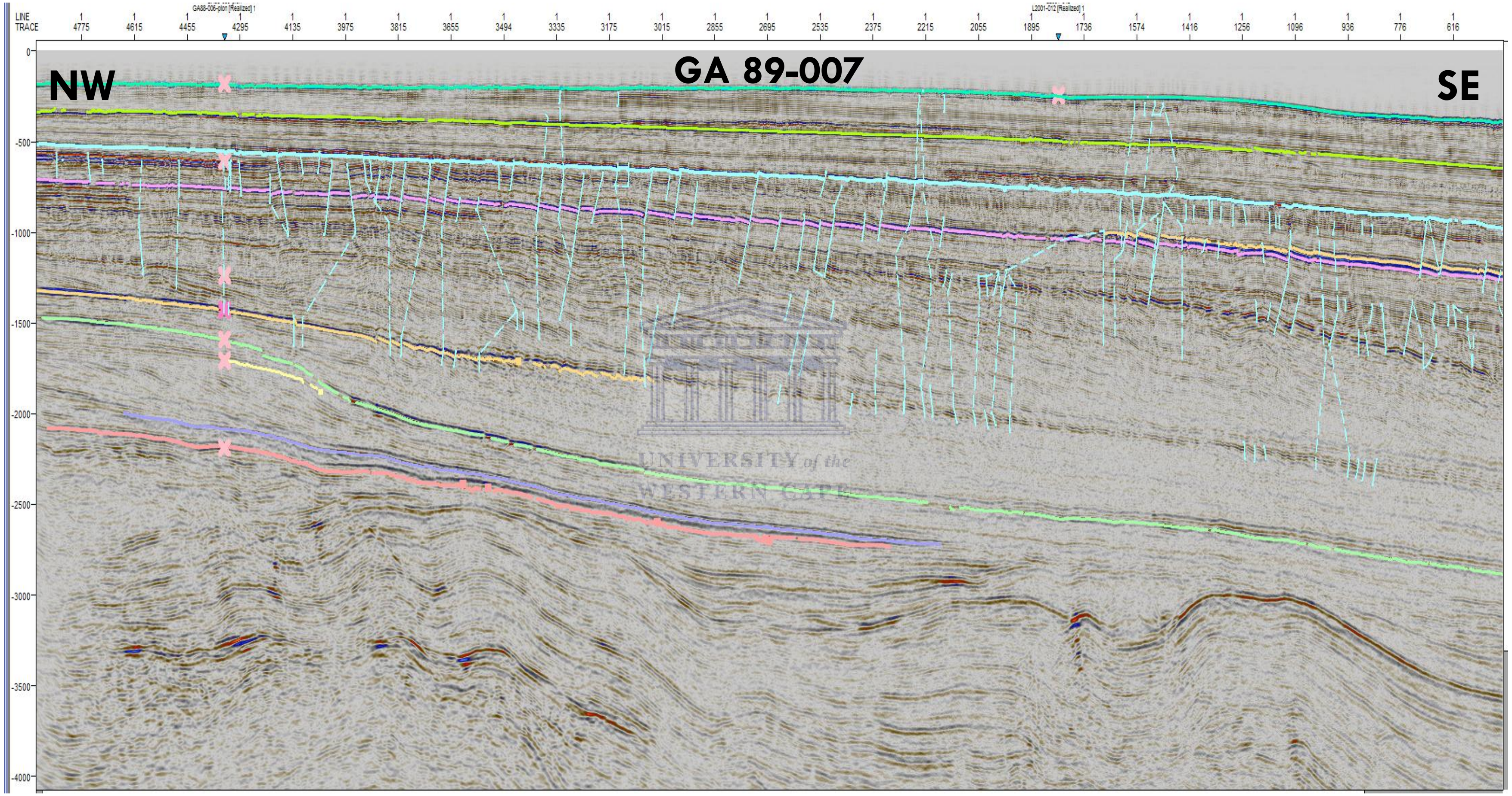
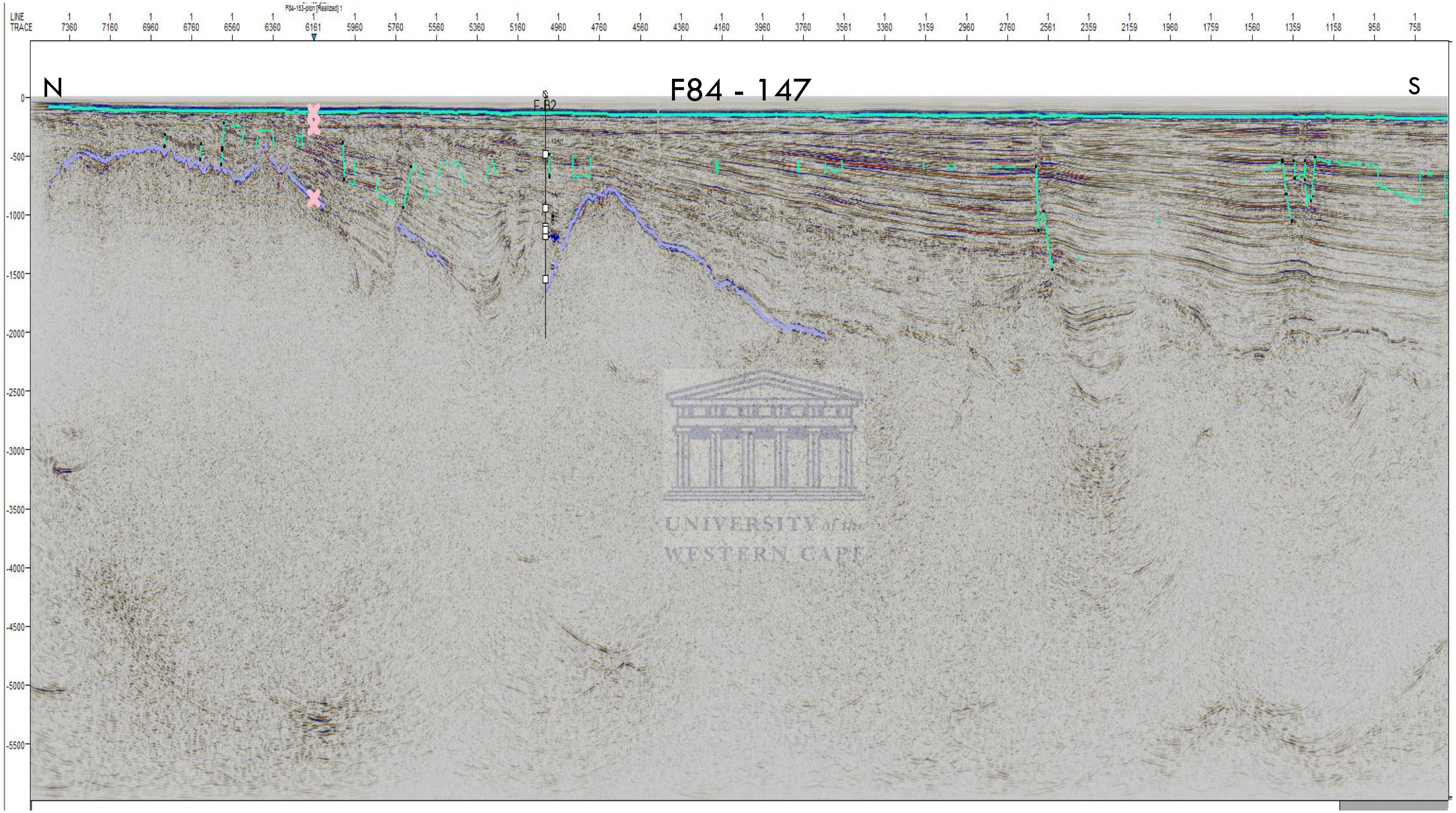
Appendices: (Fully interpreted seismic sections)

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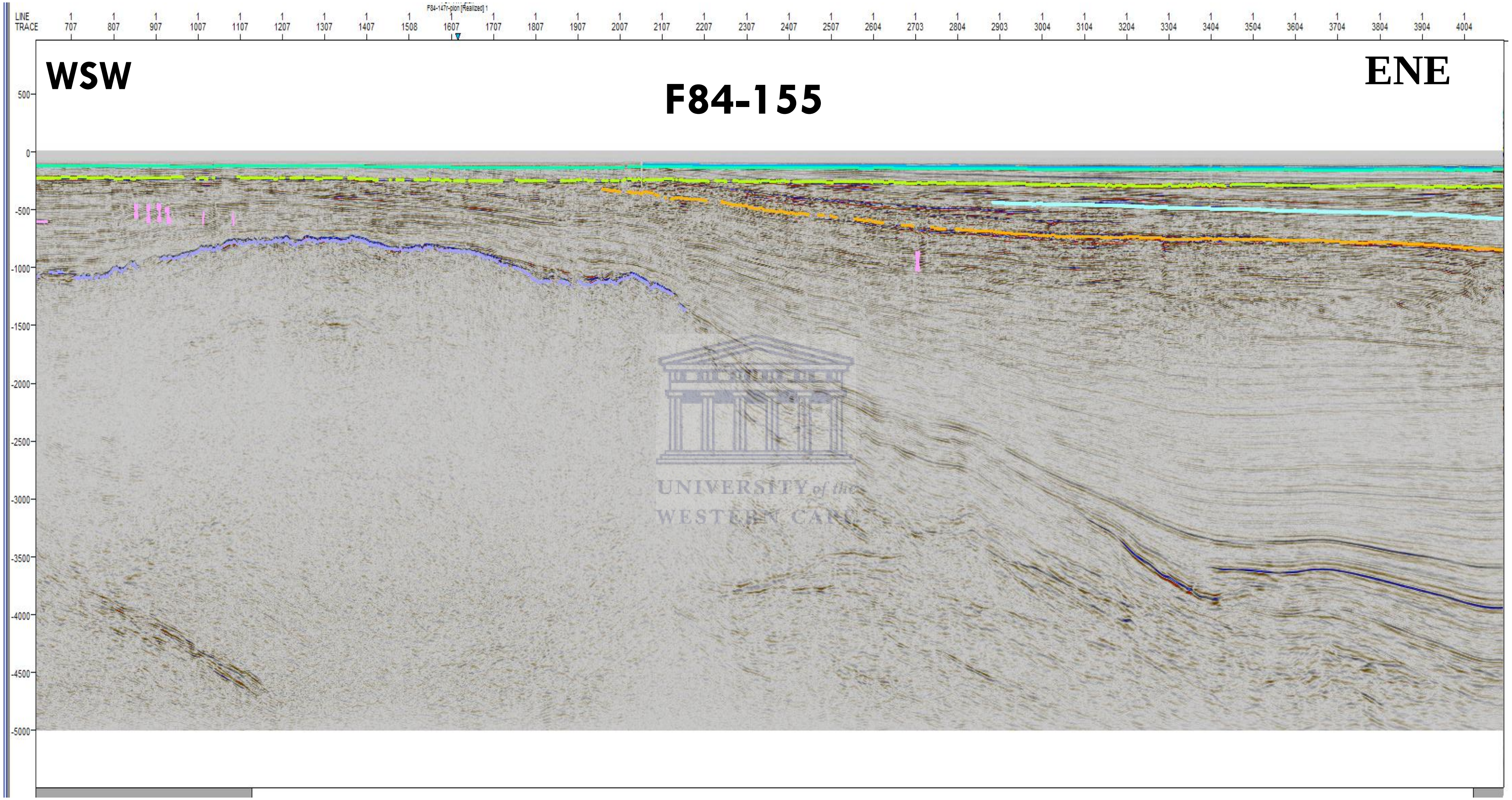
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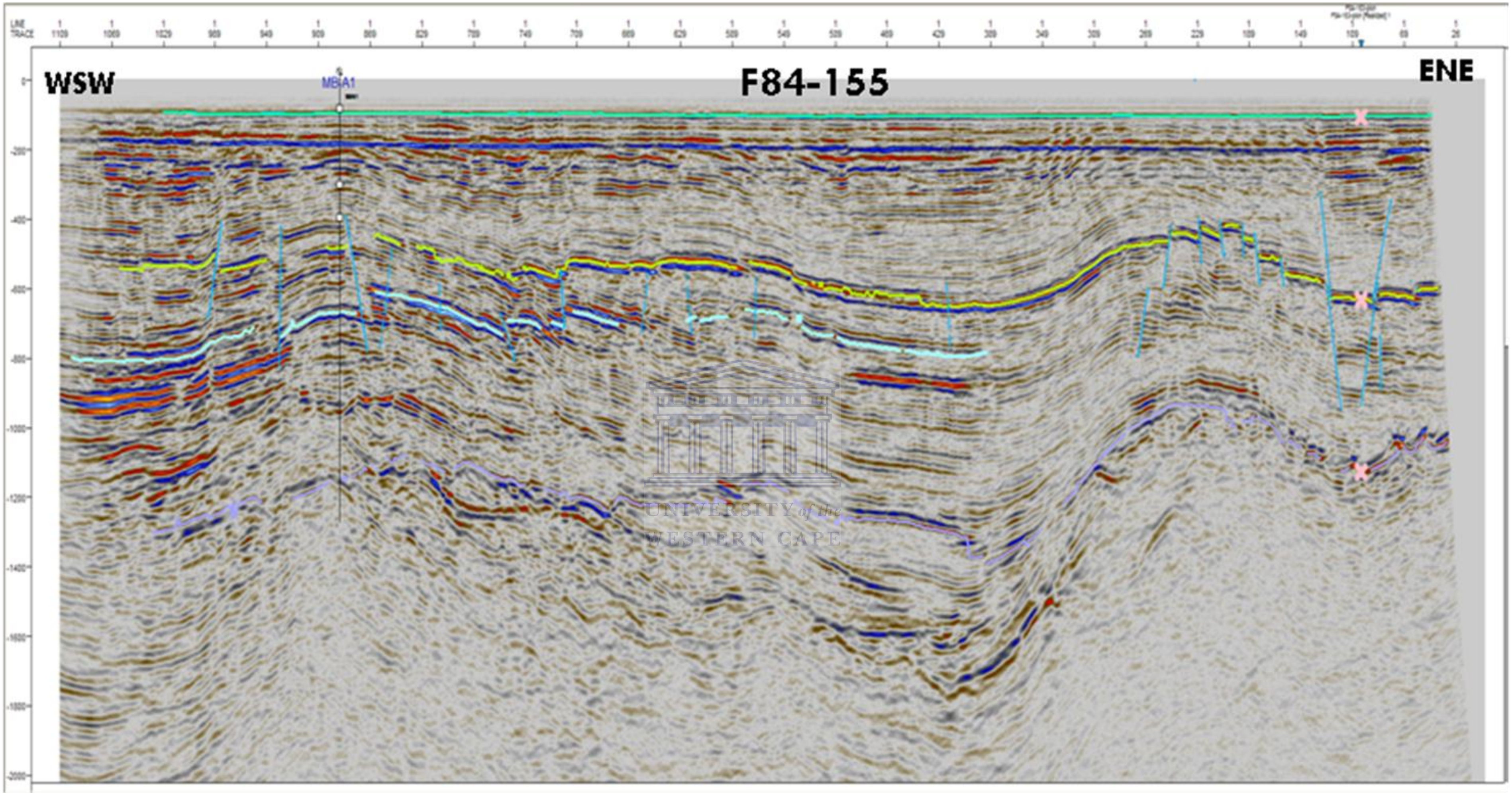
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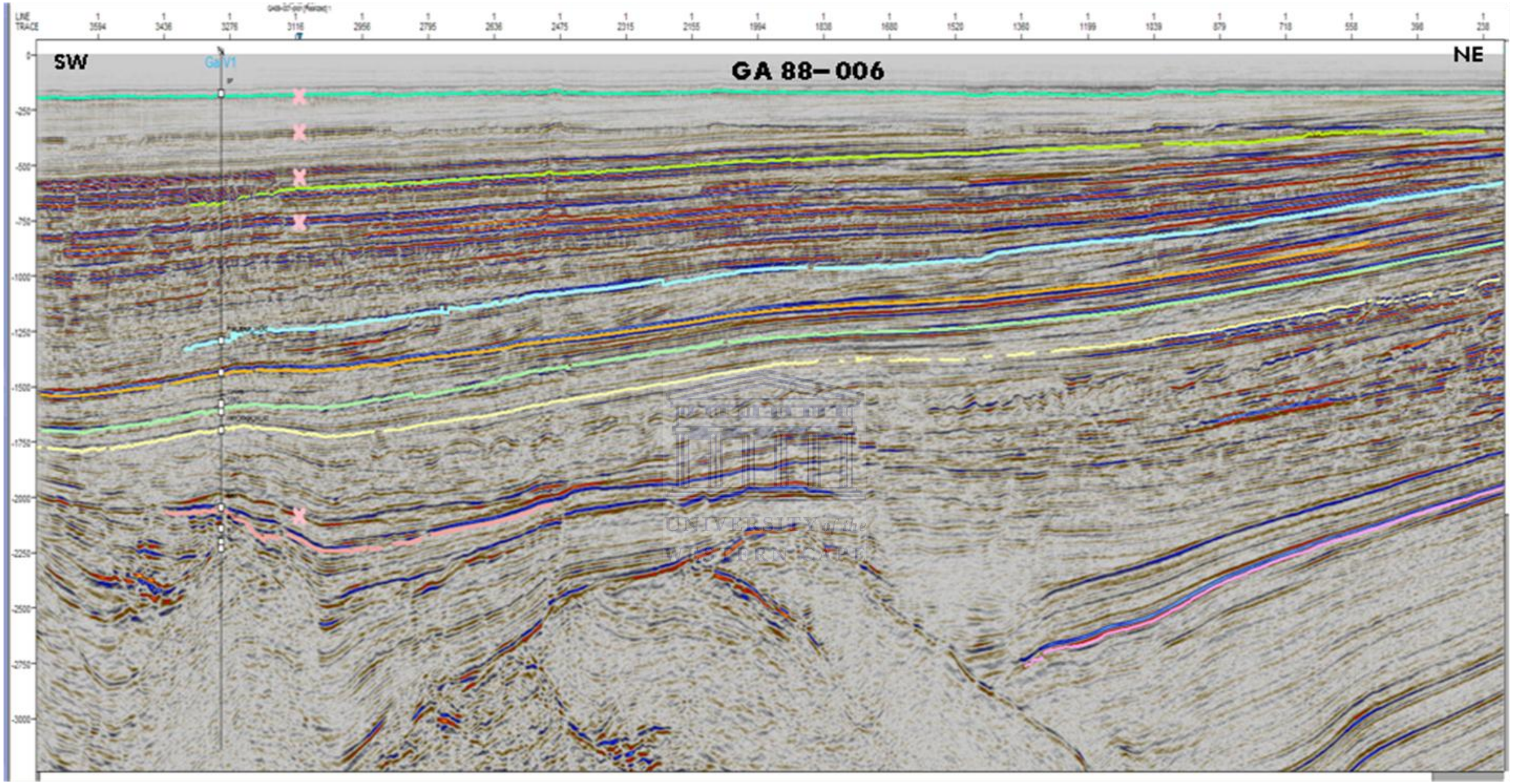
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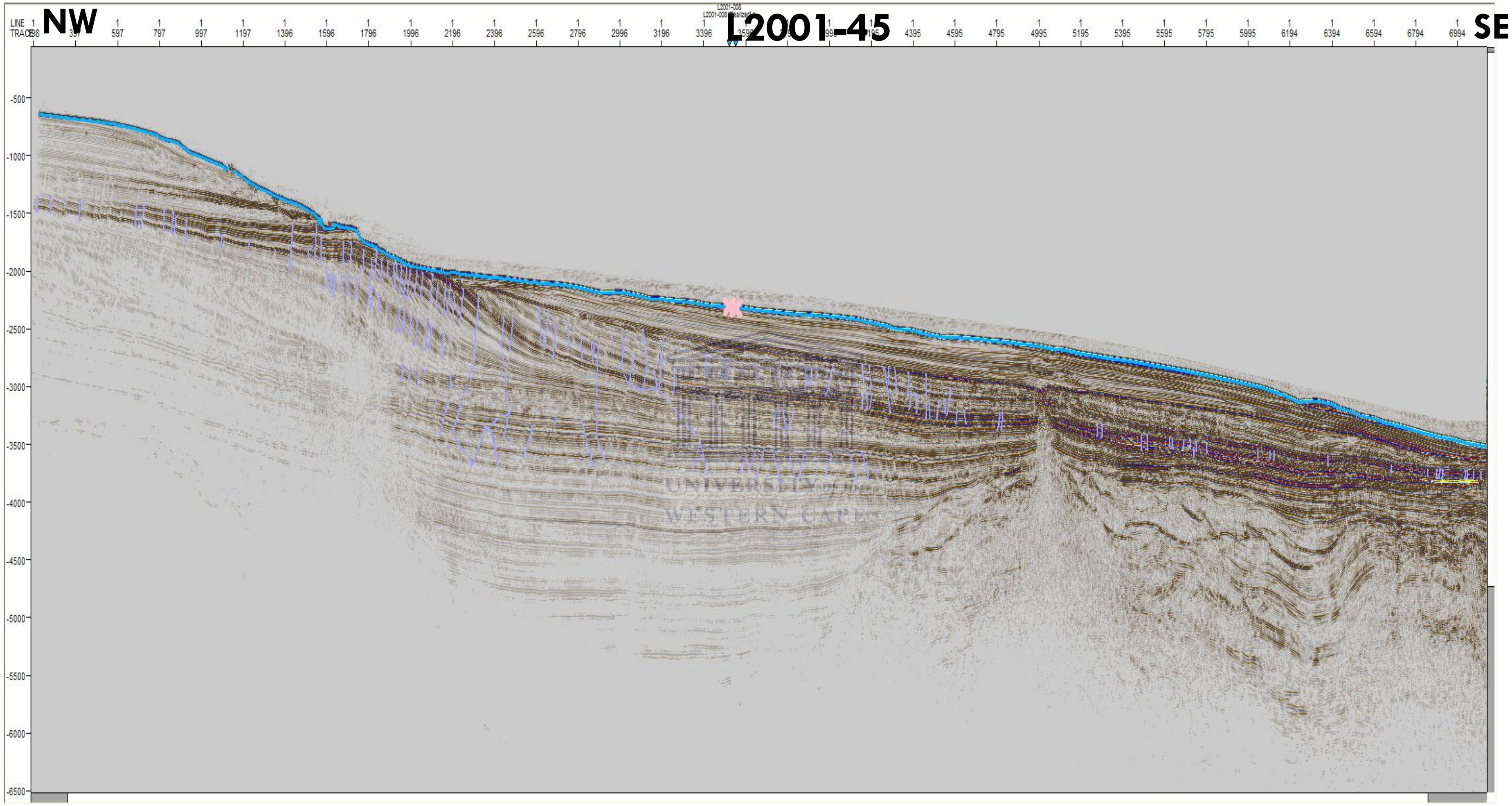
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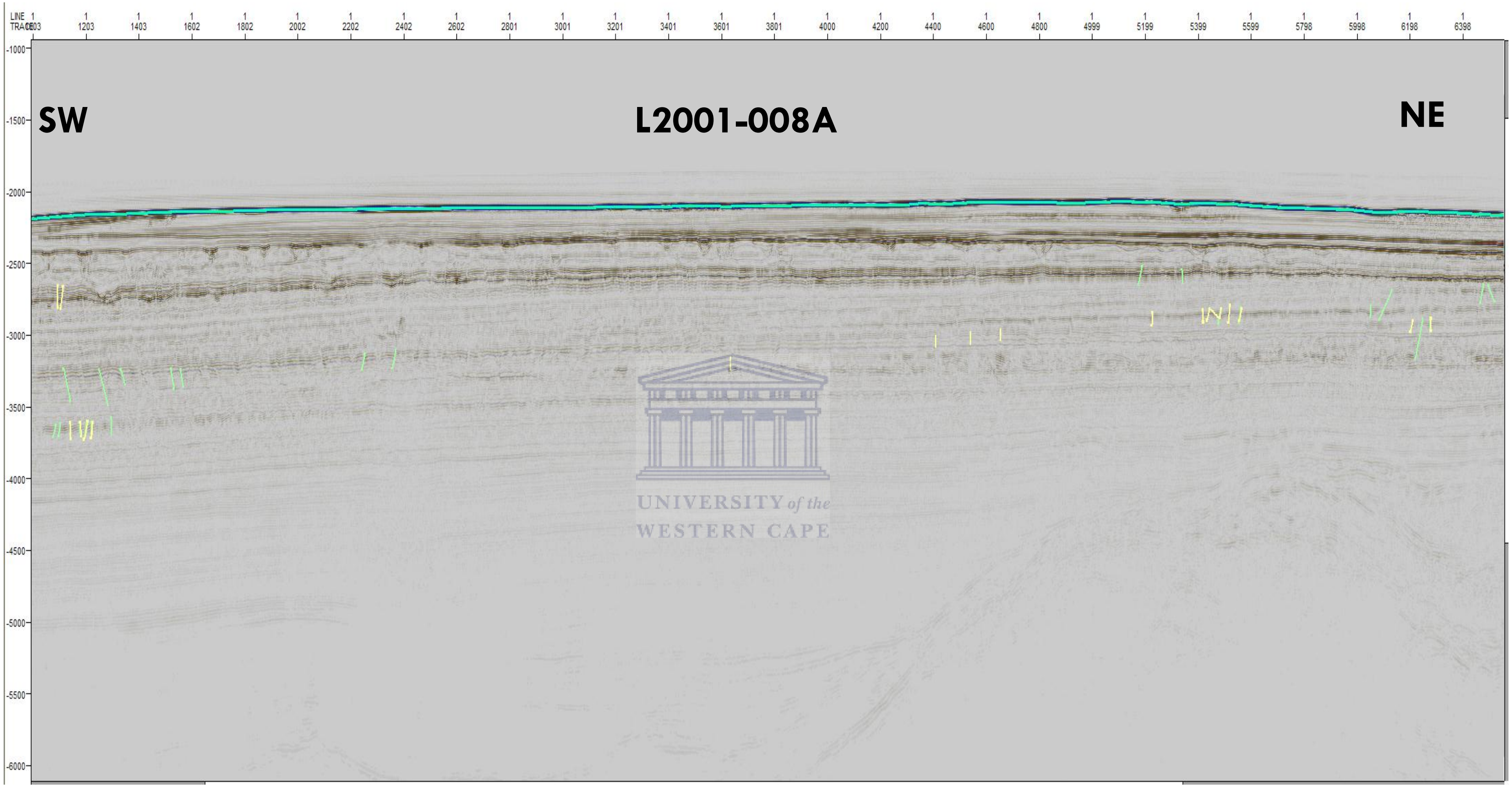
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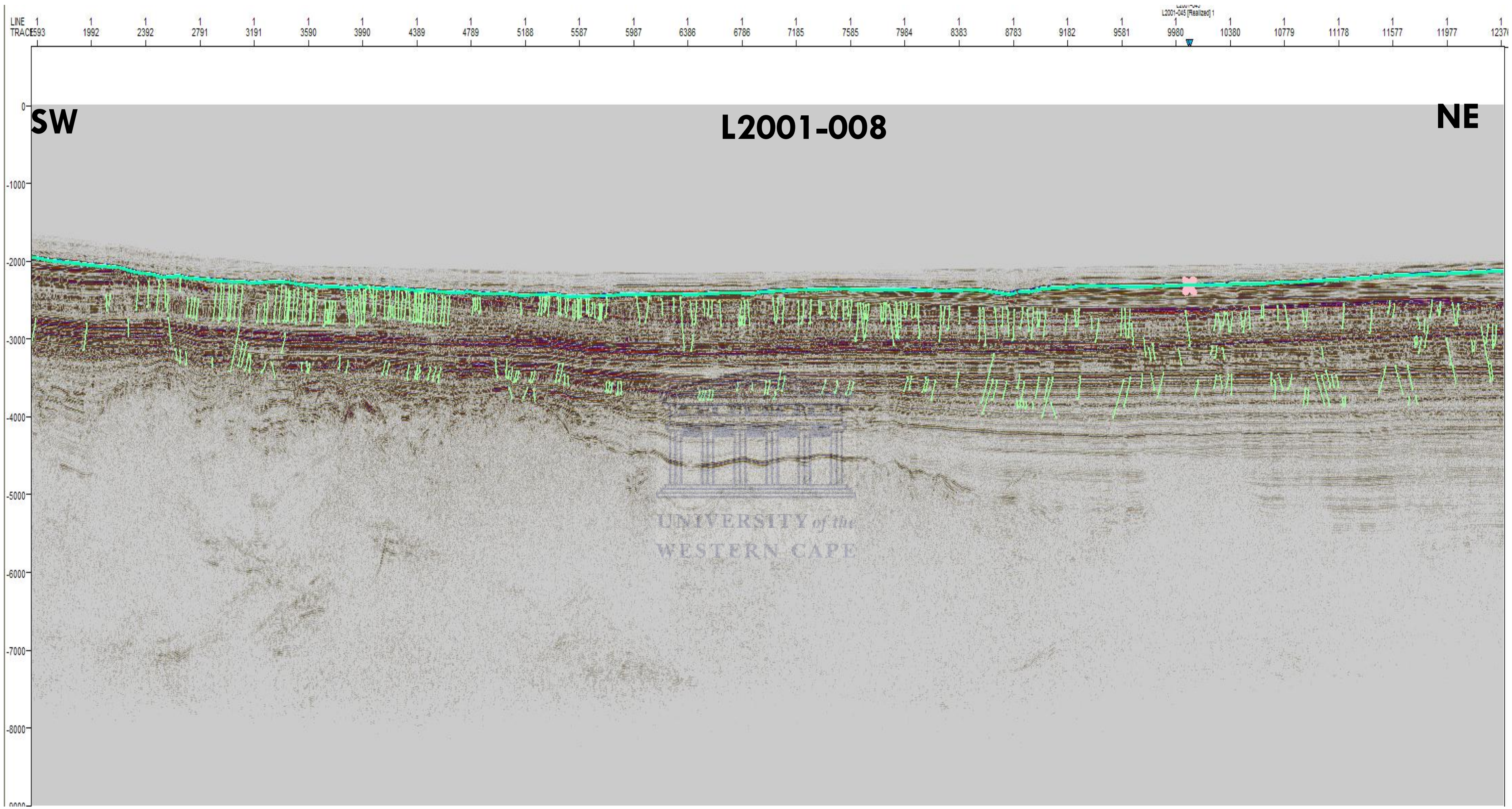
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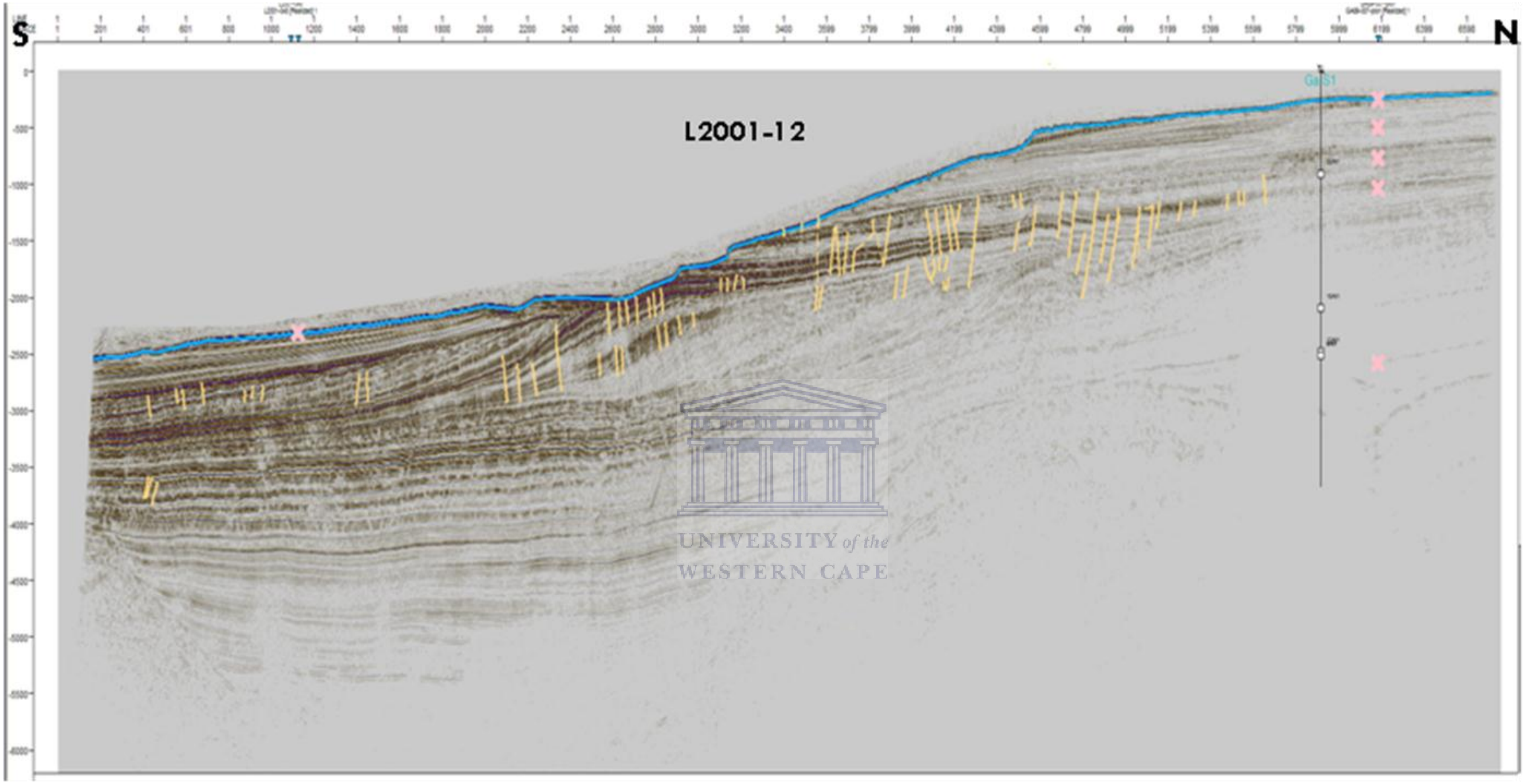
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