GEOMETRY AND GEOBODY EXTRACTION

OF A

SUBMARINE CHANNEL COMPLEX IN THE SABLE FIELD, BREDASDORP BASIN

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ABSTRACT

The Sable Field constitutes a Basin Floor Channel (BFC) complex (E-BD reservoir) and a Basin Floor Fan (BFF) complex (E-CE reservoir). The reservoir sands were deposited during early-drift sedimentation in the Bredasdorp Basin. Paleo-current flows from the west, filling the basin with sediments that are eroded off the continental shelf (Agulhus Arch) and deposited on the base of the continental slope and basin floor. Turbidite flows off the Agulhus arch have deposited the Sable Fields reservoirs, where the larger channelized reservoir body takes an 80° bend off the continental slope and flows onto the basin floor. This 3-D reservoir highlights the reservoirs internal heterogeneity and complexity at the well bore and away from the well bore. Well tops tie wells to the 3-D seismic cube for; reservoir location and delineation, velocity modelling and subsequent conversion of the mapped surfaces from time to depth. Core and petro-physical analysis were used to outline the depositional facies within the investigated wells namely: E-BD5, E-BD2, E-BD1 and E-CE1. Correlation of depositional facies at the well bore with their corresponding seismic facies, allows for extrapolation of facies away from the well bore.   The internal heterogeneity of the reservoir is outlined using an integrated methodology, which is based on log scale depositional features (channels, sheets, lobes) that are extrapolated to field scale (sand rich complex) using corresponding top and base reservoir seismic responses. The investigated thick region of sediment accumulation on: the continental slope, the base of the continental slope and basin floor is deposited on the 13AT1 early drift unconformity. The reservoir is outlined from the up-dip to the down-dip reaches of the field. Well E–BD5 has tapped into the proximal region (up-dip), with reservoir comprising of amalgamated channel sands that are deposited by laterally switching and stacking channelized sand bodies. Channel meander facies are seen in the upper portion of the reservoir, with massive channel fill in the lower parts. The channel fill constitutes a high net to gross with little to no lateral facies variations. This confined environment is dominated by amalgamated massive sands (on-axis) that are thinner bedded towards the banks of the channels (off-axis). A high degree of channel amalgamation has been interpreted in both up-dip wells E-BD5 and E-BD2. This channelized reservoir is at least 2km wide and 6km long, before the larger channel makes a rapid 80° change in paleo-current direction. This is possibly the result of basin floor topography and the stacking of previously deposited sand complexes which alter local sea floor topography. The vertical and lateral continuity of the channelised reservoir is generally excellent due to the high degree of channel amalgamation. The stacked channel complex constitutes a gross thickness of 76.2m (68.5m Net sand) in well E-BD5, and a gross thickness 25m (23m Net sand) in well E-BD2. Channel sands in well E-BD5 have an average porosity of 15% while the average porosity of channel sands in well E-BD2 (further down-dip) is 17%. This up-dip channelised region results in high amplitude reflections due to hydrocarbon charged sand juxtaposed against hemipelagic muds and silty levee facies. Well E-BD1 has tapped into a relatively confined sand complex deposited at the base of the continental slope. The amalgamated lobe and sheet sand complex is entirely encased in hemi pelagic mud. These reservoir sands are interpreted to be deposited in the Channel Lobe Transition Zone (CLTZ), thus the reservoir sands are interpreted to have a transitional depositional style (generally channelized sheets). The CLTZ region is thus dominated by both channel complex and lobe

complex elements. The E-BD1 reservoir constitutes a number of amalgamated elements that result in a reservoir zone with an average porosity of 16.4%. These include: amalgamated thick bedded sheet sand (lobe axis) associated with deep depositional feeder channels; thin bedded sheet sands (off lobe axis), broad thin amalgamated lobe elements, layered thick bedded sand sheets and deep broad depositional channels. The low sinuosity broad depositional-channels and elongate lobe elements are expressed as lobate amalgamated sheets of sand which is up to 2-3km wide, 5km long and 30m thick (29.7m nett sand) at the well bore. Well E-CE1 has intersected 50m thick reservoir sand (50m nett sand) which constitutes the axis of a lobe complex where the reservoir zone has an average porosity of 14%. The sand rich complex is deposited on the unconfined basin floor. This reservoir complex constitutes amalgamated thick bedded lobe architectural elements which are massive in nature. The laterally continuous hydrocarbon charged lobe elements result in bright parallel seismic reflections. The amalgamated lobe complex is more than 5km wide. Sub-parallel horizons are attributed to the thin bedded off axis portion of the lobe complex where the net to gross is considerably less than the highly amalgamated axis of the lobe complex. The lobe complex has a moderate to good net to gross of 40-60%. The high aspect ratio of the lobe complex severely impacts the reservoirs vertical permeability, however horizontal permeability is quite good due to the extensive lateral continuity of good quality sheet sands. Based on the nature deep water architectural elements observed in this study, the internal heterogeneity of the Basin floor Fan and Basin floor channel complex's may constitute an entire sand rich reservoir zone. All the sands may be in hydraulic communication if they are genetically related. These sands and stretch from the up-dip (wells E-BD5 & E-BD2) through to the transitional (E-BD2) and pinching out in the distal regions (E-CE1) on the basin floor. The seal constitutes a prominent shale horizon T13PW3 (8-10m thick) which is draped over the entire reservoir complex. This top seal is extrapolated from all the wells and correlated with seismic facies, thus outlining the lateral continuity and thickness variations of the top seal. This draped shale horizon exposes the thick axial portion of the amalgamated channel complex and amalgamated lobe complex.

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ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

1At1	Valanginian break-up unconformity at ca. 136 Ma
6At1	Late Hauterivian unconformity at ca. 130 Ma
13At1	Early Aptian unconformity at ca. 120 Ma
15At1	Upper Cenomanian unconformity at ca.93 Ma
17At1	Campanian unconformity at ca. 80 Ma
22At1	The Upper Maastrichtian unconformity at ca. 67 Ma
3-D	Three Dimensions
AFFZ	Agulhas-Falkland Fracture Zone
BFC	Basin Floor Channel complex
BFF	Basin Floor Fan complex
bbl/d	Barrels per day
CLTZ	Channel-Lobe Transition Zone
GOC	Gas Oil Contact
SAPIA	South African Petroleum Industries Association
OGJ	Oil and Gas Journal
OWC	Oil Water Contact

CHAPTER 1: INTRODUCTION

In this chapter the researcher discusses the background setting of the research which constitutes 3-D reservoir characterisation and its benefits in the industry. The Bredasdorp Basin and the Sable field's reservoir under investigation are highlighted with respect to the general role the Sable Oil and Gas field plays in South Africa. The research topic is introduced and the benefits and rationale of this type of research highlighted. The research question and corresponding aims and objectives as well as the methodology used to investigate and analyse the subsurface at field scale is outlined in this chapter.

1.1   BACKGROUND

Deepwater depositional processes are the consequence of sand rich sedimentary deposit, such as Channels, levees, lobes, slumps, pelagic mud. The deep water environment constitutes complex distribution patterns of depositional facies. The geometry of these depositional facies, their retained sediments, and their physical properties significantly impact the reservoir quality, connectivity and flow deliverability of hydrocarbons (Jiajie, 2012). Accurately describing stratigraphic complexity such as the architecture of sand rich deep water sediments, is a major issue facing the geoscience community tackling reservoir characterization and modelling.

Sandstones deposited in deeper waters along the continental margin have become important oil and gas reservoirs throughout the world. Once the technology became available for deep water hydrocarbon exploration and production, valuable deep water reservoirs have been found throughout the world from offshore Brazil and the Gulf of Mexico to West Africa (Hauge *et al.*, 2003). The sands are deposited in deep waters, below the wave base (turbidites and debrites), often beyond the shelf break, either on the slope apron or further on the base of the slope apron (Kirk, 2010a). These clean sands are transported from the shallow waters of the continental shelf into the deep-water depositional environments by turbidity currents.

The local flow direction of these gravity driven, sediment loaded mass flows is strongly controlled by the local topographic variations on the sea floor. With respect to the structural control on sedimentation, the geometry and orientation of turbidite sand bodies closely reflect paleo topographic features (Hauge *et al.*, 2003). This topographic structural control on reservoir geometry is a dominant characteristic of clastic turbidite sand reservoirs. Many of South Africa's producing reservoirs constitute turbidite sand bodies such as the Sable Fields reservoir under investigation.

3-D reservoir characterisation is a critical step towards developing a 3-D conceptual geological model. Reservoir characterisation has many inherent floors and uncertainties when wireline log or seismic data are interpreted independently. The research undertaken incorporates and integrates wireline logs, 3-D seismic data, well tops and cores, in order to characterise the sable fields reservoir in 3-D. This integrated approach in adopted in order to avoid uncertainties associated with the reservoir geometry such as internal heterogeneity. A 3D platform allows inherent subsurface properties to be treated in a realistic manner (MacDonald, 2008; Spilsbury-Shakel, 2006).

The Sable Field is located in the Bredasdorp sub-basin which forms part of the present day shelf offshore the Southern Coast of South Africa. This sub-basin is the westernmost of the five Mesozoic sub-basins which constitute the larger Outeniqua Basin. The Outeniqua Basin dominates the Southern South African margin which is a non-volcanic sheared margin. This continental margin originated due to the lithospheric stretching and breakup of Gondwanaland when South America rifted away from Africa along the Agulhas–Falkland Fracture Zone (Sonibare, 2014). Block 9 in the Bredasdorp basin hosts South Africa's major hydrocarbon deposits including the Sable Field which was South Africa's first oil producing field. The Block is operated by PetroSA, with the oil and Gas being transported and refined at the Mossel Bay plant.
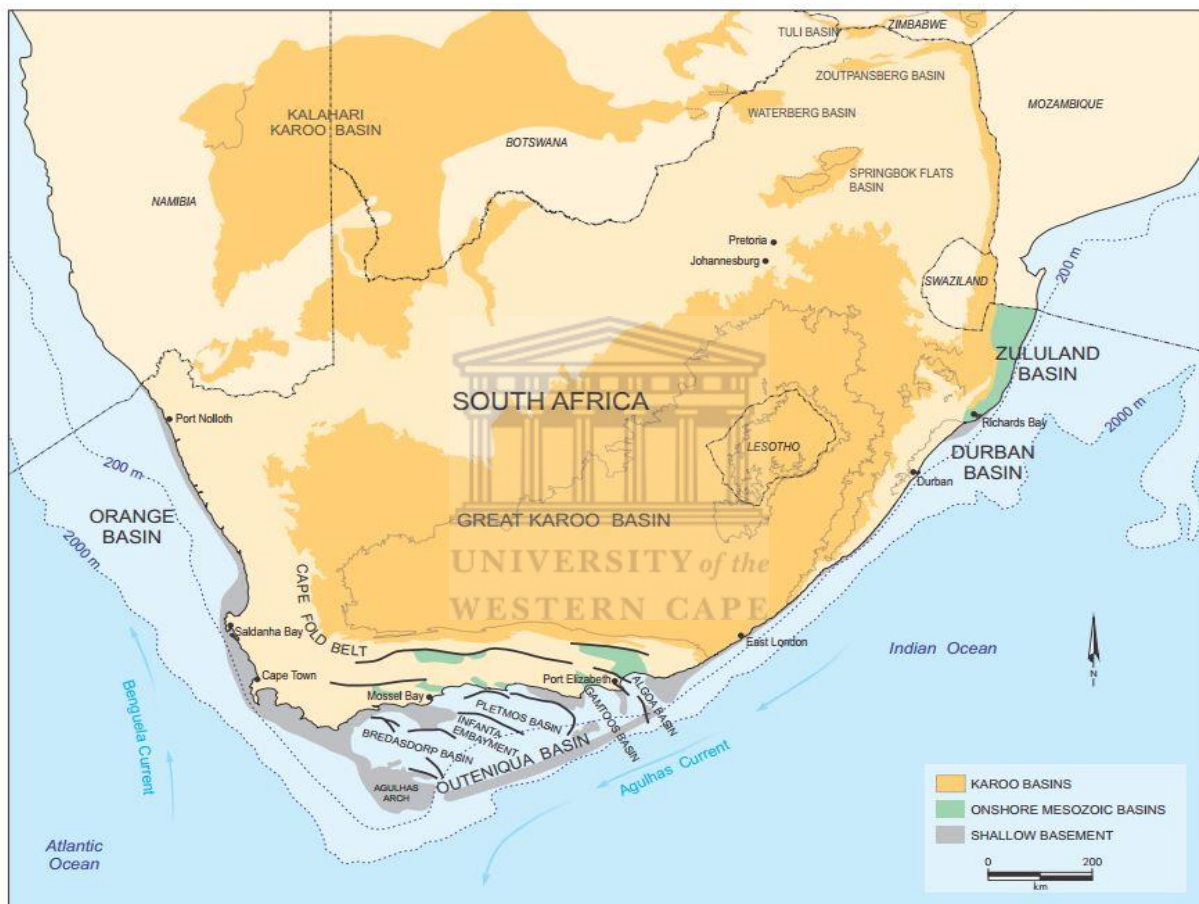
Figure 5. Major sedimentary basins of South Africa (Petroleum Agency SA, 2012).

Reservoir characterisation needs to consult a number of geological analogues in order to mitigate uncertainties associated with description of the reservoir under investigation. The deep water environment is reasonably understood with many outcrop analogies available globally. These analogues are consulted in order to direct the 3-D interpretation and characterisation of the Sable reservoir. The analogue assists in recognizing, examining and understanding the internal architecture as well as the distribution of the various deep water depositional elements such as channels, levees and lobes (MacDonald, 2008; Kirk, 2010a). These depositional elements can be associated on a local and fan-wide scale. The analogue

also assists with the recognition and examination of the hierarchical stacking patterns of these depositional elements with respect to channelized and non-channelized deposits.

When using 3-D seismic data, geological bodies which represent depositional elements such as channels and lobes can be extracted (Kirk, 2010b). These geobodies need to correspond to the analogue of deep water deposits. Geobody extraction methods are undertaken in order differentiate between channelized (confined) and non-channelized (unconfined) depositional bodies in the field.

1.2   PREVIOUS WORK DONE ON THE BASIN

South Africa hosts a number of minor Oil and Gas deposits predominantly situated offshore the southern coast. The state oil company now PetroSA (previously Soekor) which was founded in 1965, developed a stratigraphic nomenclature to characterise the sedimentary successions encountered offshore (Petroleum Agency SA, 2012, USGS, 2012)). Various offshore structural elements such as major faults, basins, sub-basins and structural highs were identified and named during the early stages of exploration.

South African oil and gas E & P activities are regulated by the Petroleum Agency SA who have been involved in many of the projects undertaken off the coast of southern Africa. 30 years of widespread exploration has indicated that South Africa's southern coast contains a number of small oil and gas fields, most of which are operated by PetroSA. The countries onshore region has no proven hydrocarbon reserves to date (Sullivan, 2012). Extensive drilling done since 1965 had resulted in the discovery of numerous syn-rift and post rift petroleum plays; including the ones made in block 9 where the Sable Field study is based.

1.3   SOUTH AFRICA AS AN OIL AND GAS PRODUCER

Sable is South Africa's first oil producing Field, however two more major fields Oribi and Oryx which were discovered later, are also oil producing fields. Due to the minimal amounts of oil and natural gas South Africa relies heavily on the production of its abundant coal deposits for the country's energy requirements (South Africa Energy Data, 2008). The country has an exceedingly developed synthetic fuels industry run by SASOL, which is mainly derived from coal. South Africa's energy sector contributes about 15 percent of the country's gross domestic product (GDP) thus domestic energy resources are critical to the economy (Country Analysis Brief, 2008).

Domestic sources of hydrocarbons and the available synthetic fuel substitutes cannot satisfy the country's current demand on their own. Thus South Africa relies heavily on imported crude oil, which accounts for over 90% of South Africa's fuel requirements (Nkomo, 2009; Country Analysis Brief, 2008). Due to this high level of dependence on imported crude oil, the country's economy is exposed to potential disturbances. Theses global scale events which cause the disturbances, could either interrupt supplies or lead to higher oil prices, in turn undermining economic growth and national development (Nkomo, 2009). In order to strengthen energy security South Africa needs to widen its diversity of supply, maintaining

strategic inventories and demand-side measures. There is however a positive aspect to South Africa's energy sector as it has the second largest oil refinery system in Africa (South Africa Energy Data, 2008).

As of January 2008 the Oil and Gas Journal (OGJ) stated that South Africa had proven oil reserves of 15 million barrels. All of the countries proven reserves are situated in the Bredasdorp basin offshore southern South Africa, with minor occurrences found off the west coast near the Namibian border . South Africa produced 199,000 barrels of oil per day (bbl/d) in 2007, with 160,000 bbl/d being from synthetic liquids which are processed from coal and natural gas with 16,000 bbl/d being natural crude. South Africa imports about 66% of its total crude oil consumption. The country consumed 505,000 bbl/d of oil in 2007, 306,000 bbl/d of which was imported (South Africa Info, 2015). The South African Petroleum Industries Association (SAPIA) states, the majority of the countries crude oil imports, refined in South Africa, is supplied by the Middle East. Iran and Saudi Arabia are the country's main suppliers, while other exporters such as Nigeria and Angola, among others also contribute to South Africas imports (South Africa Energy Data, 2008; South Africa Info, 2015).

South Africa produces minor amounts of natural gas which is mostly used in the production of synthetic fuel. Cedigaz states that of January 2008 South Africa had 318 billion cubic feet (Bcf) of proven natural gas reserves. The country produced 102 Bcf in 2008 and consumed 109 Bcf, 7 Bcf of the consumed amount being from imported Liquids Natural Gas (LNG). A large quantity of South Africa's natural gas is produced synthetically from coal. South Africa has developed natural gas supply agreements with neighboring country's Mozambique and Namibia, in order to compensate for the countries deficit in large natural gas reserves (South Africa Info, 2015). South Africa has four major basins namely the; East Coast basin, Outeniqua Basin, West Coast Basin and the Karoo Basin (Petroleum Agency SA, 2012). The former three basins are onshore basins while the later basin is an onshore basin which has recently been investigated as a potential shale gas plays.

Figure 6. Pie chart of comparative sizes of South Africa's major basins (Petroleum Agency SA, 2012)

1.4 PRODUCTION HISTORY OF THE E-BD/E-CE SABLE FIELD

The Sable Field is located in Bredasdorp Basin. This sub Basin is situated offshore the southern coast of South Africa, 150km Southwest of Mossel Bay. The field has a water depth of 100m and comprises of two reservoirs (E-BD and E-CE), which have recoverable oil reserves estimated at approximately 20 to 25 million barrels. The Sable field utilises the nearby Glas Dowr FPSO (Wood, 1995). The FPSO vessel is supplied and operated by Bluewater.

In 2003 the upgrade of the FPSO was conducted by SA Five Engineering in order to accommodate for the additional expected hydrocarbon coming from the Sable Field. Production of the Sable Field started in 2003, with production ceasing in 2008, possibly due to the intensive drop in the 2008 oil price. The first well drilled in the Sable Field, E-BD 1, had a high initial flow rate of 8,500 b/d of 38 gravity crude. Although this flow rate dropped

during testing there was sufficient encouragement to appraise the vicinity. A further four boreholes were drilled after E-BD1 (Soekor Ltd, nd; Wood, 1995). One of these well were dry while the other three wells intersected Oil and Gas reservoirs.

The E-BD2 borehole, drilled in December 1990, intersected a 25 m water bearing sandstone at a depth of 2552m below mean sea level. Borehole E-CE1, drilled in April 1991 in a 102m water column, intersected a 51 m thick massive amalgamated channel sandstone. This reservoir was intersected at a depth of 263m below mean sea level and it constituted a 31 m gas cap overlying a 20 m oil column.

On testing the E-CE1 well, the oil zone flowed 6,000 b/d of 40 gravity crude and the overlying gas zone flowed 10 MMscfd with a GOR of 7,000 scf/st-tk bbl (Soekor Ltd, nd; Wood, 1995).. The later drilled boreholes E-CE2 and E-CE3, delineated both the geological model and the extent of the two fields. These two reservoirs, E-BD and E-CE, are not in hydraulic communication.

2D seismic data from 1990 and 1991 and a 3D seismic survey acquired in late 1992, constitute the seismic coverage over the E-BD and E-CE fields. In order to assist in the delineation of these reservoirs, selected 2D seismic lines were inverted and Geostack (AVO) processed. Interpretations were made of the top and base of both reservoirs (Wood, 1995). These seismic interpretations were coupled with the geophysical modelling of amplitude variations associated with both the conventional and inverted data. The results were used to produce a series of reservoir property maps.
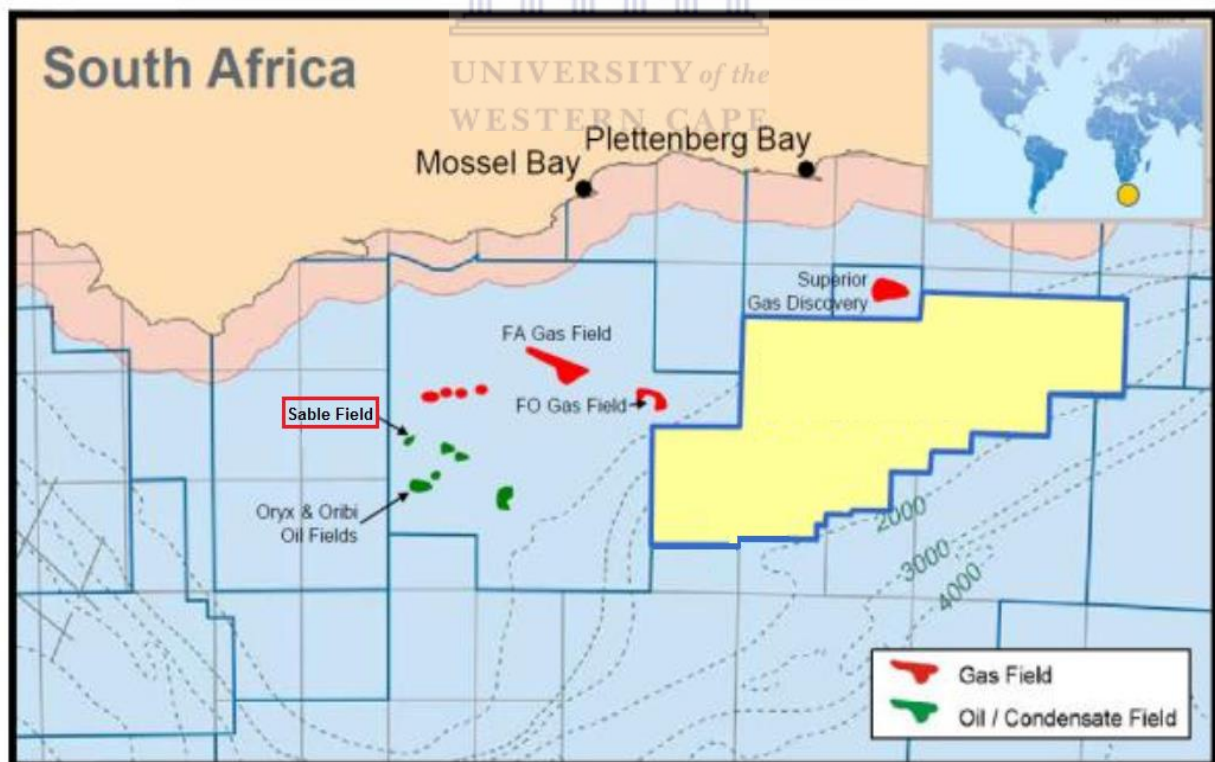
Figure 7. Location Map of the Sable Oil and Gas Field. Modified after Soekor Ltd, nd.

1.5 RESEARCH QUESTION

The Sable Field constitutes a highly complex Basin Floor Fan reservoir system which is well understood with regards to field and outcrop analogues. The Sable Field does however depict a unique reservoir configuration due to the geometry of the Bredasdorp Basin at the time of deposition. The primary research question is narrowed down to characterisation of the Sable Fields reservoir. In order to complete a thorough investigation of the reservoir it needs to be investigated in the third dimension.

WHAT IS THE 3-D DIMENTIONAL CONFIGURATION OF THE SABLE FIELDS RESERVOIR?

This primary research question is answered by combining the results obtained from answering a number of minor questions which are:

- What is the nature of the tectonic and depositional systems which have resulted in the spatial distribution of the reservoir?

- What is the nature of the reservoir at the individual well bores?

- What is the 3-D extent of the Sable fields E-BD reservoir and its vertical and lateral configuration away from the well bore?

- What is the spatial distribution of depositional elements which constitute the reservoir, there internal heterogeneity and the hierarchical stacking pattern of these depositional elements?
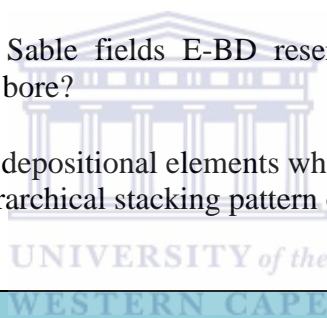
1.6 AIMS AND OBJECTIVES

The aim of the research is to characterise the Sable Fields reservoir in 3-D using an integrated approach in order to extract and define a geobody.

The objectives of the research are to integrate a seismic analysis and a petro-physical analysis (wireline log and core) of the data set under investigation; and correlate this analysis with field and outcrop analogues. The objective of the seismic analysis is to map out geological surfaces which influence the geometry of the reservoir. The seismic analysis is also used to extract the 3-D geobody that represents the Basin Floor Channel (BFC) and Basin Floor Fan (BFF) regions of the reservoir. The objective of the petro-physical analysis is to; outline reservoir zones at the well bore; extrapolate these reservoir zones away from the well bore by correlation with seismic; and to populate the geobody with reservoir properties.

Seismic and petro-physical interpretations have been correlated with field and outcrop analogues studies in order to guide the geobody extraction process. The geobody represents the reservoir zones thus is should only constitute the extraction of sand rich zones of the Basin Floor Channel (BFC) and Basin Floor Fan (BFF) complexes.

1.7 ESSENTIAL DATA

The data used in the research comprises of a 3D seismic cube and a number of wells. The Cube is cut from the original E-CC tract which constitutes a 3-D seismic survey. This 3-D seismic cube has been provided by PetroSA who are currently operating the Sable Oil and Gas field.

The wells used for the research namely; E-BD1, E-BD2, E-BD 5 and E-CE1 have been provided by The Petroleum Agency of South Africa (PASA). Stratigraphic well top data, well completion reports, velocity data (check shots) and core description reports have also been provided for each of the wells used in the research.

1.8 METHODOLOGY OVERVIEW

The general methodology of the research follows a workflow which is commonly used in the geoscience community when a similar data set is available i.e. 3-D seismic, core description and wireline log data. The interpretation and characterisation of the reservoir will be based on a method which integrates the seismic, core and wireline log analysis. This integrated method of reservoir characterisation is undertaken in order to better understand the spatial distribution of deep water depositional elements and the distribution of properties such as sediment type, porosity and permeability. Using both wireline and seismic data allows for more accurate reservoir characterisation away from the well bore (Jiajie, 2012). This integrated method also assists in understanding and delineating the reservoirs vertical and lateral depositional compartments.

Depositional elements will be outlined using the petrel software which allows for the delineation of stratigraphic horizons, geo-bodies as well as analysis of wireline logs. The interpreted architectural components of this submarine environment serve as the building blocks for the 3-D characterisation of the reservoir. The true depth of the reservoir is investigated via velocity modelling and time to depth conversion. The well is tied to the seismic data with respect well top data and seismic horizons which are captured in both time and true depth.

1.9 HYPOTHESIS

The up-dip channel deposit constitutes massive amalgamated depositional channel sands. The down-dip reservoir comprises of a lobe complex situated in the base of slope and basin floor regions of the Basin Floor Fan system. The up-dip channel complex and the down dip lobe complex may be hydraulic communication if the sands of the lobe and channel complexes are genetically related (Gordon, 2014; Wickens, 2014; Grobbler, nd and Jiajie, 2012). The E-CE reservoir is however separated from the upper E-BD reservoir due to stratigraphic pinching of the E-BD reservoir.

The channel sand is quite complex especially in the up-dip section of the channel geobody. The smaller depositional channel elements meander in the larger erosional channel body. This region constitutes the confined area at the base of the continental slope, which is dominated by depositional channels and channelsied sheet sands. The channelised sheets

arise from less confined turbidite pulses depositing sands in the larger channel (Gordon, 2014; Wickens, 2014; Grobbler, nd and Jiajie, 2012). This amalgamation of architectural elements results in a reservoir with a complex internal heterogeneity.

The down-dip lobe complex has a complex stacking and lateral swithching pattern of deposition which is further complicated by stratigraphic pinching of individual lobe elements. lobes pinch out, switch and stack at various scales even though appearing to be one continues amalgamated sand package at the well bore. This amalgamated sand package constitute stacked lobes deposited on the basin floor in the distal regions of the Basin Floor Fan System.

1.10 SUMMARY

The research has consulted literature, integrating seismic interpretation, wireline log analysis and core description. An overview of the adopted methodology has been presented. The research question being solved and the corresponding aims and objectives of the research have been outlined. The reservoir is interpreted to constitute a number of vertically restricted and laterally continuous, good quality reservoir sands, which form part of a complex Sub-marine Basin Floor Fan depositional system. The following chapter illustrates the literature review undertaken on the regional and local geological setting of the Sable Field as well as the depositional model analogue developed for this study.
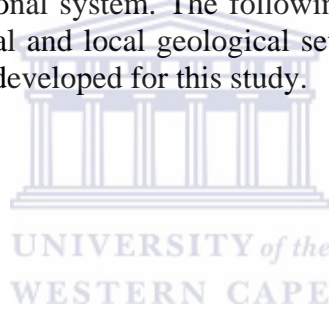
In this chapter the researcher outlines the Geology of the major Outeniqua Basin including the, basement architecture and tectonic setting which dominate this regional basin. The localized Bredasdorp Basin which hosts the oil and gas field under investigation is also defined. This local analysis of Bredasdorp Basin is outlined with respect to its local tectonic setting and resultant depositional systems, which are directly associated with the reservoir architecture of the Sable field.

2.1 REGIONAL GEOLOGY – THE OUTENIQUA BASIN

The Outeniqua Basin is Located offshore Southern Africa. Spanning approximately 500km, it is situated between the Southern African coast and the Agulhas-Falkland Fracture Zone (Ref. Fig. 4 below). The Outeniqua Basin constitutes six sub-basins, namely the shallow Bredasdorp, Infanta, Pletmos, Gamtoos, Algoa and the deep Southern Outeniqua Basin (Parsiegla, 2008).
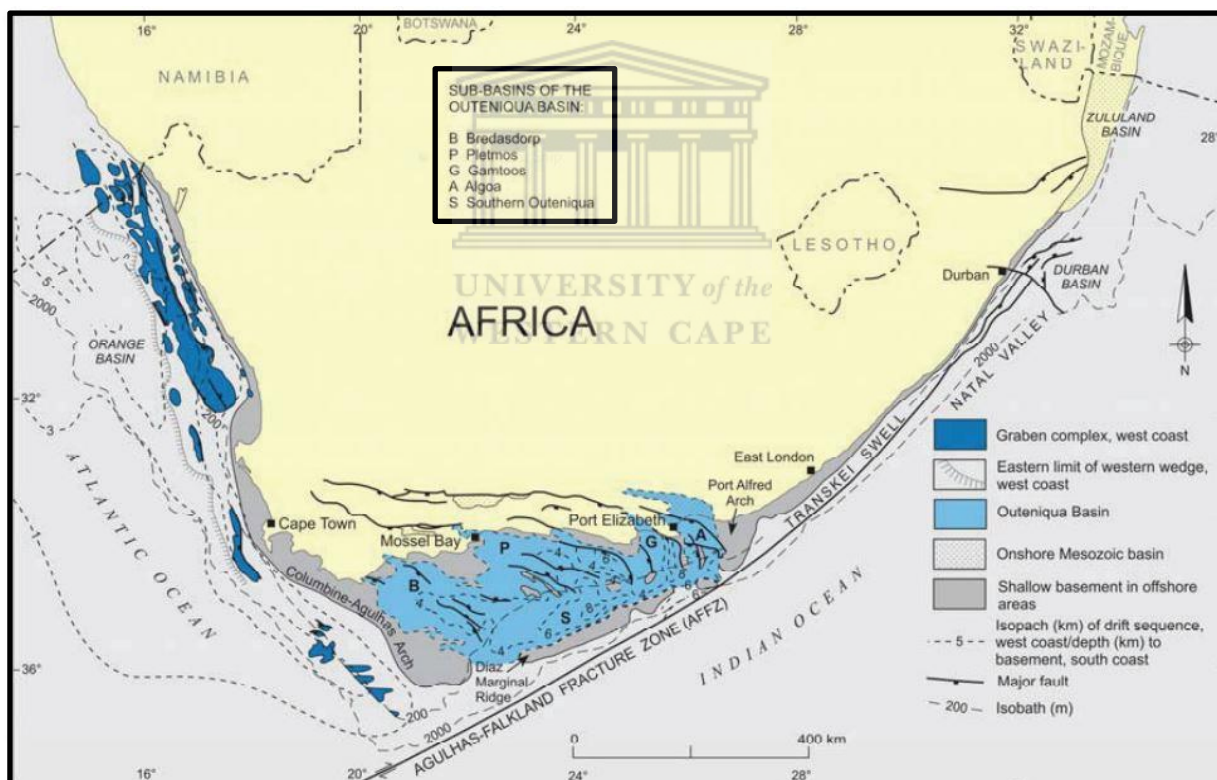
Figure 8. Location map of the Outeniqua Basin (Parsiegla, 2008)

The southern South African continental margin constitutes a complex margin system which has been subjected to continental rifting and transforms processes that result in a number of complex sub-basins. Research primarily focuses on the proximal section of the Mesozoic aged Bredasdorp sub-basin which constitutes the westernmost of the Outeniqua Basins five offshore sub-basins (Sonibare, 2014, Macdonald, 2012).

The Deep Crustal Structure and crustal stretching processes associated with the Outeniqua Basin are generally poorly understood due to the inherent complex nature for transform boundaries (Sonibare, 2014; Parsiegla, 2008). Shear motion between the African and South American plates, took place along the Agulhas-Falkland Transform Fault during the Early Cretaceous break-up of Gondwana. This tectonic event gave rise to the south and south-eastern African continental margin. Formation of the South Atlantic is also associated with the Agulhas-Falkland Fracture Zone (AFFZ) tectonic event.

The Outeniqua Basin constitutes a stike-slip (transform) basin that developed due to this early cretaceous rifting. Right-lateral strike-slip motion resulted in the separation of the African and South American continents along this transform, with a maximum ridgeridge offset of 1200 km (e.g. Barker, 1979; Ben Avraham, *et al.*, 1997 cited in Parsiegla, 2008).

2.1.1 EVOLUTION OF THE TRANSFORM PLATE BOUNDARY

The Outeniqua Basin is regarded as a transform continental margin, where the basin constitutes the Southern continental margin of South Africa. This continental boundary subsequently developed into a passive margin after the tectonic displacement of South America and Africa. The Outeniqua basin is characterised as a continental margin with a significantly long-offset transform (AFFZ), which has experienced compressional (transpressional) and extensional (transtentional) forces superimposed to the shear forces (Parsiegla, 2008, Macdonald, 2012). As a result the Outeniqua's basin formation processes are much more complex than in rifted margin basins. Long-offset transforms often represent long lasting deep seated features where fracture zones may be re-activated.

Strike-slip tectonic settings constitute a significantly smaller continent-ocean transition zone (~50 km) compared to other passive margins. As a result of this smaller continent-ocean transition zone the distinct material and temperature differences between continental and oceanic crust occur within a short distance (ref. to fig. 5 below). This significantly impacts the basin formation processes and its overall structure at the continental margin (Macdonald, 2012). The Outeniqua basins is characterised by features common of sheared margins such as, marginal ridges, large-scale fracture zones and deep sedimentary basins.

a) Initial onset of spreading - Rift stage,
b) Young oceanic crust slides past old continental crust during early drift stage,
c) The Continental margin becomes inactive during the - late drift stage, A passive continental margin develops.
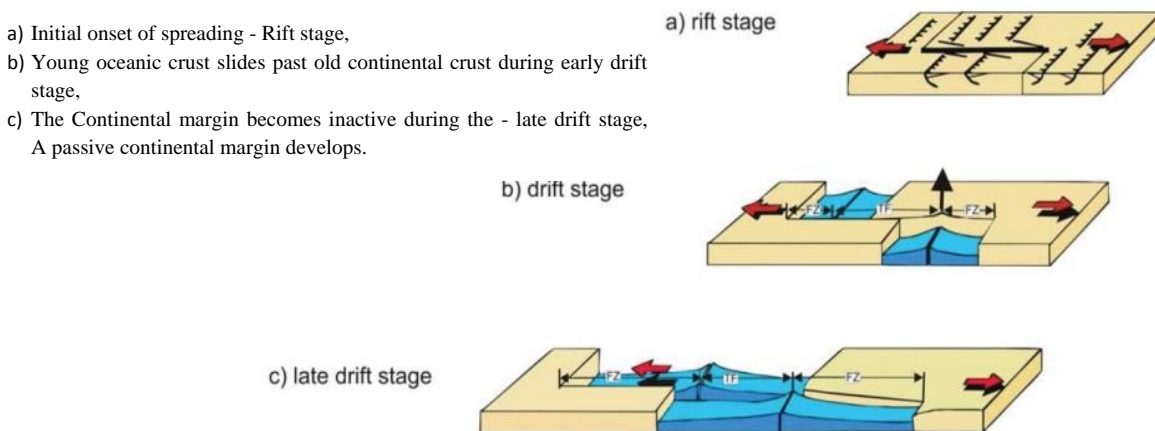
Figure 5. A diagrammatical representation of a sheared continental margin. Modified after Lorenzo, 1997 cited in Macdonald, 2012). The Red arrows indicate the plate motion, while black arrows show thermal uplift. FZ = fracture zone, TF = transform fault.

In relation to fig. 5 above, the transform margin which formed the Outeniqua basin had a complex evolution.

(a) Basin formation began with a Rift stage in the Early Cretaceous (Ref. to Appendix A - Geological Time scale). Major tectonic processes during this period include Right lateral displacement along Agulhas-Falkland transform fault and rifting. It has not yet been established whether the AAFZ transform formed entirely in the Cretaceous or exploited a pre-existing zone of weakness (Macdonald, 2012, Parsiegla, 2008).

(b) The Outeniqua Basin was subsequently subjected to the formation of young, hot oceanic crust. This oceanic crust formed south of the African continental plate, where it slides past the cold and older African continental-crust. The transform margin south of the Ivory Coast can be used as an analogue.It indicates that temperature difference along shear margins are likely to cause thermal uplift (Lorenzo, 1997 cited in Parsiegla, 2008). The Diaz marginal ridge is evidence of this thermal uplift (ref. to fig. 4 above). The southern-most extent of the Outeniqua Basin is bounded by the Agulhas-Falkland Fracture Zone and Diaz Marginal Ridge, while the Agulhas Bank constitutes the western margin of the basin.

(c) Post shear processes commenced once the spreading ridge passed the African continent. The Outeniqua basin and the development of the Diaz Marginal Ridge are evidence for a complex two phase opening history of the basin. An interpretation made of the sea floor in the eastern part of the Diaz Ridge segment hosts evidence for a renewal of tectonic activity during the Quaternary. The underlying cause for the initial development of such a long offset transform boundary is poorly understood (Macdonald, 2012, Parsiegla 1, 2008).

2.2 LOCAL GEOLOGY – THE BREDASDORP BASIN

The Bredasdorp basin is situated off the south-coast of the Republic of South Africa, southeast of Cape Town and south-west of Port Elizabeth and Mossel Bay (ref to fig. 6 below). The basin covers an 18,000 sq km region which is generally characterised by a water depth of 200m and less (USGS, 2012).

The Bredasdorp basin constitutes a complex pre-rift geological framework which subsequently developed into a two phase tectonic framework that includes:

1. A syn-rift phase which originated during the Jurassic. This tectonic event continued into the Lower Cre-taceous, resulting in the formation of grabens and half-grabens.

2. A transform-drift-passive margin phase that was initiated in the late Albian, continuing to the present day (Davies, 1997; USGS, 2012). The Mesozoic to Cenozoic stratigraphic section has a total thickness of more than 5,000 meters (m) on the outer regions of the continental shelf.
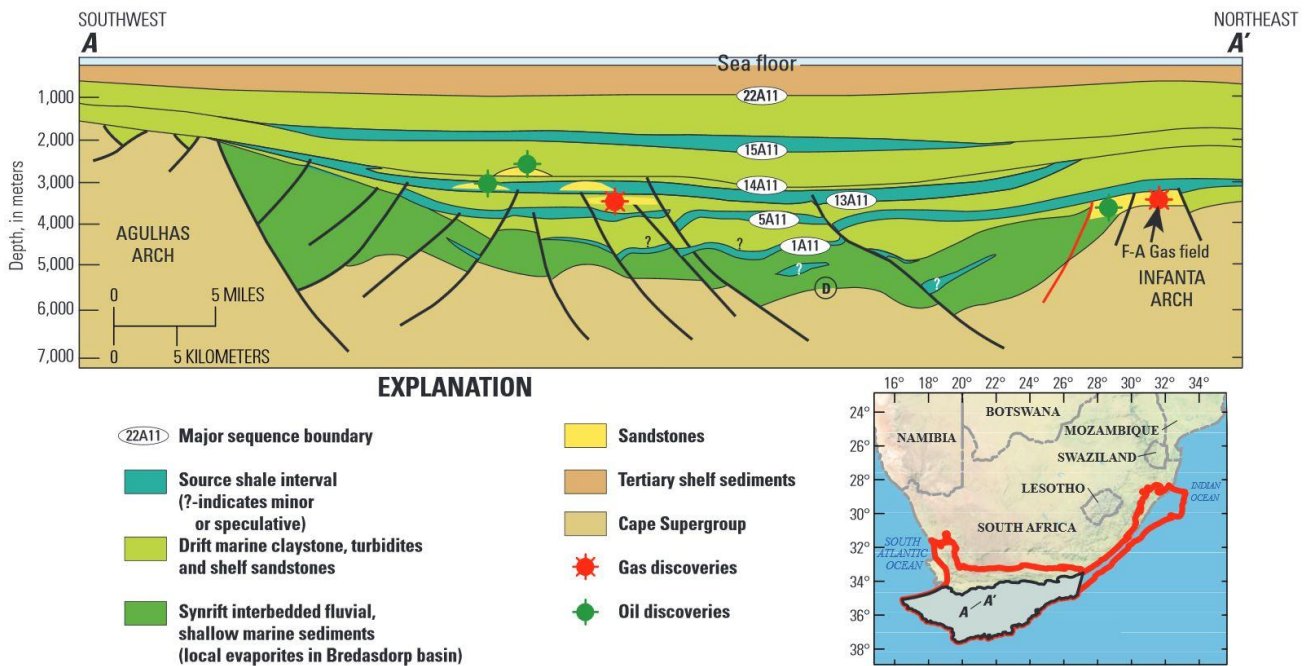
Figure 6. Location map of the Bredasdorp Basin with cross section (A-A') through the basin (USGS, 2012).

2.2.1 HYDROCARBON POTENTIAL OF THE BREDASDORP BASIN

The Bredasdorp basin is amongst the largest hydrocarbon (mainly gas) producing basins in Southern Africa. Block 9, operated mainly by PetroSA is a particularly hydrocarbon rich portion of the Basin (Petroleum Agency SA, 2012). At the time of the USGS assessment of The Bredasdorp Basin in 2012, 183 exploration wells had been drilled since 1969. These exploration wells have resulted in the discovery of 7 oil and 17 gas accumulations which exceed the minimum size of 5 million barrels (USGS, 2012).

The Mesozoic−Cenozoic Reservoirs found in the South African Coastal Province along the South African coast, were recently investigated as part of the U.S. Geological Survey's (USGS) World Oil and Gas Assessment of undiscovered, technically recoverable oil, natural gas, and natural gas liquids resources. The USGS used a geology-based assessment methodology. They derived estimated mean volumes of 2.13 billion barrels of oil, 35.96 trillion cubic feet of natural gas, and 1,115 million barrels of natural gas liquids (USGS, 2012). The estimated mean size of the largest expected oil field, to be discovered is 340 MMBO, while the estimated mean size of the expected largest gas field is 2,937 BCFG.

2.2.2 PRE-RIFT BASIN ARCHITECTURE AND FILL

The Pre rift geology of the Bredasdorp basin generally constitute the Cape fold belt and Karoo Basin sedimentary and volcanic sequences (Davies, 1997). After the formation of the Cape fold Belt and Karoo Basin a long period of erosion and peneplation took place (Ref. to fig. 7 below). This episode was subsequently followed by widespread volcanism in the Early to Middle Jurassic in southern Africa, the Falklands and Antarctica. This widespread volcanism provides the first evidence of the impending breakup of Gondwana. At the time of rift onset the Falkland Islands lay off the south or southeast coast of South Africa. The AFFZ developed as a result of this breakup of Gondwana, where South America and Africa split apart.
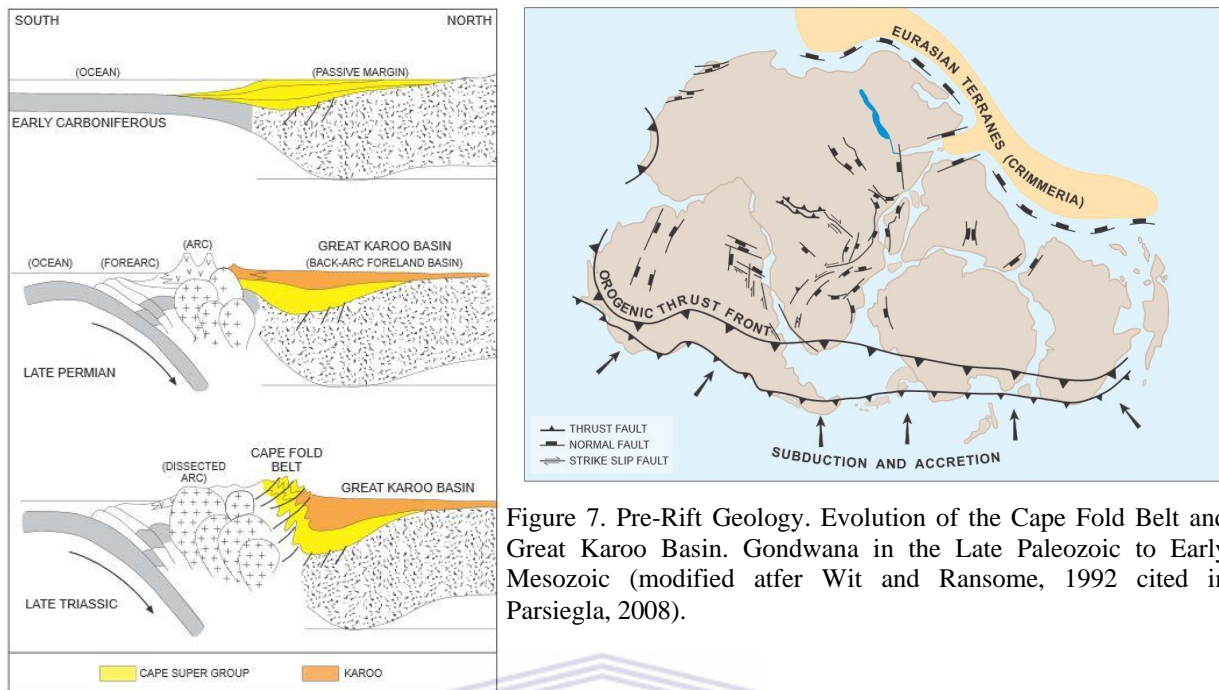
Figure 7. Pre-Rift Geology. Evolution of the Cape Fold Belt and Great Karoo Basin. Gondwana in the Late Paleozoic to Early Mesozoic (modified atfer Wit and Ransome, 1992 cited in Parsiegla, 2008).

The south coasts rift phase ended in the Lower Valanginian which corresponds to the drift-onset unconformity, 1At1 (ref. to fig 6). Initial rifting was shortly followed by at least three phases of inversion associated with continued dextral shearing. Inversion tectonic displacement ended in the mid-Albian which corresponds to the 14At1 unconformity, which represents the Falkland Plateau completely separated from Africa (Sonibare *et al*, 2014, USGS, 2012).

A true passive margin subsequently developed after this transitional rift-drift phase. The south coasts Lower Valanginian drift-onset unconformity (1At1) is contemporaneous with the generation of the earliest oceanic crust in the South Atlantic (Petroleum Agency SA, 2012, (Macdonald, 2012). The Bredasdorp Basins Lower Valanginian drift-onset unconformity is associated with the Hauterivian (6At1) drift-onset unconformity of the Orange Basin. A rift-drift transitional phase which correseponds to both Outeniqua and Orange basin occurred until the Early Aptian (13At1). The Sable Fields reservoir overlies this Early Aptian 13At1 unconformity. This reservoir which is under investigation, constitute a marine passive margin setting. Passive margin (drift) sedimentation took place in the later Cretaceous and Tertiary (Petroleum Agency SA, 2012, Sonibare *et al*, 2014,).

The southern margin of South Africa generally presents a persistent history of dextral (right-lateral) shear movements which developed from mid-late Jurassic to early Cretaceous times, when South America rifted from Southern Africa along the AAFZ (Sonibare *et al*, 2014). In the early to Mid-Cretaceous a complex series of microplates which include the Falkland Plateau steadily moved west southwest-wards past the southern coast of Africa, resulting in the initiation of important dextral shearing of the South African margin. (Petroleum Agency SA, 2012

This separation allowed for the subsequent development of the opening of the greater South Atlantic Margin. (Dingle *et al.*, 1983; van der Merwe & Fouche, 1992; Ben-Avraham *et al.*, 1997; McMillan *et al.*, 1997; Thomson, 1998; Broad*et al.*, 2006 Cited in Sonibare *et al,* 2014). Initial breakup and rifting started on the eastern margin of Africa, where Madagascar and Antarctica moved away in the Middle Jurassic. This early rifting initiated the formation of the Durban and Zululand basins. (Petroleum Agency SA, 2012).

The AFFZ is an important component of the numerous lithospheric stretching and breakup events which constitute the separation of Gondwanaland into an Eastern portion (Antarctica-Australia-India) and Western portion (South America-Africa) during the early Mezosoic. (Sonibare *et al*, 2014).

Dextral shearing along the AFFZ created the Outeniqua sub-basins as a series of oblique rift half-grabens that can be regarded as failed rifts with the oldest in the east and youngest in the west. The rift phase on the south coasts Outeniqua Basin and Bredasdorp sub-basin ended in the Lower Valanginian (drift-onset unconformity, 1At1). The Outeniqua Basin and its sub-basins (Bredasdorp, Infanta Embayment, Pletmos, Gamtoos, Algoa and deep water Southern Outeniqua Basin) have undergone multiple stages of deformation. A number of subsequent events took place in order to produce the five generally easterly trending sub-basins (Petroleum Agency SA, 2012). These events constitute a series of lithospheric stretching episodes during dextral (right-lateral) shear movements, subsequent thermal relaxation and Tectonic realignment.

These en echlon sub-basins are underlain by possible pre-rift deposits which constitute the Cape Supergroup (Dingle *et al.*, 1983; Davies, 1997a) (Sonibare, 2014). These sub basins are characterised by a series of oblique normal faults which become more listric towards the east. Basement arches which constitute pre-rift Ordovician to Devonian Cape Supergroup meta-sediments, separate the Outeniqua depocentres (sub-basins) from one another. (McMillan *et al.*, 1997; Thomson, 1998; Broad*et al.*, 2006). The Diaz Marginal Ridge (Ben-Avraham*et al.*, 1993) bounds the sub-basins southward and separates them from the AFFZ lineament (Sonibare, 2014).

The spatial distribution of these sub-basins decreases systematically from west to east. The strike direction of each basins bounding faults gradually changes orientation from a dominantly east-west trend in the western sub-basins to north-south trend in the easternmost sub-basins. This variation in spatial distribution and strike orientation of each sub-basin depicts a more complex paleo-kinematics as the AFFZ is approached. The variability in tectonic and structural imprints associated with these sub-basin is accompanied by the development of both regionally extensive and localised unconformities (Brown *et al.*, 1995; McMillan*et al.*, 1997; Davies, 1997a,b; Broad *et al.*, 2006 cited in Sonibare *et al*, 2014). These unconformities play a significant role in the the stratigraphic and the petroleum system evolution of the bredasdorp basin.

2.2.3 SYN RIFT BASIN ARCHITECTURE AND FILL

With respect to tectonic stages, Basin fill of the Bredasdorp Basin is sub-divided into isolated fault-bounded syn-rift sedimentary sequences. These syn-rift sediments have been overlain by variable thicknesses of post-rift sediments (Sonibare *et al.*, 2014). The syn-rift successions in the Bredasdorp sub-basin comprise mainly fluvio-lacustrine and shallow marine sediments.

Microplate movement along the southern African margin during the Mesozoic, remains largely controversial. Valuable plate reconstruction studies of from limited seismic data do however define syn-rift sequences as 'Syn-Rift 1' and 'Syn-Rift 2' (van der Merwe & Fouche, 1992; Ben-Avrahamet *et al.*, 1993, 1997; McMillan *et al.*, 1997; Thomson, 1998; Broad *et al.*, 2006 cited Sonibare *et al.*, 2014). Syn-rift 1 comprises of a block-faulted sedimentary package which were initiated by rifting. Extensional reactivation of the Cape Fold Belt took place during Oxfordian and Kimmeridgian times. The contrasting syn-rift 2 episode is considered to be a renewed phase of rift tectonics which followed Valanginian transform processes along the AFFZ in the western sub-basins (Bredasdorp, Infanta Embayment and Pletmos).

Syn-rift reservoirs which generally originated in the Jurassic and Lower Cretaceous, are associated with the grabens and half grabens situated in the deeper offshore regions. Seals found in the Bredasdorp Basin are primarily Cretaceous and Paleogene marine mudstones and shales (USGS, 2012).

2.2.4 TOTAL PETROLEUM SYSTEM

Source rock can be considered as the most important depositional factor in a basins evolution because a successful petroleum system firstly requires a rich source rock. Regionally developed, basin wide, good quality Aptian source rocks prove to be a critical component of a petroleum system defined in the Bredasdorp Basin (Davies, 1997). Upper Palaeozoic; Mesozoic and Tertiary reservoirs are found in the basin. Barrimian to Aptian Reservoirs dominate exploration and production activities in the region.

Davies (1997) conducted the first comprehensive petroleum geochemistry study of the Outeniqua Basins, namely; the Bredasdorp and Southern Outeniqua Sub-basins. These studies have documented a substantial number of hydrocarbon shows and regionally distinctive marine source rocks. A detailed analysis and correlation of reservoir hydrocarbons with corresponding source rock bitumens, indicate two regionally extensive source rocks have expelled oil in commercial quantities. The other two source rocks have expelled commercial quantities of wet gas/condensate.

The Aptial source rocks have been intersected by a number of exploration and scientific research boereholes throughout the sub basins of the Outeniqua Basin and off the West Coast. Studies indicate that cretaceous sands of producing fields such as Oribi, Oryx and Sable Oil Fields, have been charged by oil from Aptian Source rocks.

The Bredasdorp Basins Early Aptian source rock has been delineated well. An organic rich shale (200m thick) extends across a large area of the basin. The organic material is largely Type I and II kerogen which is generally oil and wet gas prone. Burial history studies indicate that Aptian sediments are in the oil window, mainly in large areas west of the basin depocentre (Davies, 1997; Petroleum Agency SA, 2012).

The geologic elements of a total petroleum system (TPS) concept include:

(1) Hydrocarbon source rocks where the source rock has matured and hydrocarbons have been generated and migrated;
(2) Reservoir rocks with good quality and distribution.
(3) Traps mechanism for hydrocarbon accumulation.

Based on the TPS concept, the USGS has defined the Bredasdorp Basins Mesozoic TPS. The Bredasdorp Basins TPS constitutes Middle to Upper Jurassic lacustrine source rocks which contain 1.0 to 3.7 weight percent total organic carbon (TOC). A Cretaceous marine source rock constitutes Aptian strata which contain Type II kerogen ranging from 2.0 to 4.3 weight percent TOC (USGS, 2012). Cretaceous marine source rock also include Cenomanian Turonian strata containing Type II kerogen ranging from 1.0 to 3.0 weight percent TOC.

A number of Mesozoic–Cenozoic Reservoirs have been outlined in the basin. The Bredasdorp Basins Mesozoic–Cenozoic Reservoirs constitute Cretaceous and lower Paleogene clastic reservoirs. Various types of hydrocarbon traps play a role in the basin. These traps are mostly associated with geological factors such as; growth fault-related structures and rotated fault blocks within the continental shelf. A number of stratigraphic traps play a role, such as: deep water fans and fan complexes, turbidite channels and slope sandstones which are truncations adjacent to the present-day shelf and paleo-shelf edge (USGS, 2012). Cretaceous and Paleogene stratigraphic pinch-outs can be found along the southern margin of the basin.

2.2.5 POST-RIFT ACHITECTURE - SABLE FIELD GEOLOGICAL BACKGROUND

Located in the Western Bredasdorp Basin the Sable field constitutes a submarine, structurally confined, Basin Floor Fan (BFF) system. Wood, 1995 has proposed a general depositional model for the early drift sand rich sediments of the Bredasdorp Basin. The model constitutes basin floor fans which are confined by a fault controlled erosional valleys. The Basin floor fan system of the Sable Field is characterized by stacked deep-marine channel deposits and less confined lobes. Trap combinations originate due to stratigraphic pinch outs and localized inversion tectonics.

A number of Barremian (9A) to Aptian (13B) aged reservoir sequences are well developed in the Bredasdrop Basin. These reservoirs are mainly deep marine Basin Floor Channel (BFC) and Basin Floor Fan (BFF) Complex's'. The Sable field constitutes both BFC and BFF complex's that are encased in a dominant volume of Hemi-Pelagic mud. These organic rich muds comprise both source rock and seal of the Sable Fields reservoir (Petroleum Agency SA, 2012; Grobbler, nd). These sand rich depositional complexes contain hydrocarbon bearing sand which are both structurally and stratigraphically trapped. These sands are interpreted to be deposited by tubidite processes and they constitute moderate to good reservoir properties (Grobbler, nd).

The Sable Oil and Gas Fields Basin Floor Channel (BFC) and Basin Floor Fan (BFF) Complex reservoirs, are located in the upper region of this Barremian (9A) to Aptian (13B)

early drift turbidite system. Sable constitutes a structurally confined, distributive submarine fan complex which is dominated by the submarine channel-lobe transition zone (CLTZ) (Gordon, 2014). The seismic cube cropped for the research mainly depicts CLTZ of the Sable Field.
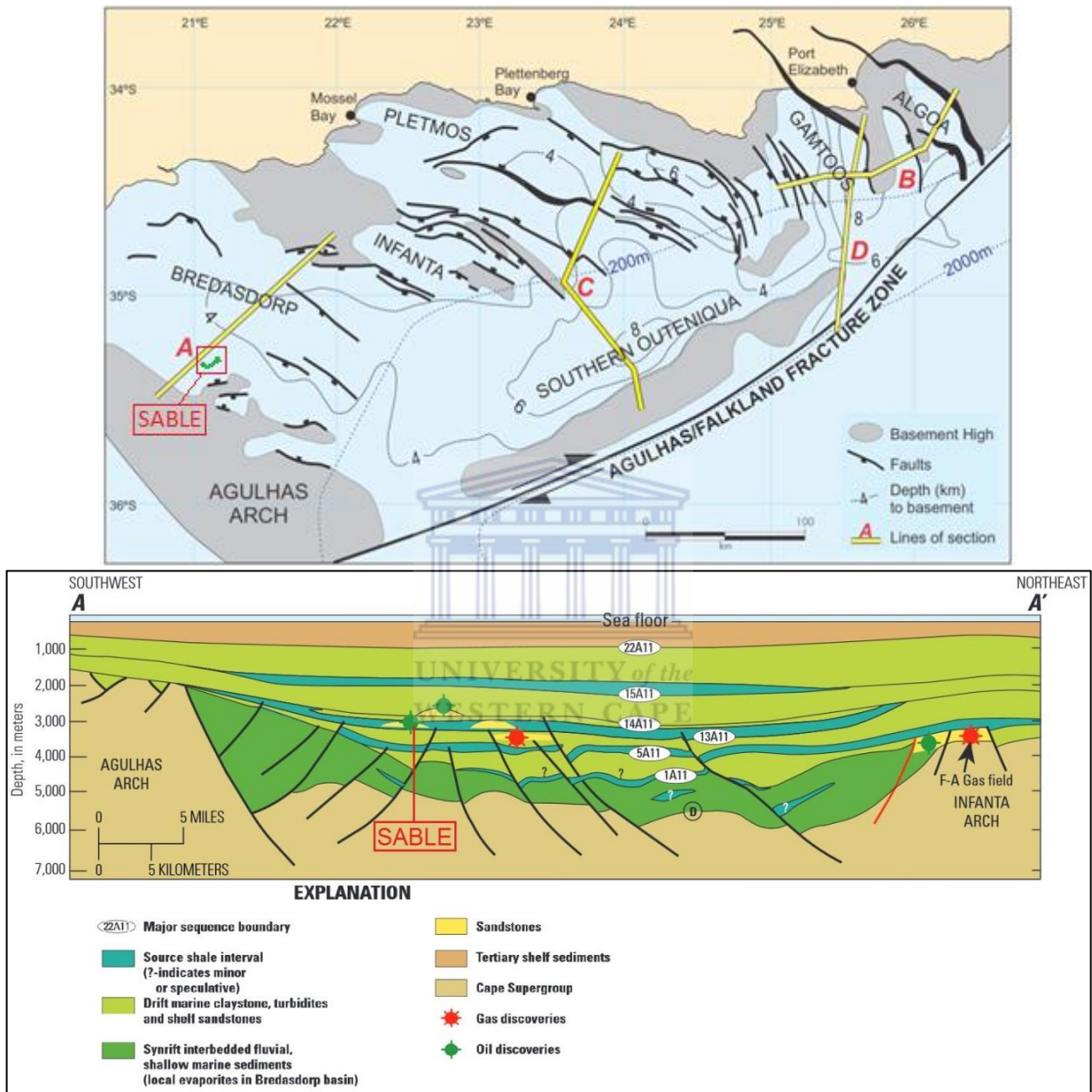
Figure 8. Location map and cross section of the Bredasdorp Basin indicating Sable Field. Modified after (Petroleum Agency SA, 2012; USGS, 2012).

During this early-drift tectonic and stratigraphic drift episode, the basin progressively enlarged to a scale where the basin flooded and integrated a number of initial post-rift embayment's, that had connections to the proto Indian Ocean.

Well defined sequence boundaries have been deposited, as well as a number of type 1 erosional unconformities. Episodes of both thermal subsidence along the basin axis and fault reactivation, are associated with the third-order (onlap-fill) sequences. Thermal subsidence causes sediment influx into the basin when post rift slopes change angle. This phenomenon results in an increased in accommodation space that coincides with an increase of sediment influx into the basin (Grobbler, nd). The Sable Fields reservoir is situated above the 13AT1 type 1 erosional unconformity as seen in fig. 9 above.

The Sable Field comprises of two major reservoir zones (ref. to fig. 10 below). The Upper E-BD oil reservoir constitutes a submarine Basin Floor Channel (BFC) complex. The lower E-CE oil and gas reservoir constitutes a slope fan and Basin Floor Fan (BFF) complex (Soekor Ltd, nd; Grobbler, nd). The E-BD reservoir hosts average porosity and permeability values of 18% and 380 md, respectively. Average porosity and permeability values of The E-CE reservoir are 18% and 410 md, respectively. The STOOIP for both E-BD and E-CE reservoirs of the Sable field was estimated by wood (1995) to be within the range of 43-90million st-tk bbl.
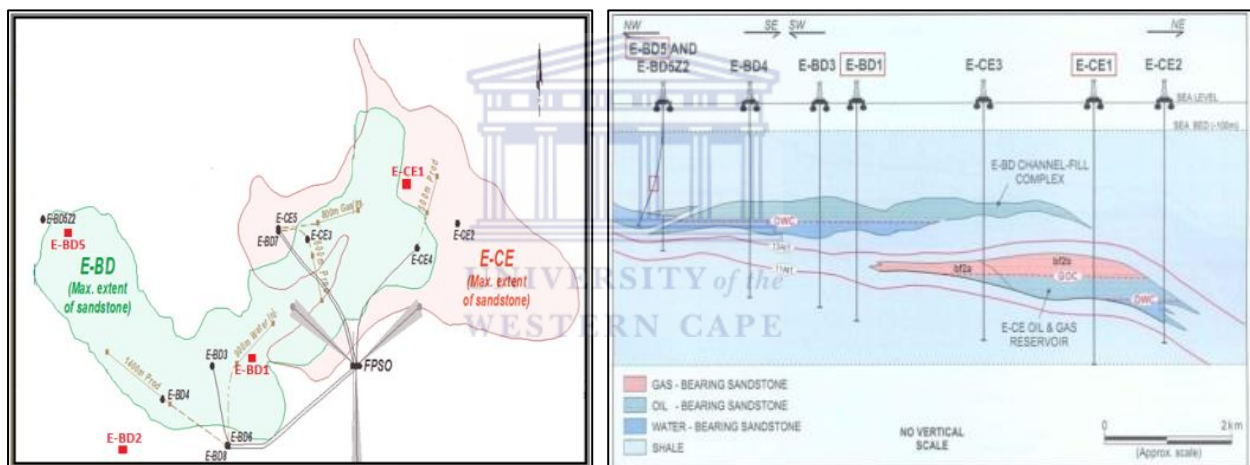
Figure 9. Map and cross section view of the Sable Field (Soekor Ltd, nd).

Generalised facies distributions for the region has been developed by core data, log patterns and maximum grain size data. These data sets have assisted in the generation of geological model for the portion of the Bredasdorp Basin where the Sable Field is situated. The poorer reservoirs in the basin such as channel overbank and sheet sand (distal) deposits are below seismic resolution thus unresolvable. The geological model consulted for this research, takes this into account in order to include these 'invisible' volumes of hydrocarbon (Grobbler, nd). The general depositional model for BFF systems ideally presents a radial pattern. The Bredasdorp basins topography has resulted in a BFF system with a predominantly elongated geometry due to its steep topography which also affects the geometry of the Sable Field.

A number of sandstones in the Basin have a provenance which constitutes Table Mountain quartzite and Cape granites, sourced from the mainland and Agulhas Arch. The Basin maintained its predominantly northwest-southwest elongation throughout its evolution. This

basin configuration is inherited from the syn-rift sub basin geometry. The syn-rift Bredasdorp Basin was subjected to relatively free marine circulation in the southeast region where the basin meets the Southern Outeniqua Basin and Indian Ocean (Soekor, Ltd; Grobbler, nd). This marine influx is also related to the deposition of extensive marine source rocks. The influx of sediment into the Bredasdorp Basin, predominantly constitute a main input from the west.

The Western Bredasdorp Basin is mainly filled with marine Aptian to Maastrichian deposits. These post rift sediments were deposited on pre-existing Late Jurassic to Early Cretaceous fluvial and shallow marine syn-rift sequences (Grobbler, nd). This western region of the basin also hosts a number of shallow marine Valaginian shallow marine Berriasian fluvial reservoirs. The remaining reservoirs in the basin are Barremian and Aptian aged and characterised as deep marine channel and associated deposits. These sand rich deposits are difficult to model due to sandstone beds and stratigraphic structures being below seismic resolution.

2.3 DEPOSITIONAL MODEL ANALOGUE FOR THE SABLE FIELD BFF SYSTEM

A number of field analogues have been consulted in order to guide the 3-D reservoir characterisation of the Sable Field. These analogues provide examples of the BFF depositional environment with respect to seismic and wireline log response. Outcrop analogues have also been consulted in order to betrer understand the internal heterogeneity of BFF complex reservoirs.

2.3.1 THE ANALOGUES PURPOSE IN THE INTERPRETATION PROCESS

The analogue facilitates recognizing, examining and understanding the sedimentary facies and facies associations of the BFF depositional environment. The analogue outlines the distribution of the fine grained slope to basin floor distributive turbidites and relates the field and outcrop analogues to the Sable Field.

The field analogues consulted, serves to outline the internal architecture as well as the distribution of the various deep water depositional elements such as channels, levees and lobes. The depositional elements can be associated on a local and fan-wide scale (Wickens, 2014; Jiajie, 2012). Recognizing and examining the hierarchical stacking pattern of channels, levees and lobes, is a crucial component of reservoir characterisation. These elements are characterized with respect to being channelized and/or non-channelized deposits. The stratigraphic evolution and growth pattern of fine grained fan systems will be evaluated with respect to confined and/or confined settings (Wickens, 2014)

Reservoir characterisation is heavily dependent on field and outcrop analogues. They play an important role in the development of a perception for scale. The scale and aspect ratio of the depositional features as well as their relationship with their counterparts such as seismic

reflection data, cores and logs are justified with the analysis of analogue. Reservoir characterisation and possibly a subsequent 3-D static reservoir model, will assist in understanding the internal heterogeneity and propose reasons for reservoir behaviour. The analogue also assists with understanding the influence that structural control or basin floor and slope topography have on the sediment gravity flows. The structural configuration of the basin floor and slope topography significantly controls the distribution of depostional elements.

2.3.2 DEPOSITIONAL MODEL ANALOGUE

The extensive turbidites outcrops of the Tankwa Karoo in South Africa and a number of other turbidite reservoirs and outcrops, serve as an analogue for the sable fields' deep water submarine reservoir. The Tankwa turbidites are extensively understood and globally recognized by the petroleum industry as an outcrop analogue for sand rich deep water deposits. These types of depositional environments are extremely difficult to study at present day due to their deep submarine nature (Slatt, 2006; Wickens, 2014).

A number of structurally confined and ponded turbidite systems constitute prolific hydrocarbon reservoirs. These turbidite systems serve as important records of relative sea-level fluctuations. They also record tectonic episodes and sediment transfer from shallow-marine environments into the deeper offshore regions. Outcrop studies of Turbidite depositional systems indicate that they yield sedimentological and stratigraphic detail which is sub-seismic resolution (Slatt, 2006;Wickens, 2014).

Analogue outcrop exposures such as the Guaso I turbidite system (Lutetian) in the Ainsa basin, north-eastern Spain, reveal a ponded, distributive submarine fan which is confined at the distal end of the basin by a syn-depositionally active anticline, for example (Gordon, 2014). Other analogues of deep water turbidite sand rich deposits indicate that there stacking pattern of lobe and channel systems has an inherent structural confining ablility. For example, according to the architectural framework of these deposits, the channelized portion of lobe will be structurally confined by its neighbouring lobes (Wickens, 2014; Gordon, 2014).

Turbidite deposit analogues indicate lobes can be overlain by a variable association of channels, lobes, and mass-transport deposit. These depositional elements constitute wider variance in paleo-current values which Indicates that the system gradually became more distributive through time (Gordon, 2014). These observations also reveal an increase in architectural diversity and the compensational stacking of elements as time progressed.

The variation in depositional elements as the bowl-shaped basin filled, is attributed to an increase in depositional area, and a decrease in accommodation relative to sediment supply (A:S). Isopach mapping indicates a prominent sediment thick, which generally coincides with the Turbidite channel flows depositional axis. In the proximal region of the fan, this thick constitutes a mass transport system, channel mudstone sheets as well as rip up clasts on the base of the channel amongst sands. In the more distal regions of the fan on the basin floor, the thick generally originates as a result of a significant succession of high-reservoir-quality

sandstone. The depositional system analogue built for this study, presents a geometric model which relates reservoir connectivity and compensational stacking to effective area of deposition (Gordon, 2014).

The deposition of sand and mud rich sediments on the basin floor alters the short term local topography of the sea floor. The channelized component of a turbidite longitudinally evolves into less confined lobes on the interpreted basin floor, such as the 13 AT1 unconformtiy which can represent a period of deposition on a new sea floor. Confined turbidite systems basically constitute deep-water clastic depositional systems whose depositional elements and resultant architectures have developed due to topographic features of the basin floor and/or basin margin (definition modified from Lomas and Joseph, 2004; cited in Gordon, 2014). Basin-margin topographic features that interact with turbidite mass transport sediment flows can include geological features such anticlinal seafloor highs, salt diapirs, and fault scarps.

The depositional patterns and stratigraphic architectures that are produced from the interaction of turbidity currents with these features can differ from those where basin-margin topographic features are not present, such as in unconfined basin-floor settings (Mutti and Normark, 1987; Mutti and Normark, 1991; Lomas and Joseph, 2004; Amy *et al.*, 2007; Covault and Romans, 2009; Mutti *et al.*, 2009; Callec *et al.*, 2010; Mayall *et al.*, 2010 cited in Gordon, 2014).
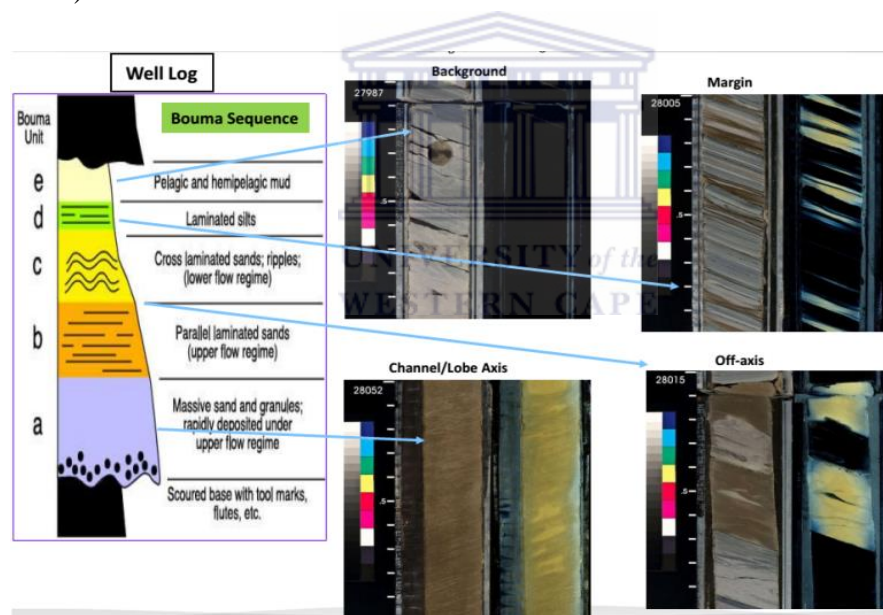
Figure 10. Diagram relating the Bouma sequence to core that originates from various areas of the BFF system (Jiajie, 2012).

The regions outlined in fig. 11 above, namely; the channel margin, channel/lobe axis and off axis areas of the BFF system. These core sample need to be related to these 3-d diagrammatical representation of a BFF system below. The BFF system is present with respect to its three main regions including:

1. The up-dip proximal channel environment which is relatively confined.
2. Channel Lobe Transition Zone (CLTZ) Transitional from Proximal to medial fan
3. Distal-medial fan outer
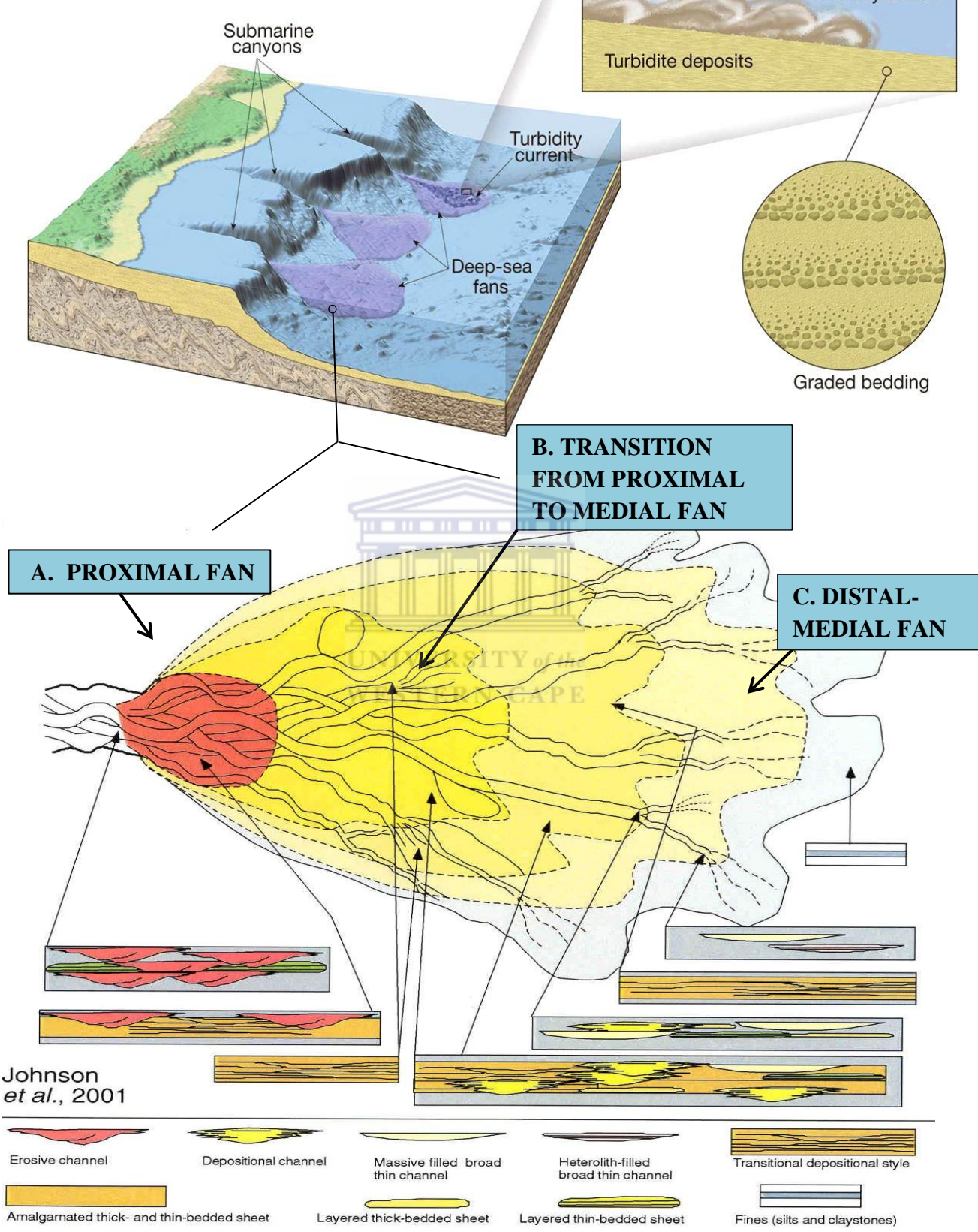
Figure 11. Diagramatical representation of turbidite deposits and general depositional model of deep submarine environments Modified after ((Posamentier and Kolla, 2003; Wickens, 2014).

2.3.3 DEPOSITIONAL ELEMENTS AND PROCESSES OF BFF ENVIRONMENTS

A number of rock facies associated with submarine fan complexes have been identified and noted in Jiajie, 2012).

The major facies categories include:	
Structure-less - slightly altered sandstone	lobe center facies
laminated sandstone	lobe margin and transitional
bedded/graded mudstone	in situ deep water shale
turbidite tail flows; and	pelagic mudstone

Table 1. The major facies categories of the Basin Floor Fan system.

The vertical facies successions generally result in vertical compartmentalization of reservoirs. Thus, facies recognition using a 3-D conceptual geological model, sheds light on the vertical separation of reservoir compartments. An investigation of depositional elements which includes, object modelling, scale comparison and aspect ratio: width, length, and thickness charscterisation is needed to understand the compartmentalisation of the Sable Field. Facies assist in outlining Progradational versus retro-gradational succession as well as reservoir property distribution (Jiajie, 2012).

The developed analogue consults studies of the stratigraphy, paleogeography, and depositional controls of the submarine fan depositional system (Gordon, 2014). Outcrop analogues of the Sable Fields depositional system, indicates examples where this deep-water depositional system flows through a fault-controlled longitudinal transect. The turbidite flows progress from proximal structural terraces, through a submarine canyon which eventually progresses towards the basin floor and basin margin. The analogue and the investigation of the Sable Field study area is divided into three regions based on geographic location, interpreted paleogeographic environment and stratigraphic character.

Region A -Feeder System,
Region B - Proximal Basin Floor, and
Region C - Medial-Distal Basin Floor.

In some cases,
Region A. Feeder systems contains syn-depositionally active normal faults near the proximal basin margin. These faults are generally associated with abrupt changes in paleo-bathymetry, depositional environments, lithofacies associations, and stratigraphic thickness. The proximal submarine canyon constitutes a region of bypass, with low net-sandstone content. Isopach maps indicate gross thickness is generally greatest near the canyon mouth.

Region B constitutes a proximal-basin-floor fairway which is located immediately basinward (down-dip) of the canyon. In some cases proximal basin-floor region can contains the highest sandstone content in the basin.

Region C constitutes the Medial-Distal Basin Floor region which is associated with gradual changes in proportions of lithofacies associations. Isopach mapping indicate these changes originate due to subtle variations in the gradient of the basin floor near the distal basin margin.

The proximal channel complexes constitute structure-less, amalgamated sandstone that overlies thin-to-medium bedded "dirty" sandstones which are deposited at the lobe fringe. These upward architectural pattern are generally interpreted to result from an outwardly expanding depo-center through time (Wickens, 2014).
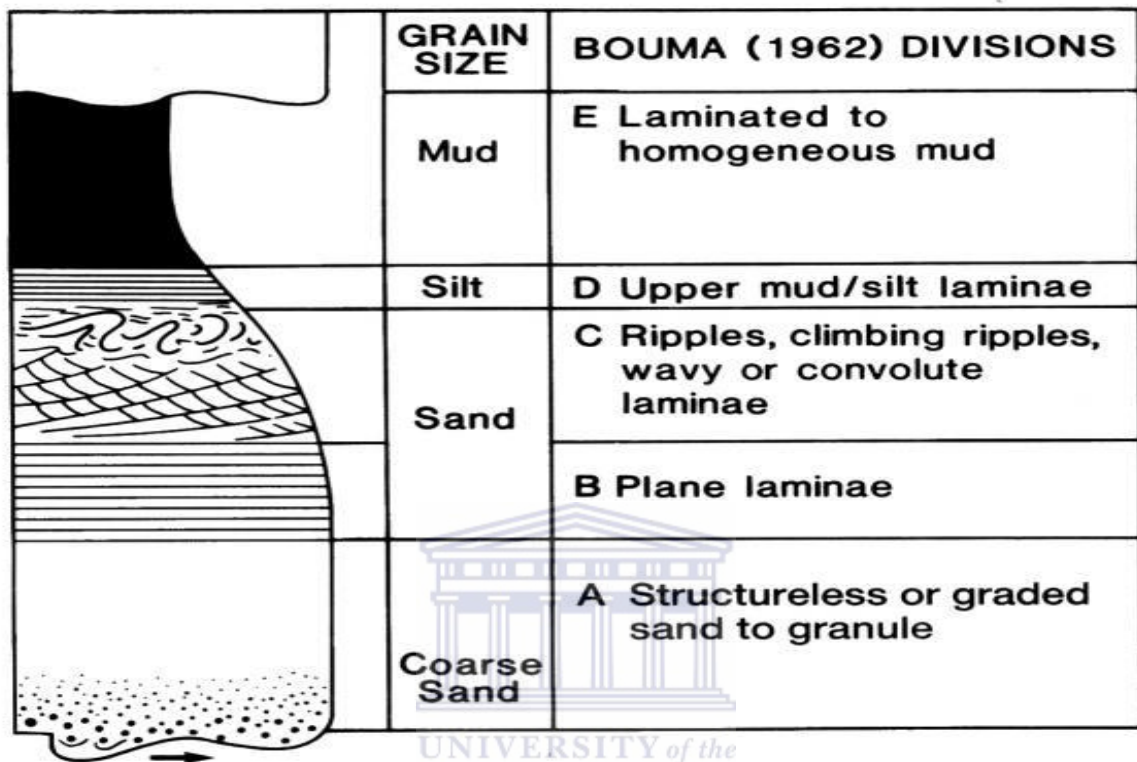
Figure 12. Diagramatical representation of the Bouma Sequece (Wickens, 2014).

E. Deposition of mud from the tail of the turbidity current, hemipelagic or pelagic settling

D. Segregation of mud flocs and silt into discrete bands by shear

C. Ripple migration in the lower part of lower flow regime, possibly with high rate of fall out from suspension and water escape deformation. Dune field not represented (Wickens, 2014).

B. Upper flow regime plane bed transport with primary current lineation on bedding surfaces

A.   Progressive settling from suspension, high grain concentrations at the depositional boundary layer inhibit the formation of tractional laminae, grains deposited via a transient grain flow (collision) condition Turbulent erosion by the frontal, head portion of the turbidity current (Wickens, 2014).

The analogue developed for this study presents a four-stage sequential model that defines the stratigraphic architecture and evolution of a channel-lobe element. These elements can be seen in log form in figure 13 Below.

The model includes:

1. proximal erosive channels,
2. sand filled channels,
3. the CLTZ and the distal lobe region.

Correct delineation of the depositional model has important implications for reservoir and fluid-flow modeling of distributive channel-lobe systems (Gordon, 2014).
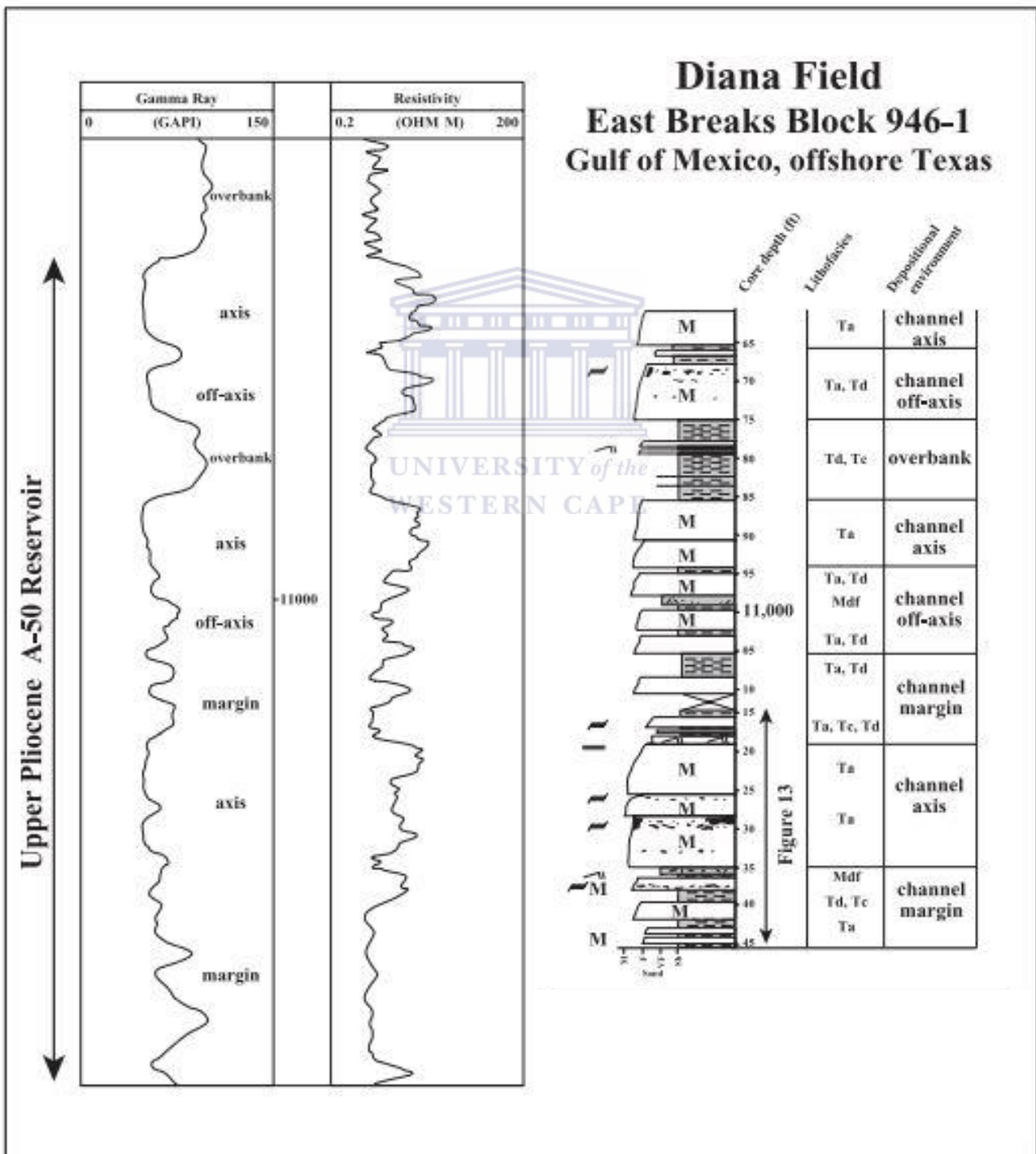
Figure 13. A generalised Analogue example of the Diana Field which correlates: Gamma Ray, Resistivity, core, lithofacies and depositional environments for the BFF complex (Jiajie, 2012).

2.3.4 SUMMARY

In this chapter the researcher outlined the geological aspects of the regional Outeniqua Basin, with respect to the basement architecture and tectonic setting. The localized tectonic setting and resultant depositional systems of the Bredasdorp Basin has been outlined with respect to the Sable Oil and Gas field. The following chapter outlines the methodology adopted for the 3-D investigation and characterisation of the Sable Field.

CHAPTER 3: METHODOLOGY

In this chapter the researcher outlines the various workflows undertaken such as, Geological background and reservoir analogue literature review; quality assurance of the data; sesimic workflow prior to interpretation; Seismic interpretation workflow, Petro-physical work flow and the 3D Reservoir Characterisation and delineation of the reservoir. These various interpretation methods have been integrated for this study. The methods used have been adopted from common industry procedures and recent publications.

3.1   LITERATURE REVIEW

A literature review was undertaken with the purpose of assisting the researcher in outlining the general background of the study, general petroleum exploration and production environment of South Africa and the geological setting of the Field and regional basin.

➢ Project Background
➢ Previous work done in the Basin and Sable Field (Davies, 1997 and USGS, 2012).
➢ South Africa's and the Sable Fields production history.
➢ Literature review for the development of a research question and associated aims and objectives (Wickens, 2014 and Jiajie, 2012)

➢ Geology
• Regional tectonic and sedimentary framework of the Outeniqua Basin
• Local tectonic and sedimentary framework of the Bredasdrop Basin (Davies, 1997 and Sonibare, 2014)

➢ Literature Review for analogue studies
• Depositional Model Analogue background
• Purpose of the analogue
• Depositional processes of Turbidite environments
• Depositional elements of Turbidite environments
• Outline of Proximal, Transitional and distal basin floor fan regions, using outcrop, wireline log and seismic response analogues (Wickens, 2014 and Jiajie, 2012).

3.2 WORKFLOW FOR QC/QA AND EXPORT OF WELL DATA

The wireline log data needed to be extensively cleaned using the IP (Interactive Petro-physics software before petro physical analysis could be undertaken. The data also had to be cleaned and converted in order to export it to the software used for the integrated well and seismic analysis of the field.

> **QC/QA OF WELL DATA**
>   > Using Interactive Petrophysics (IP)
>   > 4 wells were used. Wells include: E-BD 5, E-BD 2, E-BD 1 and E-CE 1.
>   > Well E-BD 5 does not intersect the seismic cube by a very small distance;
>   however well E-BD 5's wireline log data is still cleaned and used for a petro physical investigation of the reservoir zone.

- IP workflow
  Interactive Petrophysics software was used to clean and convert data from D.lis to LAS format.
  > Input D. Lis files
  > Select required wireline logs for each well
  From D.Lis files:
  > GAMMA RAY (GR)
  > BULK DENSITY (RHOB)
  > NEUTRON (NPHI)
  > SONIC (DT)
  > DRHO (DENSITY)
  > RESISTIVITY (LLD, MSFL, LLS)
- Deselect unwanted logging data as well as duplicate value and values which are corrupted.
- Las write each well
- Export Las files for each well to hard drive and Petrel project.

> Logging Data points with incorrect depths such as 11000m, have been deleted
> Correct logging Data points are sufficiently continuous for a thorough evaluation of the wells.

3.3 SESIMIC WORKFLOW PRIOR TO SEISMIC INTERPRETATION

Before seismic interpretation commences, well and seismic data needs to correlate without any impediments. The 3-D characterisation of the reservoir relies extensively on the correct correlation of well and seismic data.

Creation of data base

- Loading 3-D seismic data cube into Petrel software (segy format)
- Well top/checkshot

- Loading wireline log data into Petrel software
- Wireline Log Data in LAS format (Exported from interactive Petrophysics (IP) software

QC/QA of Seismic Data

Inputting the correct geographical co-ordinates and checking if all the wells intersect the seismic cube. Only well E-BD5 is slightly outside the cube due to the cropping of the cube.

- Load Well Top Data and create well tops
- Check well top time on excel spreadsheet with time of intersecting seismic horizon.
- Correlate this seismic horizon well top from well to well.

- Well to seismic tie
- Using sonic and density logs to generate a synthetic seismic trace
- Match trace amplitude with corresponding seismic horizon
- Check that all wells correlated with seismic data

- Realising 3-D seismic cube
- Seismic cube thus exhibits Xlines; INlines and time slices (z axis)
- Time slice are used to identify the channelized depositional environment

- Well top correlations (onajite, 2014)
- Miss tie analysis

3.4 SEISMIC INTERPRETATION WORKFLOW

The seismic interpretation workflow (using Petrel software) is conducted with the purpose of investigating the geometry of the basin floor fan system which constitutes the Sable Fields reservoir. Seismic interpretation is correlated with well data in order to characterise the reservoir by delineating the spatial distribution of the reservoir at and away from the well bore. Seismic interpretation workflow also takes the setback of seismic resolution into account. Reservoir characterisation thus infers internal heterogeneity from the wells and extrapolates the reservoirs internal heterogeneity away from the well bore (Onajite, 2014).

> ➢ Manual, 2-D and 3-D guided auto tracking Seismic interpretation
> ➢ Seismic interpretation is conducted on both inline and xlines
> ➢ Xlines and inlines are displayed simultaneously in a 3-D window in order to tie the interpretation
> ➢ Inline and xline interpretation is also tied to tie slices in order to track the complex channelized deposition environment from a birds eye view (Onajite, 2014)

> ➢ Paleo current flow according to time slices indicate the Channelized region of the BFF takes a roughly 90 degree turn.
> ➢ The bend in the channel is interpreted to take place at the base of slope region as channel flow off the continental slope.

Evaluate structural controls on sedimentation

> ➢ Before the bend
> • Xlines - transect as strike sections of the channel
> • Inlines - transect as paleo-current parallel intersections of the channel

> ➢ After the bend
> • Xlines - transect as paleo-current parallel intersections of the channel
> • Inlines - transect as strike sections of the channel

> ➢ Make Stratigraphic Surfaces

> ➢ Surfaces for 11 well tops from all wells
> ➢ Syn-rift Horizon
> ➢ Drift unconformity
> ➢ Top of early Drift sedimentary bulge
> ➢ Base reservoir horizon
> ➢ Top reservoir seal

SEISMIC FACIES

- **Six basin types**
  - Parallel
  - Sub-Parallel
  - Divergent
  - Chaotic
  - Prograding
  - Reflection free

- Match facies found in core with wireline log responses

- Match reflection of facies in well logs with corresponding seismic zones
- Seismic zones are separated by well tops

- Match interpretation of seismic facies and wireline log facies with with outcrop and subsurface analogues

- Detailed facies analysis from core description, wireline log responses and seismic facies

Seismic Facies infer (away from well bore) = Depositional Environment + Rock Type + Properties (Jiajie, 2012)

FAULT INTERPRETATION

Fault interpretation has been minimal as the reservoir is associated with post rift sedimentation of the Bredasdorp Basin and unaffected by faulting. The faults are also poorly defined due to the highly deformed pre-rift geology and the small size of the 3-D seismic cube under investigation.

> **FAULT INTERPRETATION**

> Manual 2-D and 3-D fault interpretation

> Fault cleaning

DEPTH CONVERSION

Seismic data has been gathered and interpreted in the time domain. The depth conversion process has thus been undertaken in order to convert the interpreted surfaces and geobodies to their correct depth below sea level.

DEPTH CONVERSION

Create new velocity model

Input seismic horizons which were created for well tops into velocity modelling process

Well tops have depth and time values thus Petrel software makes straight forward velocity model using average values between well tops

Domain convert surfaces and faults from TWT to depth by active velocity model
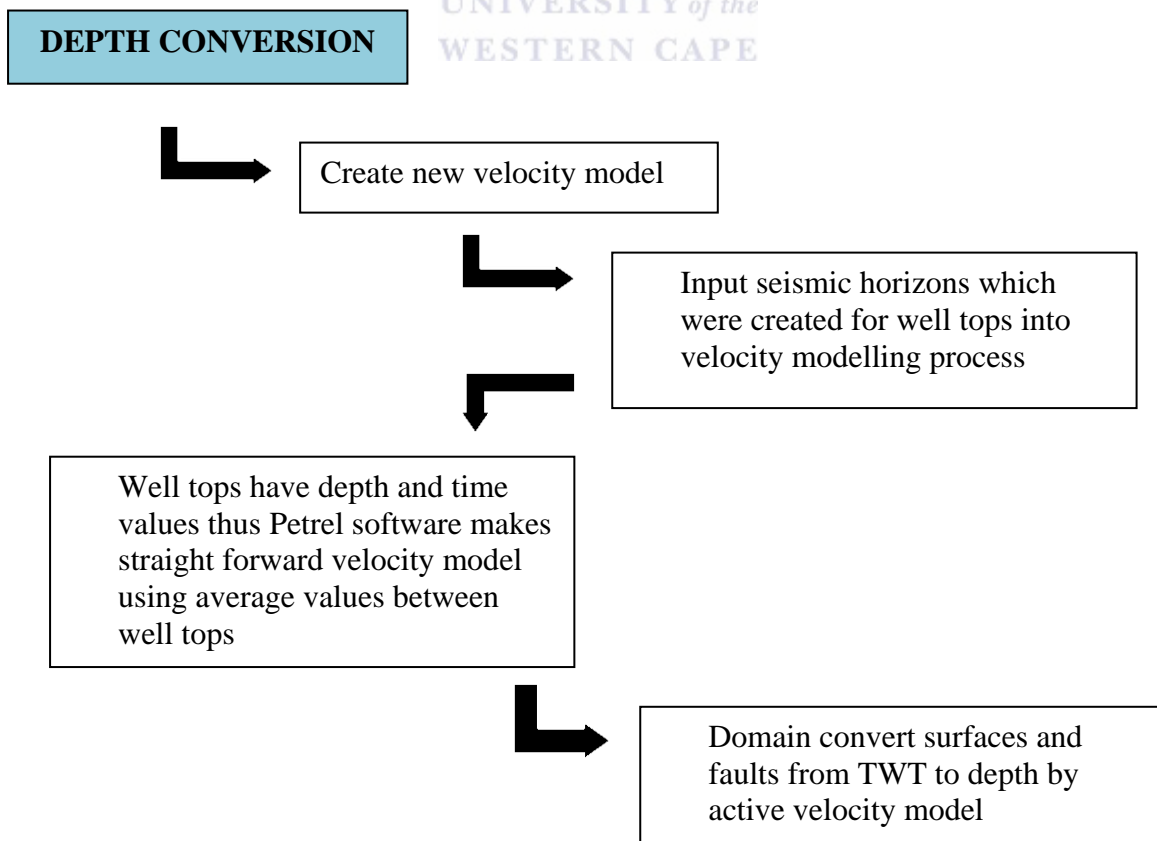
3.5 PETROPHYSICS WORK FLOW

A Petro-physical analysis was undertaken on the 4 wells Namely E-BD5, E-BD2, E-BD1 and E-CE1. Well E-BD 5 is used for a petro-physical analysis even though it doesn't intersect the seismic cube by approximately 350m. The petro-physical evaluation of the reservoir is conducted via the interactive Petro-physics software.

Wireline logs for petro-physical analysis	➢ Gamma Ray (GR)

- ➢ Gamma Ray (GR)
- ➢ Spontaneous potential (SP)
- ➢ Bulk Density (RHOB)
- ➢ Neutron (NPHI)
- ➢ Sonic (DT)
- ➢ Drho (DENSITY)
- ➢ Resistivity (LLD, MSFL, LLS)

Zones with invalid log data are identified and depth correction was applied (Q.C)

PETROPHYSICAL ANALYSIS

GENERATE FOR RES. ZONE IN EACH WELL:

- Lithology type
- Volume of clay
- Porosity
- Estimate Permeability
- Fluid Contacts
  - ➢ OWC
  - ➢ GOC
- Pay and non-pay sand
- Reservoir Depth
- Water Saturation
- flow capacity
- Net to Gross

Oil Water Contact

Calculated by
- In Agreement with Core Data
- Logs & RFT Plots (Brown *et al.,* 1990)

Water Saturation

Calculated by
- Waxman-smits Equations (Brown *et al.,* 1990)
- Indonesia Equation (Brown *et al.,* 1990)

Well Tops → Correlation of reservoirs and seal horizon– All four wells included

3.6 3-D RESERVOIR CHARACTERISATION AND DELINIATION

The Basin Floor Fan System (BFF) reservoir under investigation is characterised in the third dimension by the integration of well and seismic data. The reservoir zone is characterised at the well bore and extrapolated away from the well bore with assistance of seismic data.

```
                              ┌──────────┐
                         ┌────│ Data Set │────┐
                         │    └──────────┘    │
                         ▼                    ▼
              ┌──────────────────────┐  ┌──────────────────┐
              │ Geological Framework │  │ Seismic Framework│
              └──────────────────────┘  └──────────────────┘
                         │                    │
                         ▼                    ▼
              ┌──────────────────────┐  ┌──────────────────┐
              │  Input Wireline logs │  │ Mapping of Horizons│
              └──────────────────────┘  └──────────────────┘
                         │                    │
                         ▼                    ▼
              ┌──────────────────────┐  ┌──────────────────┐
              │ Delineation of Reservoir│ │ Seismic to well tie│
              └──────────────────────┘  └──────────────────┘
                         │                    │
                         ▼                    ▼
              ┌──────────────────────────┐  ┌──────────────────┐
              │Characterise Depositional │  │  Seismic Facies  │
              │        Facies            │  └──────────────────┘
              └──────────────────────────┘         │
                         │                          │
                         ▼                          ▼
              ┌──────────────────────────────┐
              │ Calibration of Seismic Facies│
              │   with depositional Facies   │
              └──────────────────────────────┘
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┌──────────────────────────────────────────────────────┐
│ Outline depositional regions of Basin floor fan system│
└──────────────────────────────────────────────────────┘
   │       │                              │
   │       ▼                              ▼
   │  ┌──────────────┐          ┌──────────────────────┐
   │  │  PROXIMAL    │          │ Extrapolate depositional│
   │  └──────────────┘          │ facies away from well bore│
   │       │                    │ using seismic facies │
   │       ▼                    └──────────────────────┘
   │  ┌──────────────────┐
   │  │ Wels E-BD5 + E-BD2│
   │  └──────────────────┘
   │       │
   │       ▼                    ┌──────────────────────────┐
   │  ┌──────────────┐          │Confined depositional channels│
   ├─▶│ TRANSITIONAL │          └──────────────────────────┘
   │  └──────────────┘
   │       │
   │       ▼
   │  ┌──────────────┐
   │  │ Well E-BD1   │
   │  └──────────────┘
   │       │
   │       ▼                    ┌──────────────────────────┐
   │                            │Channel Lobe Transition Zone│
   │  ┌──────────────┐          └──────────────────────────┘
   ├─▶│   DISTAL     │
      └──────────────┘
           │
           ▼
      ┌──────────────┐
      │ Well E-CE1   │
      └──────────────┘
           │
           ▼
      ┌──────────────┐
      │Unconfined lobes│
      └──────────────┘
```

GEOBODY EXTRACTION

Geobody representative of entire Basin Floor Fan

Outcrop and field analogue consulted to development of conceptual depositional model to characterise geometry of Geobody

Geobody Outlines complex Paleo-current flow direction

Paleo-current flow direction assists in characterisation of reservoir based on unique depositional model

Geobody interpreted and extracted as:

Base of a channelled BBF reservoir (red pick) and unconfined lobe complex reservoir

Base of channel and lobe geobody is situated directly Above 13AT1 unconformity

Paleo-current and geometry of Geobody

➕

Depositional Facies (from log and core)

➕

Seismic Facies away from well bore

=

vertical and horizontal permeability and porosity and Net to Gross

in lobes, levees channels

➕

Correlation of sand rich zones from well to well

Correlation of up-dip channels with down dip

CHAPTER 4: RESEARCH INTERPRETATION AND DISCUSSION

In this chapter the researcher outlines the integrated reservoir characterisation of the Sable field. The interpretation is made by integrating both 3-D seismic and wireline log data of the four wells under investigation. This integrated methodology which yields more reliable results, is undertaken in order to define the 3-D spatial characteristics of the Sable fields reservoir. The various literature consulted to construct a depositional model analogue (Chapter 2.3), are used as a guideline for the interpretation made in this chapter. A significant portion of the interpretation will be presented with respect to the depositional model that is broken up into 3 sections which include: The proximal channelized Basin floor fan region, the Channel Lobe Transition Zone and the distal regions of the Basin Floor Fan.

4.1 GENERAL PALEO-CURRENT FLOW OF THE SABLE FIELDS RESERVOIR

The Sable Field constitutes a channelized BFF reservoir which has a complex flow regime towards the local down-dip Bredasdorp depo-centre. The flow regime is outlined by the green and geobodies in figure 14 below. The flow pattern of these sand rich deposits is predominantly governed by the basin architecture at the time of deposition. The entire early-drift sedimentary succession which includes the Sable Field, has been governed by the topography of the Bredasdorp Basin sea bed. The flow pattern of sediments can be best described with respect to a prominent lower post rift horizon (early Drift unconformity). This unconformity generally represents the onset of the drift phase of basin development and sedimentation which includes deposition of the Sable Fields reservoir sands (ref. to fig.14 below).
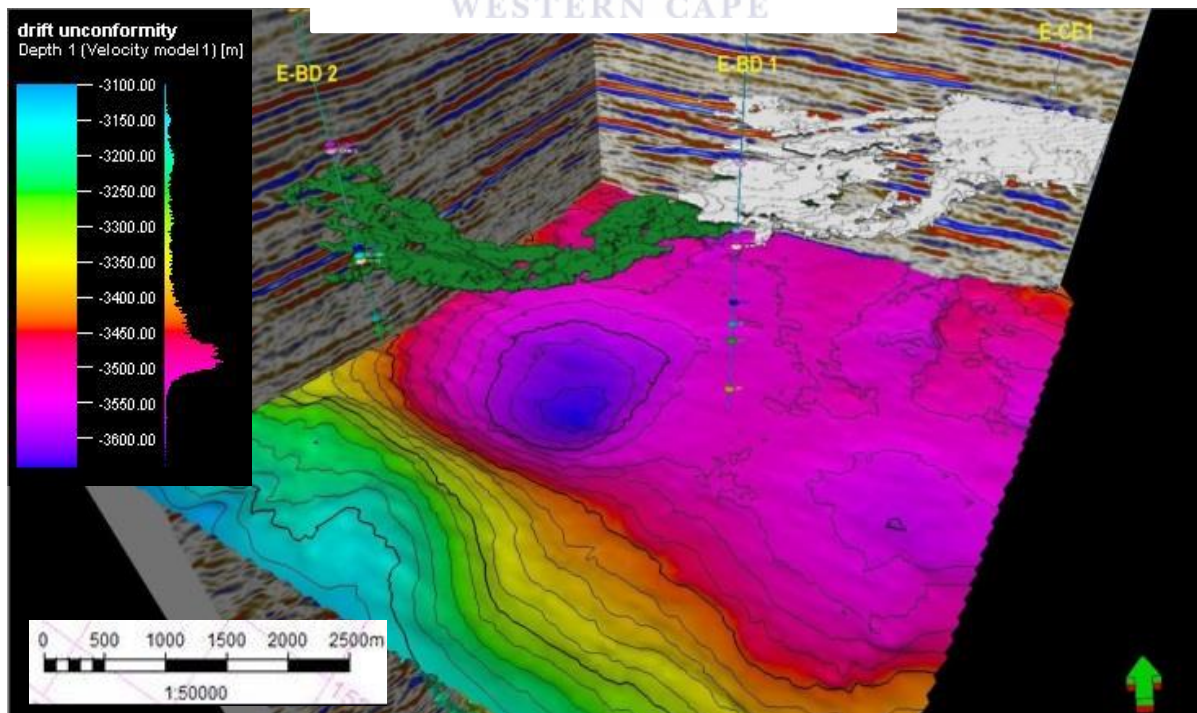

Figure. 14. 3-D image of the Sable Field. The green and white geobodies indicate general Paleo-current flow direction of the BFF complex. The Structural control on sedimentation is defined by the Drift unconformity displayed.

The drift unconformity is interpreted as the Late Hauterivian unconformity (6At1 at ca. 130 Ma). Seismic horizon mapping of this drift unconformity has outlined a NW-SW Orientated rise which constitutes the Agulhus Arch. This structural high is situated in the western to south western region of the seismic cube. Sediment flows off the Agulhus Arch prominent lower post rift horizon (early Drift unconformity).

The 6At1 unconformity corresponds to an erosional period, found on the Agulhus Arch, where sediment was removed from the Agulhus Arch and deposited in the Bredasdorp Basin. This early drift influx of sediment into the basin has resulted in the BFF system of the Sable Field. Turbidite currents flow off the Agulus Bank structural high, thus sediment supply into the Bredasdorp Basin is predominantly from the west. Deposition of the Sable reservoir followed this early drift pattern of sedimentation.

The green and white geobody in fig. above serves to outline the paleo-current flow pattern of sedimentation off the Agulhus Arch. Since the geobody is extracted from one seismic horizon (red pick) it has been interpreted to represent the base of a sand filled confined channel (green geobody) and a less confined sand filled deposit which constitutes an elongated lobe. The channelized reservoir has a paleo-current which is generally WNW-ESW trending in the up-dip regions of the of the BFF system. The sand bodies which represent lobe elements are generally elongated instead of cylindrical. These elongated depositional patterns are an example of structural control over the deposition of sediments. The steep topography of the basin floor results in the elongated lobe elements.

In addition to the prominent rise which represents the Agulhus Arch, there is an elevated region in the South-Western section of the surface indicated in figure below. The rise depicts a depocentre that hosts a bulge of turbidite sediment which have been eroded off the Agulhus Arch. The Sable Fields channelized reservoir lies in the upper portion of these early drift sediments flowing off the Agulhus Arch, into the depocentre (Bredasdorp Basin) situated in the NE section of the 3-D seismic cube (ref. to fig.).

Eroded sand rich sediments flows Off the coastal shelf –Agulhus Arch region, parallel to the WNW-ESW Agulus Arch, into the major depo-centre. The confined channel then turns off the Agulus Arch and flows in a NW direction, down-dip into the major depocentre. This sediment, including the Sable Field reservoirs, forms a low stance systems tract (LST) above the 6At1 unconformity. These sediments could be part of the larger continental rise which comprises of sediment deposited at the base of the Agulhus Archs continental slope.

Isopach mapping of the Drift unconformity and the LST sediments eroded off the Agulhus Arch indicate a prominent thick which corresponds to the depositional axis of the BFF complexes deposited in the basin. Proximal regions of the BFF system comprises of mass-transport complexes, erosive channels, sand filled channels and mudstone sheets. The prominent thick on the basin floor is predominantly caused by a significant succession of high-reservoir-quality sandstone.

4.2 SEISMIC HORIZON MAPPING

The seismic horizons have been interpreted with the aid of well top data for the three wells under investigation. Even though the well tops are not present in all the wells, these horizons could be correlated from well to well using the 3-D seismic cube. The well tops have been interpreted as prominent bright reflectors which represent significant unconformities and sediment horizons. With respect to relevant literature the dominant regional unconformities associated with the Sable Field include amongst others:

- Valanginian break-up unconformity (1At1 at ca. 136 Ma)
- Late Hauterivian unconformity (6At1 at ca. 130 Ma)
- Early Aptian unconformity (13At1 at ca. 120 Ma)
- Upper Cenomanian unconformity (15At1 at ca.93 Ma)
- Campanian unconformity (17At1 at ca. 80 Ma)
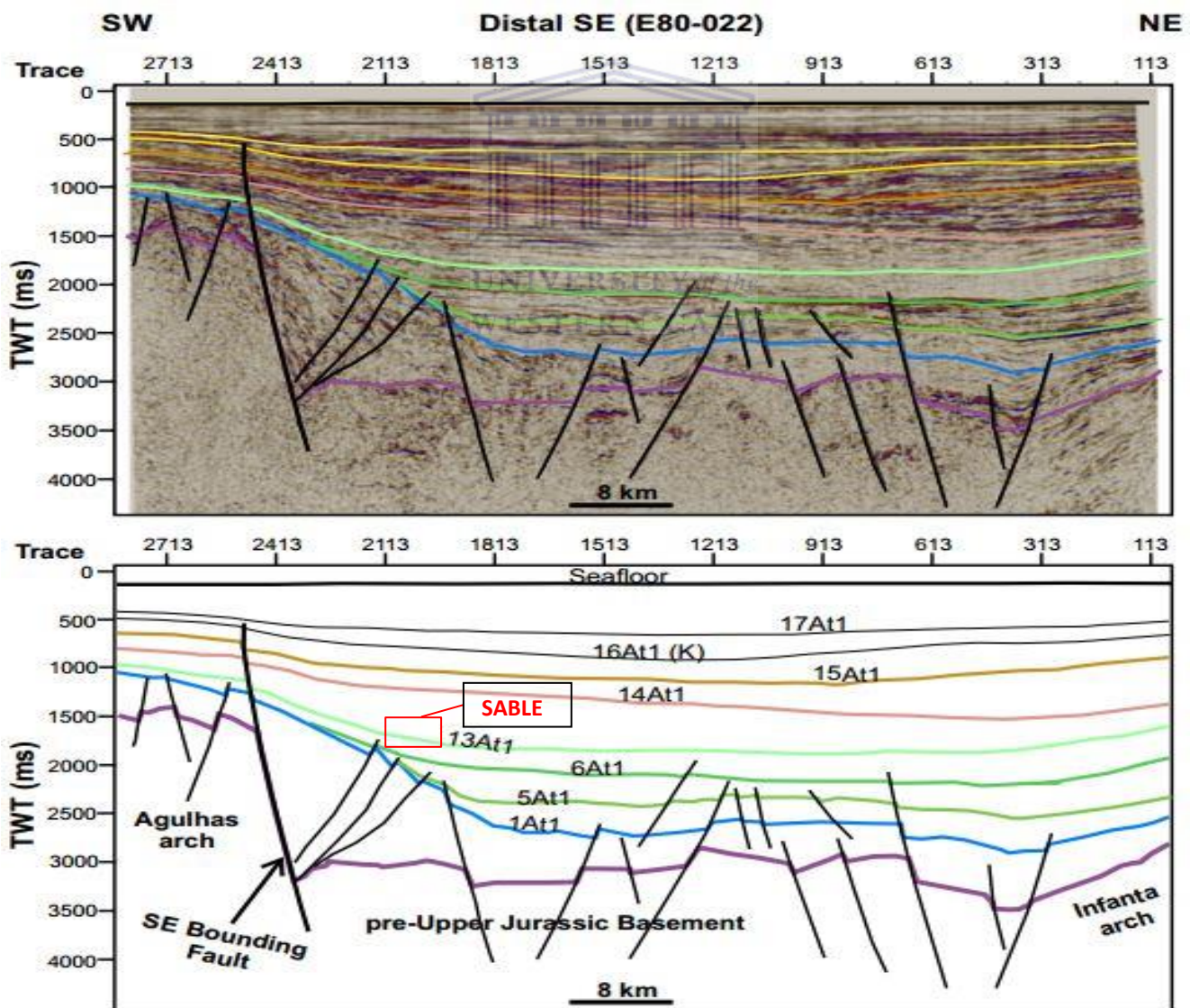- The Upper Maastrichtian unconformity (22At1 at ca. 67 Ma) (Sonibare, 2014).

Figure 15. Seismic Horizon Mapping of Bredasdorp Basin, indicating major unconformities. Modified after Sonibare, 2014.

4.3 SYN-RIFT BASIN ARCHITECTURE

The Bredasdorp Basin is characterised to have two syn-rift episodes that overly the pre-rift geology of the Basin. The Valanginian break-up unconformity (1At1 at ca. 136 Ma) is associated with this breakup of this pre rift geology. With respect to this study there is no well top data available for the 1At breakup unconformity.

The breakup phase of the Sable Fields geology has however been interpreted on a field scale using a bright horizon which represents both a steep normal fault as well as a pre-rift horizon. The surface depicted below outlines a complex haust and grabben configuration which is associated with transpressional tectonic forces. The exact position of the extensional faults could not be precisely outlined due to broad damage zone and poor seismic resolution in the deeper parts of the seismic cube. Guided 3-D auto tracking has been used to interpret the horizon in fig. below.

The syn rift surface has been interpreted from a prominent blue horizon which is representative of a bright early syn-rift horizon. The dominant normal faults constitute a complex horst and graben structural configuration which is the result of regional transtentional tectonic forces. Small sections of the surface have also been interpreted from part of this blue horizon which represents the shallow dipping sections of the faults.
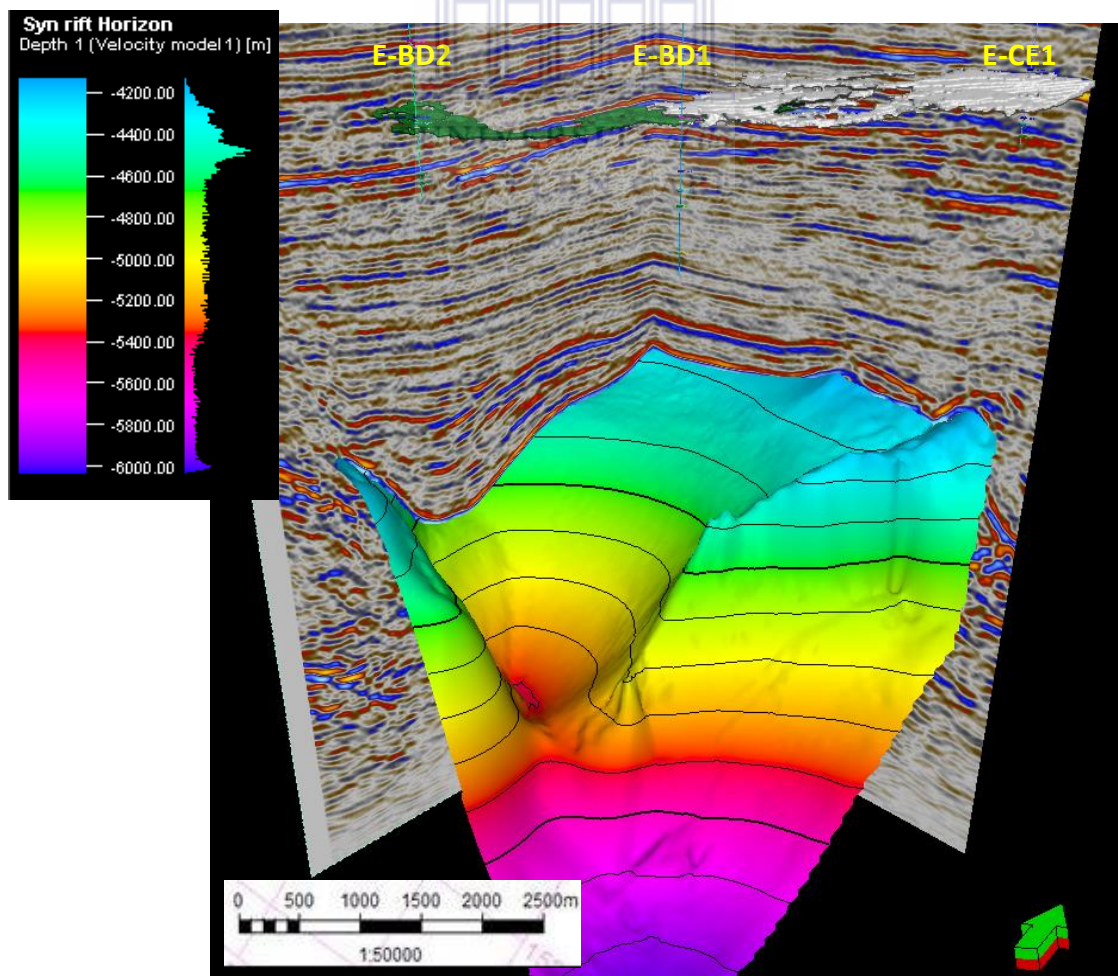

Figure 16. 3-D image of the mapped syn-rift horizon.

The Syn Rift phase of tectonic and sedimentary activity associated with Strike slip (wrench) system basins result in sub-vertical faults. These Extensional faults (normal) constitute pull apart basins with fault jogs that are caused by transpressional force. Rapid sediment supply in a relatively small basin, during the syn-rift sedimentation has resulted in rapid subsidence and high heat flow. Wrench basin commonly constitute lacustrine source rocks which are however globally characterised as a small play (Underhill, 2014). The Brerdasdorp Basin and the other embayment's of the Outeniqua Basin however experienced periods of flooding from the Paleo-Indian Ocean, thus syn-rift source rocks are predominantly marine in nature.

With respect to Syn-Rift deformation of the Basin, the controlling normal faults generally determine the syn-rift structure of the basin. These normal faults have varied styles of deformation and this structural control impacts sediment influx into the basin. In relation to the small scale seismic cube under investigation, the large controlling normal faults are predominantly syn-thetic in nature with minor anti-thetic normal faults.

The seismic line in figure 18 below represents a region of the seismic cube where syn-rift activity can be observed clearly. Fault controlled subsidence dominates syn-rift activity where deformation if both brittle and ductile in nature.

The footwall predominantly undergoes deformation in a brittle fashion. A number of transverse faults transect the footwall. Throughout the study area these minor transverse faults in the footwall can be interpreted as short normal faults with low displacement maxima (Underhill, 2014). Maximum displacement of these minor syn-thetic faults occurs at their branch point with the main controlling fault. Deformation and subsidence in the footwall wall is linked with the expansion of sedimentary layers which is associated with the footwall faults.

Deformation in the hanging wall predominantly occurs in a ductile manor. Deformation and subsidence in the hanging wall is mostly associated with open wavelength folds. These folds originate due to syn-depositional faulting. Sediment is eroded off the footwall fault scarp and deposited in the basin (ref. fig. 18).
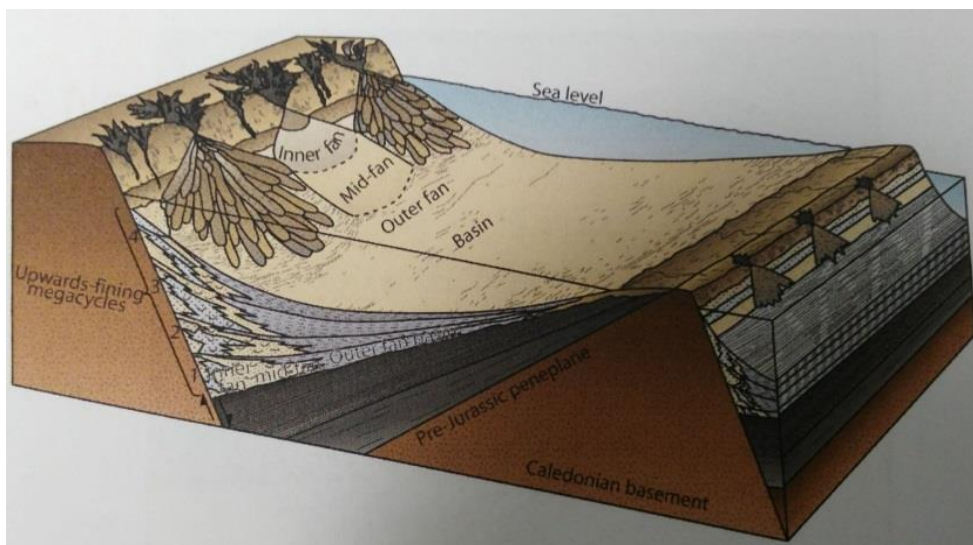

Figure 17. Diagrammatical representation of deep marine syn-rift sedimentation and basin fill when growth faults dominate subsidence (Underhill, 2014).

The controlling normal fault has a cut-off point which is interpreted as the drift unconformity that represents the end of fault controlled subsidence. Post rift sedimentation overlying the drift unconformity follows a sedimentation pattern which is governed by the underlying structural control set by syn- rift deformation of the basin.
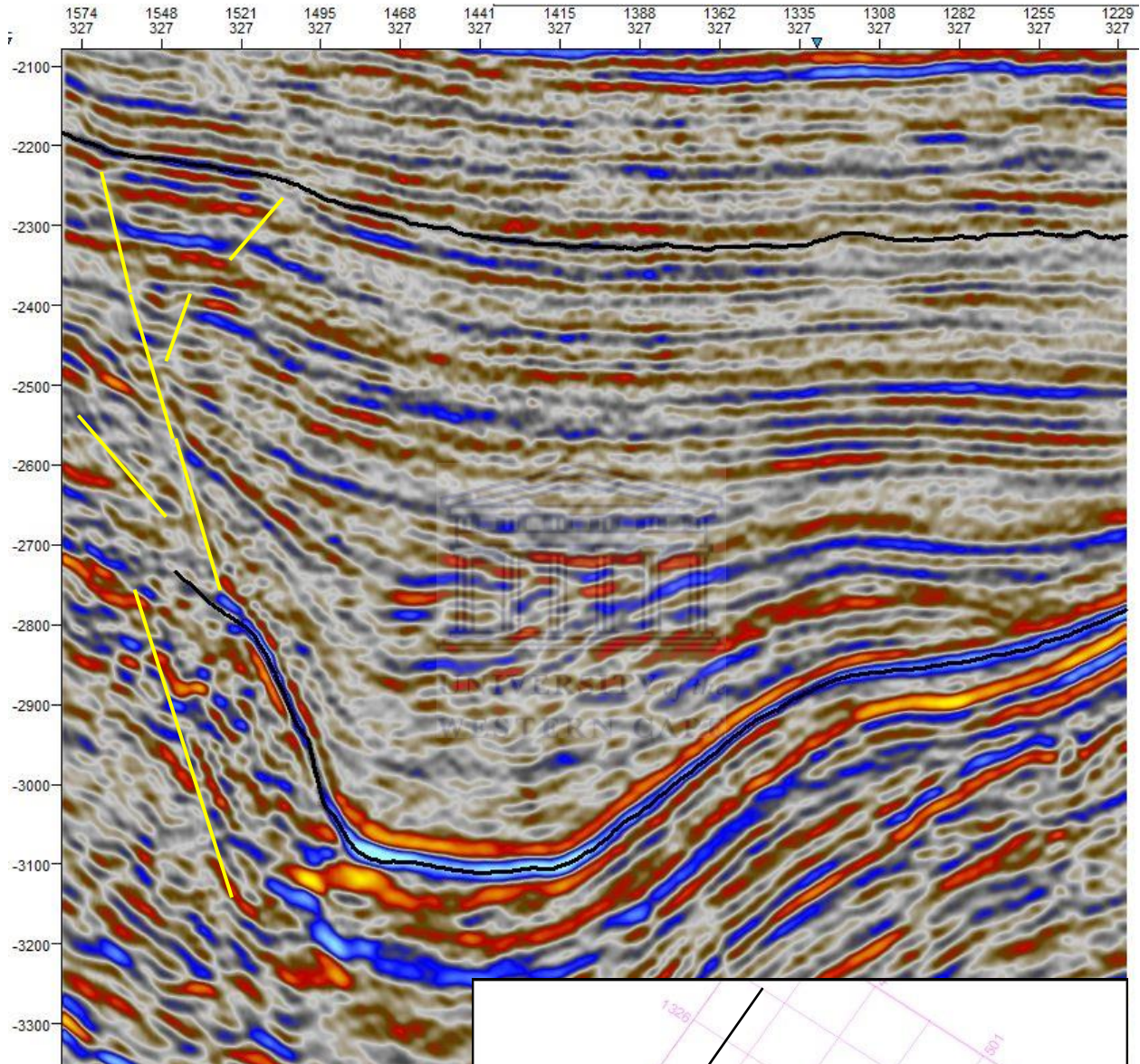

Figure 18. Xline 327. Seismic line indicating fault zone (yellow lines) and a prominent syn-rift horizon (blue pick). The faulted zone and syn-rift horizon merge into one bright seismic horizon in most areas. This is due to the shallow fault angle at lower sections of the lystric fault and shale smear in the major fault, where shale could originate from the syn-rift horizon.
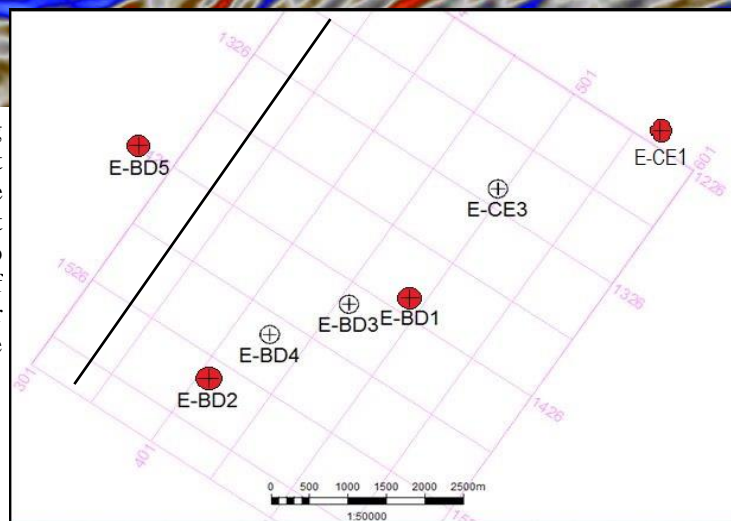
4.4 EARLY DRIFT BASIN FLOOR ARCHITECTURE AND SEDMIENT INFLUX

The early drift phase of sedimentation takes place after the stage of fault controlled subsidence in a basins evolution. Thermal subsidence and other factors contributing to accommodation space such as sea level fluctuations are the dominant factors in drift sedimentation.

The early drift/breakup unconformity outlined below has been interpreted from a prominent seismic horizon. The widespread on lapping nature of the overlying horizons are evidence for the regional extent of this interpreted unconformity, regardless of the size of the seismic cube.

As seen in the seismic line and 3-D image below (figure 19) the mapped surface indicates a depo-centre towards the North Eastern section of the seismic cube. Sediment flows from the west off the rise which overlies the Agulhus Arch, into this depo-centre. The depo-centre hosts a prominent thick of sediment which is represented by parallel and sub-parallel horizons. These horizons have characteristics common of deep water sedimentary environments.

Sediment influx from the west has resulted in possible sand rich lobe and fan elements and complexes, interbedded with clay and silt rich deposits in the proximal regions of the deep water environment. These alternations of sand and shale lithologies constitute bright parallel seismic reflectors. The more distal region of these deep water submarine fan system is dominated by dimmer sub-parallel seismic reflections which are the result of mud and silt rich sediments.
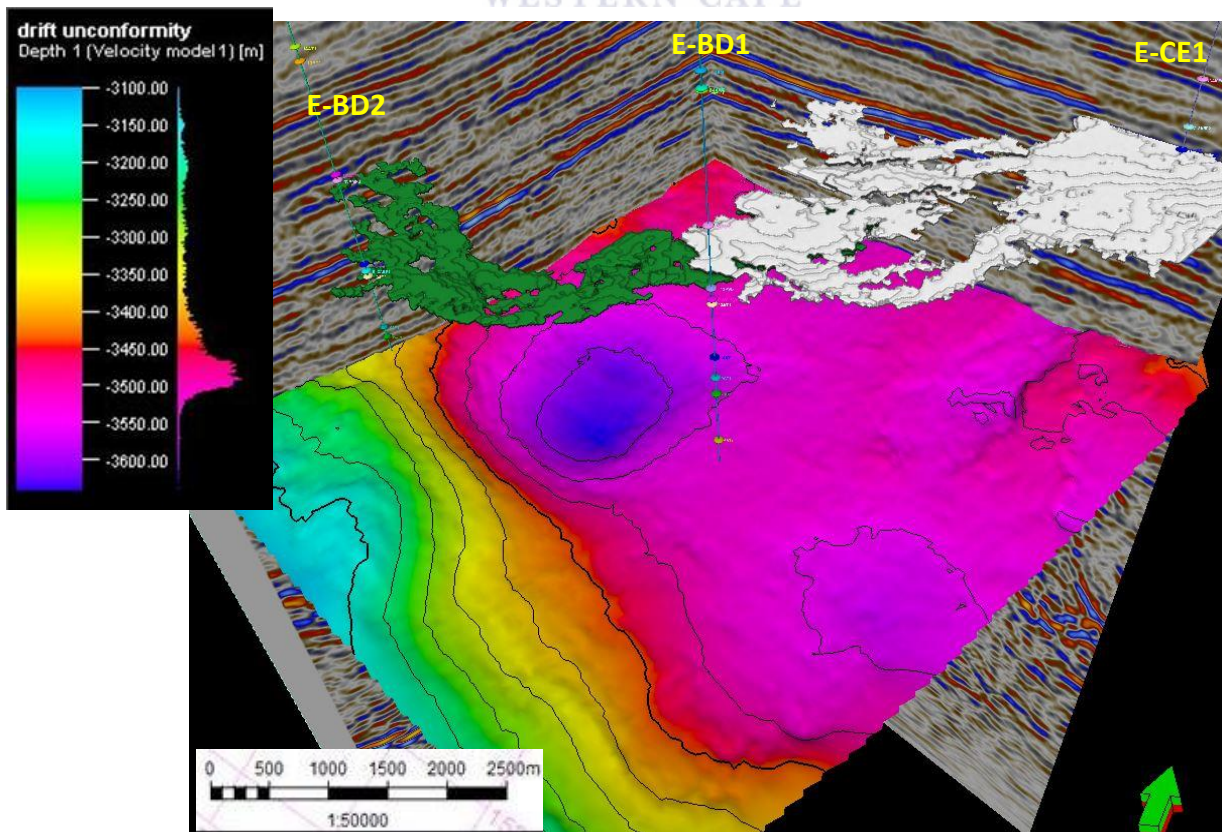

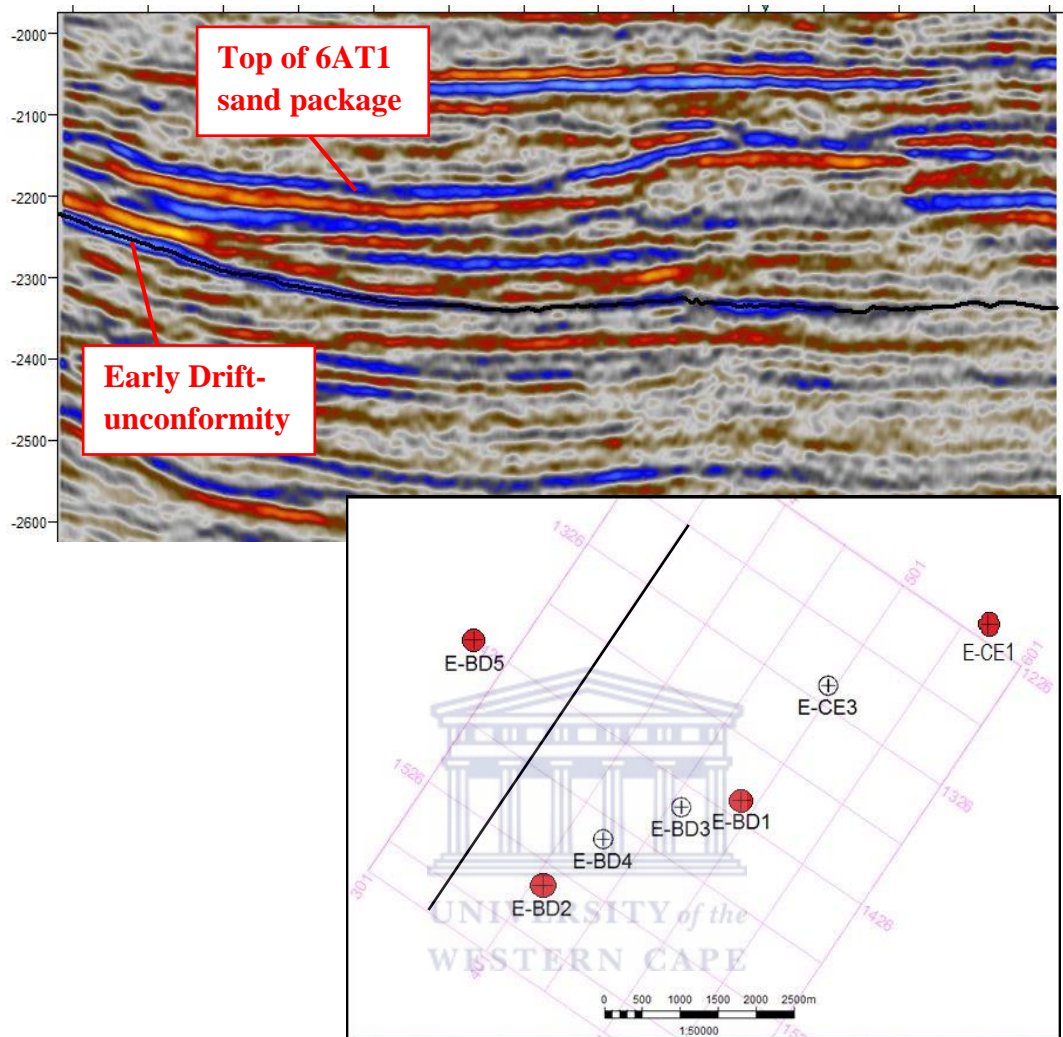Figure 19. 3-D image of the mapped early drift-unconformity and geobody geometry.

42

Figure 20. Xline 357 indicating the dip direction geometry of the early drift-unconformity and the Top of the 6AT1 sand package. A sediment bulge is mapped on the basin floor (right hand side of the xline image)

The seismic horizons which represent the low stand system track sediment influx into the basin are brighter and more parallel above the Agulhus Arch. These horizons progressively become dimmer and increasing sub-parallel basin-ward. This change in seimic amplitude can be attributed to the fact that the shelf and slope region host a great influx of sand rich sediment, thus the alternation of sand and shale in this region results in bright parallel seismic reflections. The basinward region is dominated by hemi-pelagic muds with minor pulses of sand which reach this far onto the basin floor. Thus this region is dominated by sub-paralell dim horizons which are chaotic.
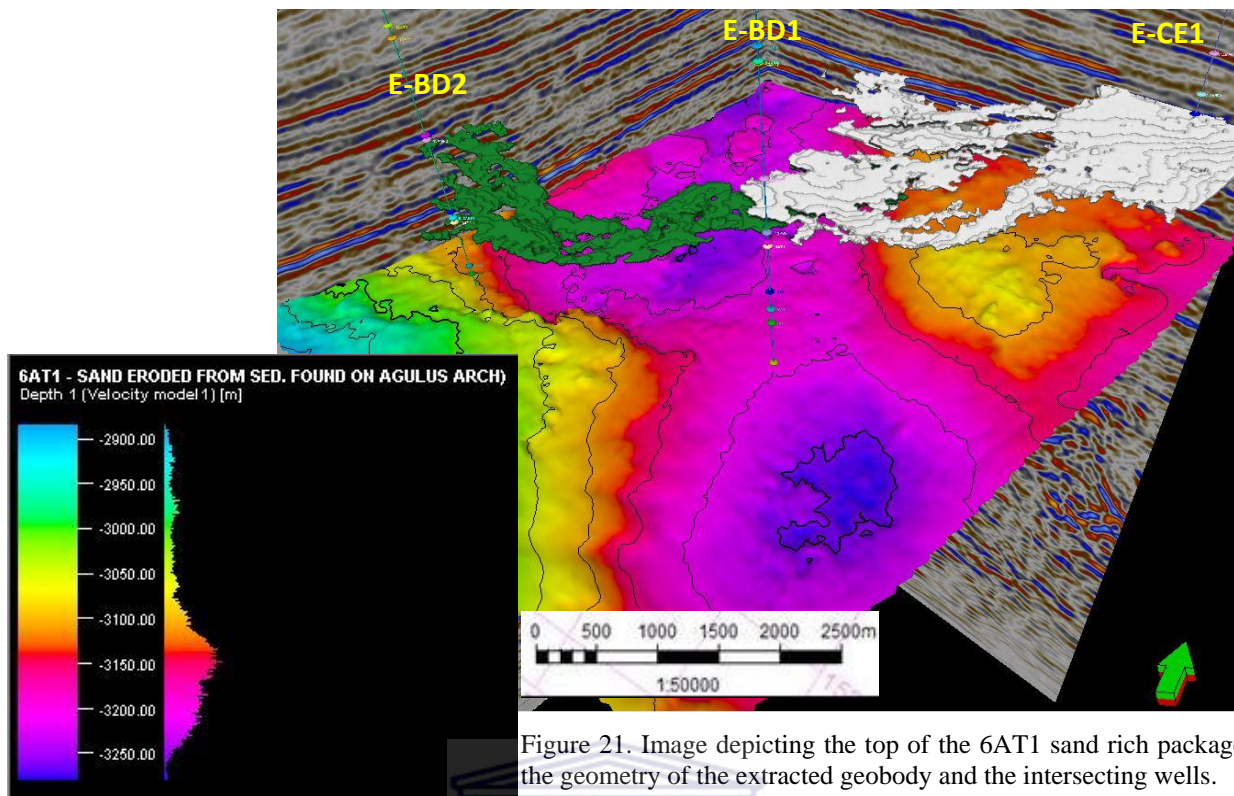
Figure 21. Image depicting the top of the 6AT1 sand rich package, the geometry of the extracted geobody and the intersecting wells.

The regional sequence stratigraphic framework cannot be outlined due to the limited nature of the seismic cube. However the investigated early drift sedimentation can however be characterised to constitute a Low Stand Systems Tract. The LST encompasses a set of progradationally stacked parasequences. These parasequences progressively build basinwards and form a net shallowing-upward succession. The lowstand systems tract is underlain by a sequence boundary (unconformity) and overlain by the transgressive surface (ts), the first major flooding surface of the sequence. The LST is deposited during a slow relative rise in sea immediately following a relative fall in sea level (Underhill, 2014).

The depositional pattern of this LST is associated with an increase in depositional area as the bowl-shaped basin filled. This increase in basin area is accompanied by a decrease in accommodation space relative to sediment supply (A:S).

4.5 BASE OF CHANNEL COMPLEX RESERVOIR

The Sable reservoir is associated with early post-rift (drift) sedimentation. The interpreted drift unconformity (fig. above) is the base of a sedimentation period which includes the Sable reservoir.

The surface outlined below is interpreted as the 13AT1 unconformity. This reservoir base has similar characteristics to the drift unconformity. The topographical characteristics of the underlying drift unconformity predominantly dictate the sedimentation pattern of all the overlying early drift sediments. The early drift 13AT1 unconformity (base of Sable

Reservoir) has similar paleo topographical characteristics as the underlying early-drift unconformity. The south-western section of the unconformity has a dominant high ground which mimics the underlying structural control of the Agulhus Arch.

Sediment flows from the west off the high which overlies the Agulhus Arch, thus this structural high is associated with the proximal region of the investigated BFF system. The green geobody is representative of this proximal region while the white geobody is representative of a less confined depositional region. The Sable field constitutes the Submarine Channel-Lobe Transition Zone (CLTZ) of the basin floor fan system.

This transitional depositional region commonly results in sand filled channels deposited at the base of the continental slope where the basin floor topography progresses basinward to a dip angle of approximately 2°. The Sable reservoir is a perfect example of this sand deposition at the base of slope in a confined depositional environment.
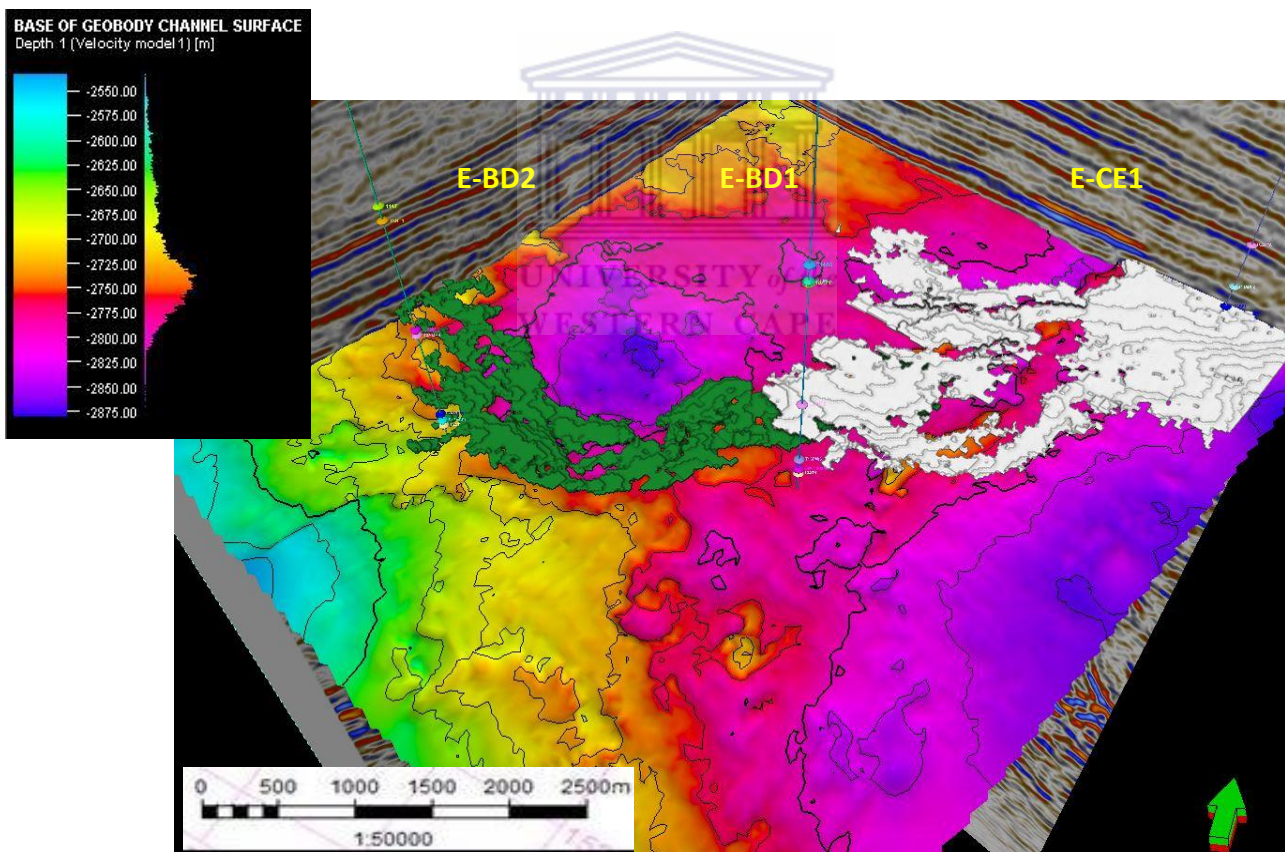

Figure 22. Image depicting the base of the Sable BFF system. This mapped surface corresponds to the 13AT1 well top.
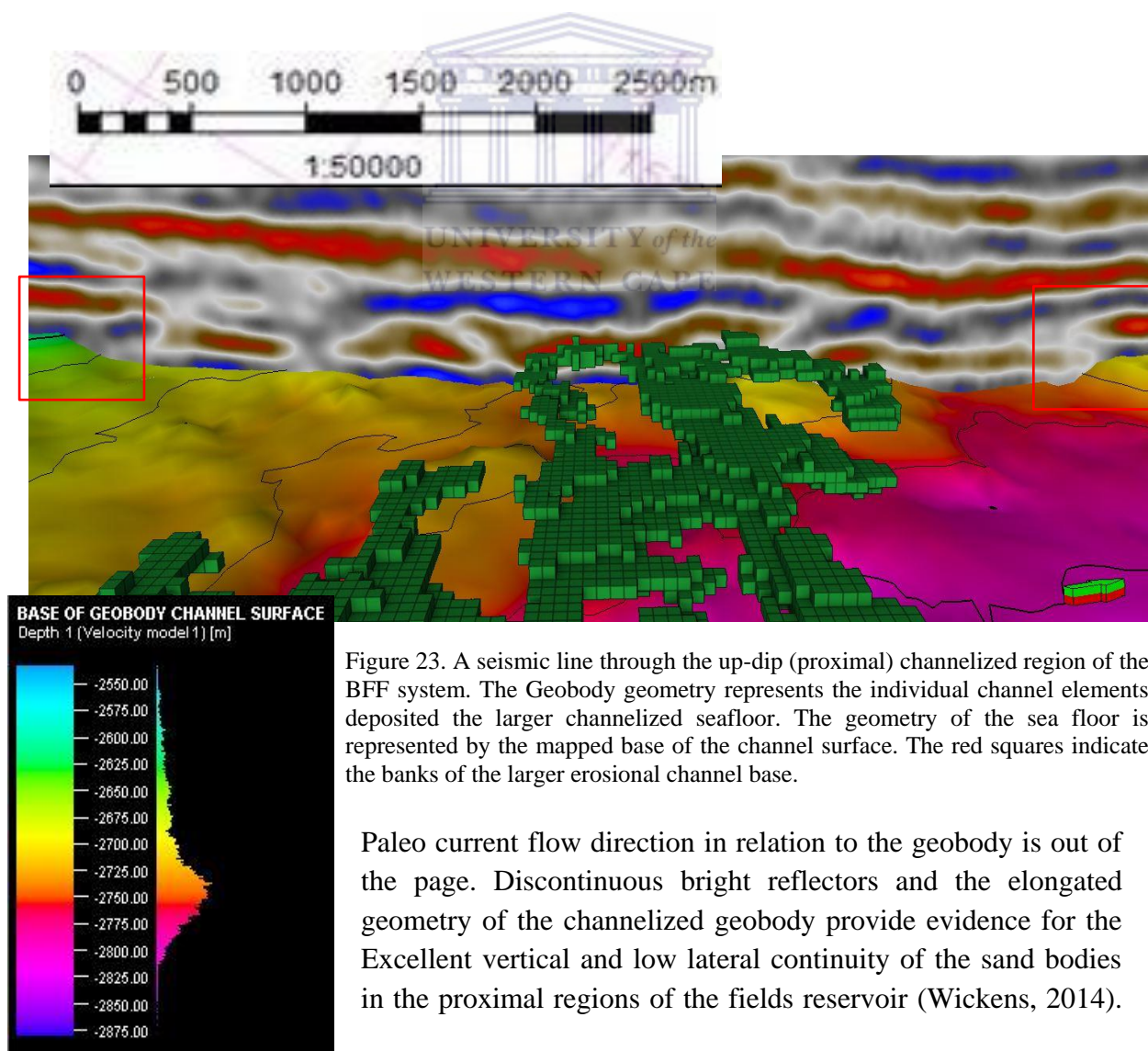
4.6 RESERVOIR GEOMETRY

This section of the research splits the interpretation into a proximal, transitional and distal regions of the Basin Floor Fan system.

4.6.1 PROXIMAL BASIN FLOOR FAN REGION

The proximal region of the Sable field's basin floor fan reservoir is characterised by unique seismic and well log responses. The Base of the channel complex is observed to have two flanks which confine sediment transport and deposition. A number of elongated sand bodies can be observed which are interpreted as lateral switching and stacking channelized and amalgamated sand lenses.

The extracted geobody depicts the elongated nature of sand bodies which have been interpreted from a seismic horizon that represents the base of one of the channelized deposit. The surface which represents the base of the channel can be characterised as an unconformity due to a number of onlapping horizons and erosive channel bases which dominate the channelized proximal regions of this deep water depositional environment.

Figure 23. A seismic line through the up-dip (proximal) channelized region of the BFF system. The Geobody geometry represents the individual channel elements deposited the larger channelized seafloor. The geometry of the sea floor is represented by the mapped base of the channel surface. The red squares indicate the banks of the larger erosional channel base.

Paleo current flow direction in relation to the geobody is out of the page. Discontinuous bright reflectors and the elongated geometry of the channelized geobody provide evidence for the Excellent vertical and low lateral continuity of the sand bodies in the proximal regions of the fields reservoir (Wickens, 2014).

The geometry of these sand bodies results due to the steep nature of the channels base in the proximal region. This up-dip region is generally associated with erosive channels however this period of net erosion is followed by periods of net deposition where channels become sand filled. These large scale channel is filled with smaller scale sand filled channels which constitute amalgamated sand bodies that are laterally switching and stacking in nature.

Outcrop and analogue studies indicated the proximal regions of BFF may constitute Single incised straight channels that are up to 40 m deep with levees up to 3 m high. Reservoir sands generally have a low aspect ratio (width vs thickness) which is predominantly caused by deposition of fine grained deep water sands in a channelized and confined environment.

These channels have a highly erosive base which isn't clearly seen in seismic, however gamma ray responses of electro facies indicate Erosional contacts at the base of the amalgamated channels.

The proximal region hosts a number of depositional facies. Theses facies can be interpreted and inferred from seismic responses, however one must keep in mind the seismic resolution is poor and the internal heterogeneity of the reservoir can be better understood with well log analysis.
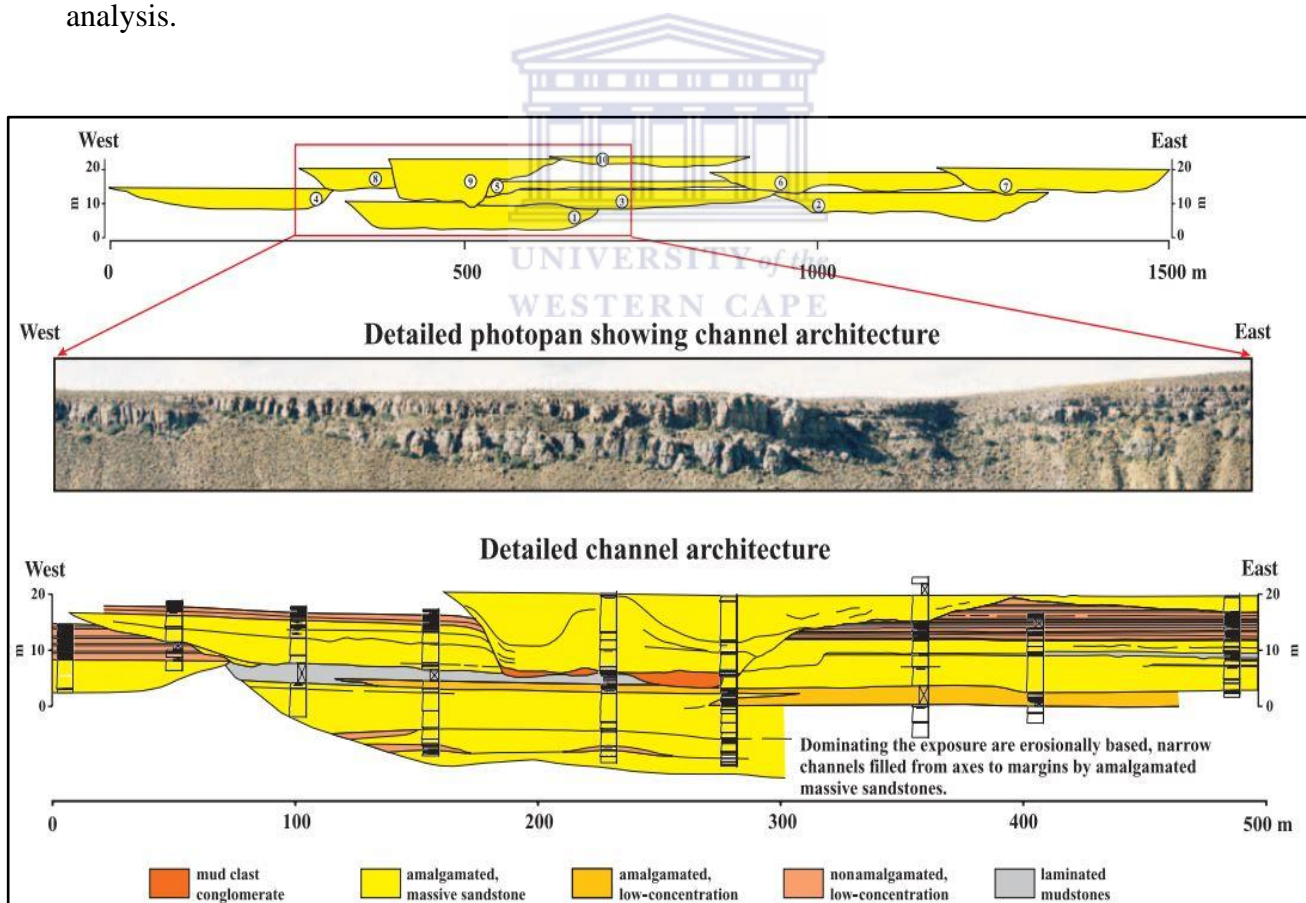

Figure 24. Diagrammatical representation and outcrop photograph of the proximal region of the BFF system. The diagram depicts the various depositional elements which arise in this confined depositional environment (Wickens, 2014).

With respect to the well log data for well E-BD5, the reservoir is characterized to have a high reservoir quality net to gross of approximately 90%.

Gamma Ray log responses indicate alternating layers of large sand bodies separated by shale horizons. The total reservoir constitutes an 85 metre thick sand and shale succession. The thickest sand package in the reservoir is 34 metres and separated from the sand packages above and below thin shale layers.

These sand packages are interpreted to be proximal channels fill sands where the shale horizons arise due to the meandering nature of the channelized environment.

The high gamma ray response between clean channel sands could also be due to the erosive nature of each channels base. The sand package in contact with the channels base may contain mud clast conglomerates. Mud rip up clasts have been eroded by the shale horizons further up-dip as well as from the banks of the channels complex.

The sand packages may however be in hydraulic communication further up dip or down dip of the well. This is an inherent depositional characteristic of the proximal channel environment. Sand packages may be relatively continuous and cut by large channels which then cause communication between various sands or pinch out to cause communication between sands.

Well E-BD 5 appears to be situated at the erosive entry point of feeder channels into the basin. These feeder channels wind and meander lightly in a larger channelized base. This base of the channel is governed by the topography of the basin, where the steeper regions overlying the Agulhus Arch, constitute channelized turbidite sedimentary environments.

This up dip region is associated with channelized sand rich bodies which are encased in a predominantly mud rich deep water environment. The E-BD5 well sheds light on this sedimentary characteristic of turbidites, where massive hemipelagic muds have been eroded by turbidite flows to form channelized depressions on the basin floor which have been filled by well sorted fine grained sands that constitute good quality reservoirs.

The channel sand reservoirs found in the E-B5 well have been overlain by several metres of hemi-pelagic mud which constitute a top seal which is draped over the entire channel deposit.

Sand influx into the basin by turbidite flows, takes place in times of lower sea level where sediments are eroded off the shelf and deposited on the basin floor. These sand rich channels on the base of the continental slope have been tapped by wells E-BD5 and E-BD2. Well E-BD5 is situated up-dip of E-BD2 in the more proximal confined region BFF Complex. E-BD 5 thus constitutes a more channelized and compartmentalised reservoir which extends up –dip and down-dip of the well bore, instead of extending laterally towards the flanks of the extensively confined channel complex.

Well E-BD 2 has tapped into a reservoir which constitutes a combination of channel fill sand as well as weakly confined channel sands are interpreted to be elongated lobe like structures.

Facies in well E-BD5 from core #1 and #2

Three Litho-facies have been identified: sandstone, siltstone and shale. They occur with four distinct unit types:

> A: Flaser-bedded lenses and pods of cross-bedded light coloured siltstone. Dark grey shale pinch and swell structures are also found.
>
> B: Massive, fine grained sandstone with occasional low-angle carbonaceous lamination, argillaceous clasts and numerous amalgamated clasts.
>
> The sandstones intersected are generally well sorted although fine carbonaceous detritus is disseminated throughout. These sandstones have sharp contacts and occasional planar bedding. Floating shale clasts appear in some regions of the core. (
>
> C: Carbonaceous claystone which is finely laminated with dark grey siltstone.
>
> D: Clay clasts conglomerate. This constitutes a chaotic mixture of shale rip-up clasts that have varied shapes and sizes (rounded to elongate and irregular). These clasts are supported in fine-grained sandstone.

Interbedded laminated units have been characterised as meander facies which can also be found in other boreholes. This facies type is a transitional facies between Facies B and Facies D. It is generally associated with the upper parts of the channel fill sequence. This type of facies is regarded as having a uniform thickness for great lateral distances (Howell, 1982 cited in McAloon, 2000). The Bouma sequence doesn't generally apply however sections of cross laminated divisions could represent low-density turbidity currents which could be equivalent to Tc Bouma divisions.

The sandstones found in well E-BD5 are quartz arenites. They are slightly feldspathic and lithic (volcaniclastics and metasiltones) with varied amounts of mica and heavy minerals
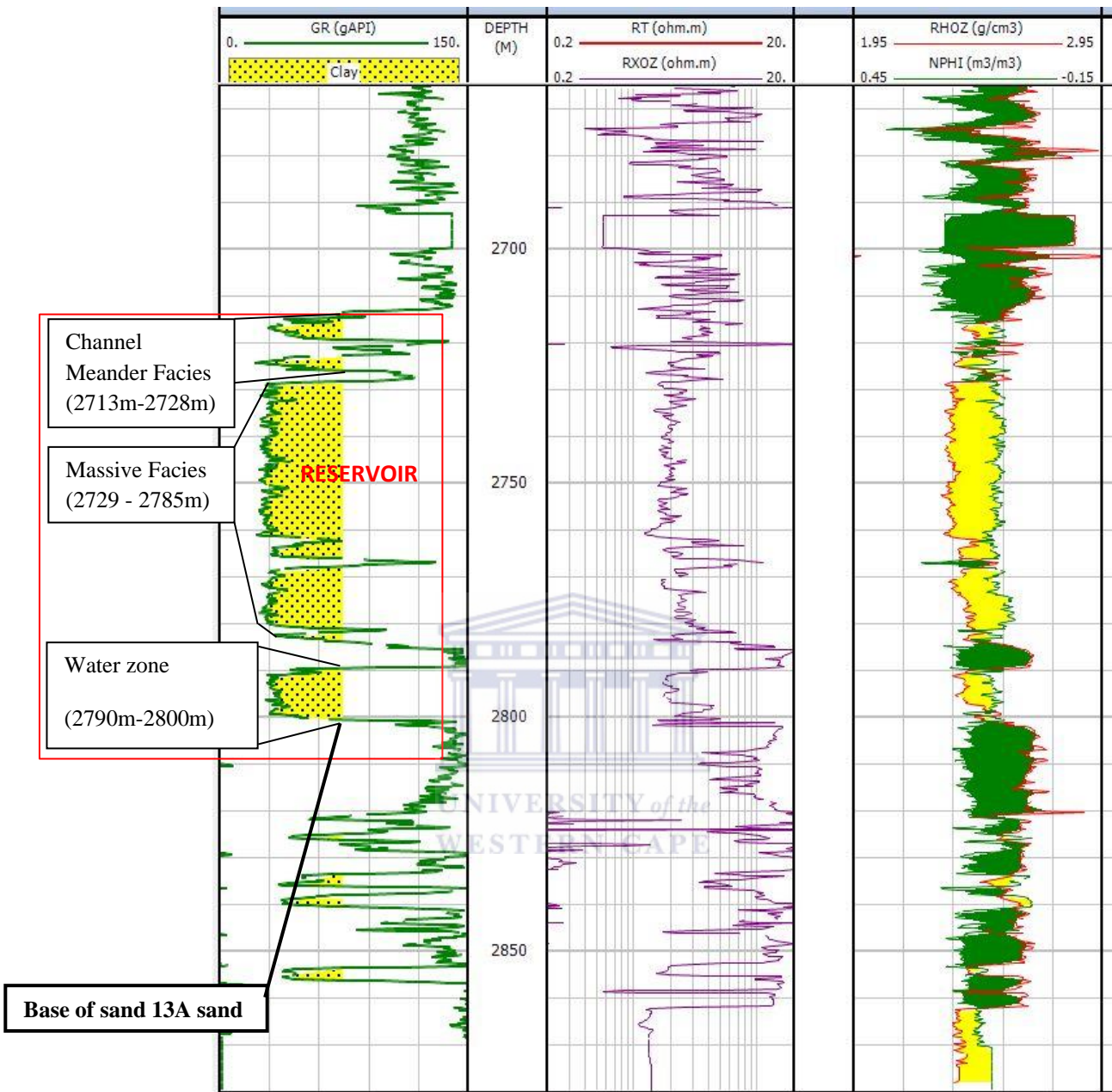
Figure 25. Well log analysis of well E-BD5. The image constitutes well log display on
Interactive Petro physics. Electro facies are adopted from core, modified after McAloon, 2000.

Table of comparative petro-physical reservoir characteristics

	COMPARITIVE RESERVOIR CHARACTERISTICS			
Petro-physical properties	E-BD5 (proximal channel)	E-BD2 (proximal channel)	E-BD1 (Base of slope)	E-CE1
Gross thickness (m)	76.2m	25m	30m	50m
Nett Sandstone (m)	68.5m	23m	29.7m	50m
Nett average porosity (%)	15%	17%	16.4%	14%

Table 2. Comparative reservoir characteristics of wells E-BD5, E-BD2 and E-BD1.

E-BD1 has exceptional net sand as it constitutes a channelized and amalgamated sheet sand deposit at the base of the continental slope.

E-BD2 situated on the up-dip end of the bend in the channel. This well thus taps into amalgamated channels and confined sheet sands. the reservoir has an exceptional net sand value which are associated with amalgamated depositional channels, situated just up-dip of the base of slope basin floor region. E-BD5 exhibits a thick succession of amalgamated channel sands, with meandering channel facies in the upper section of the reservoir.

The well has tapped into the channel deposit in a position where the paleo current flow direction changes and the channel takes a left turn as it flows out of the channelized region onto the unconfined basin floor. Well E-BD 1 situated at the down-dip end of the bend, has tapped into a sand accumulation which is less confined and channelized than the sand found in well E-BD2.
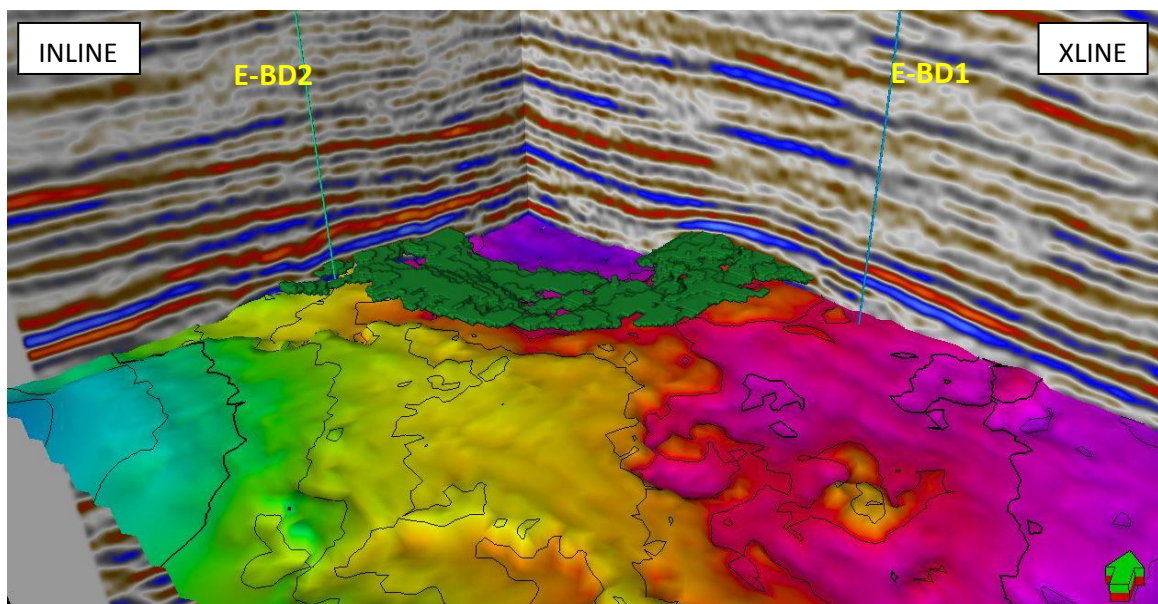

Figure 26. 3-D image representing the geometry of the channel body at the bend of the channel. Wells E-BD2 and E-BD1 are situated before and after the bend respectively.
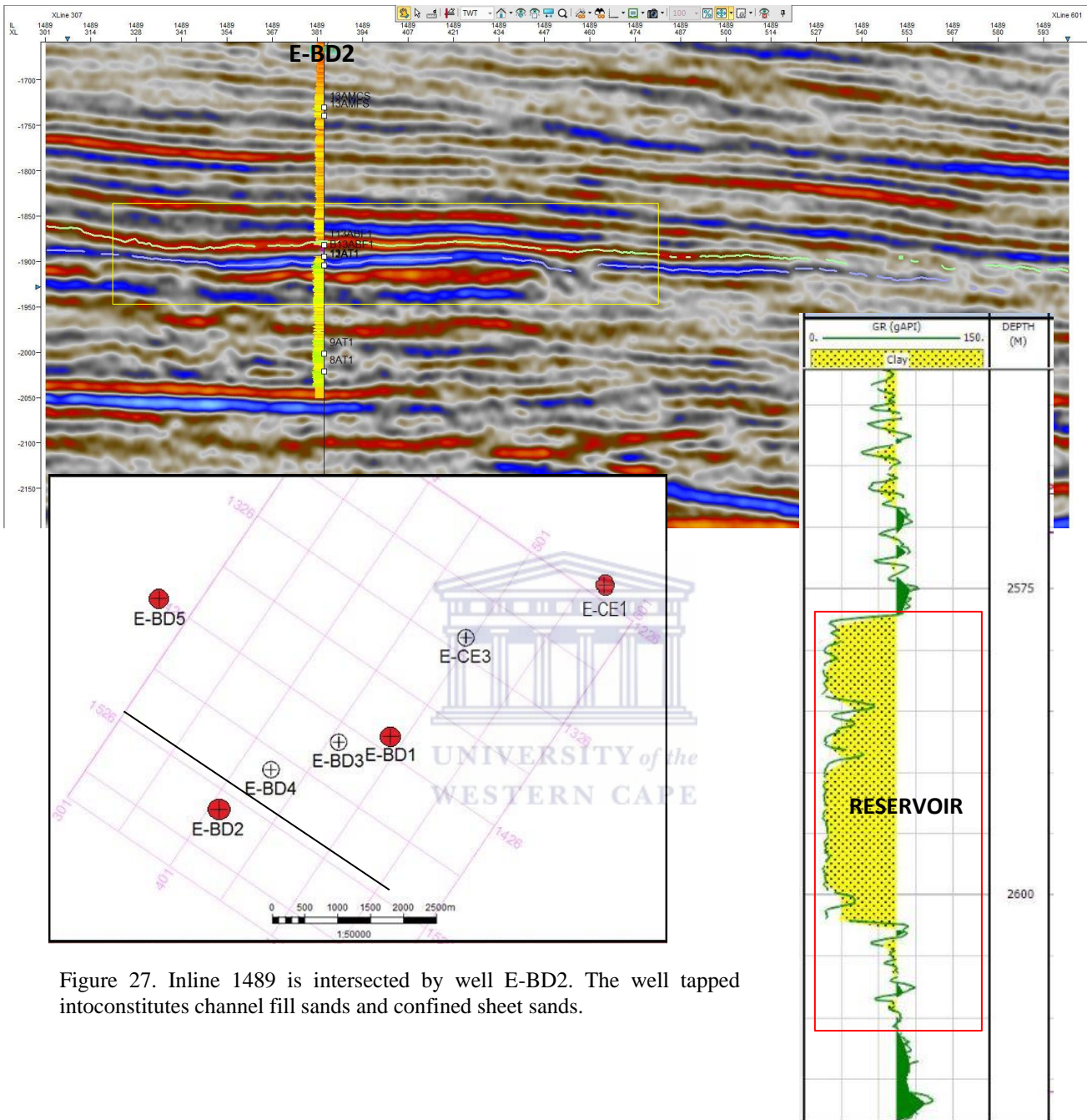
Figure 27. Inline 1489 is intersected by well E-BD2. The well tapped intoconstitutes channel fill sands and confined sheet sands.

Inline 1489 above outlines a cross Sectional view of the channel at E-BD2. The cross section is cut in such a way that it indicates geometry of the up-dip and down dip portions of the channel. The left side of the yellow square on xline 1489 above indicates the up-dip portion of the channel where the seismic horizon in thinner due to angle which the cross section cuts the channel as well as a more channelized and irregular depositional elements.

The righ hand side of the square indicates thicker horizons which represent the outer cut bank of the channel where it takes the left bend and continues into the page relative to the cross sectional view.

The outer cut bank appears to host a thicker accumulation of sand filled into the section of the channel which experiences the most erosion when a channel takes a bend, thus provides the most local accommodation space for sand to back fill the channel. The banks of the channel are interpreted as hemipelagic mud and silt lithologies which are outlined by sub-parallel seismic horizons. The top of the E-BD2 reservoir is marked by a bright continuous horizon. This horizon marks an end to channel fill sand deposition and the possible onset of sea level rise which resulted in the deposition of hemi-pelagic muds that seal the reservoir.
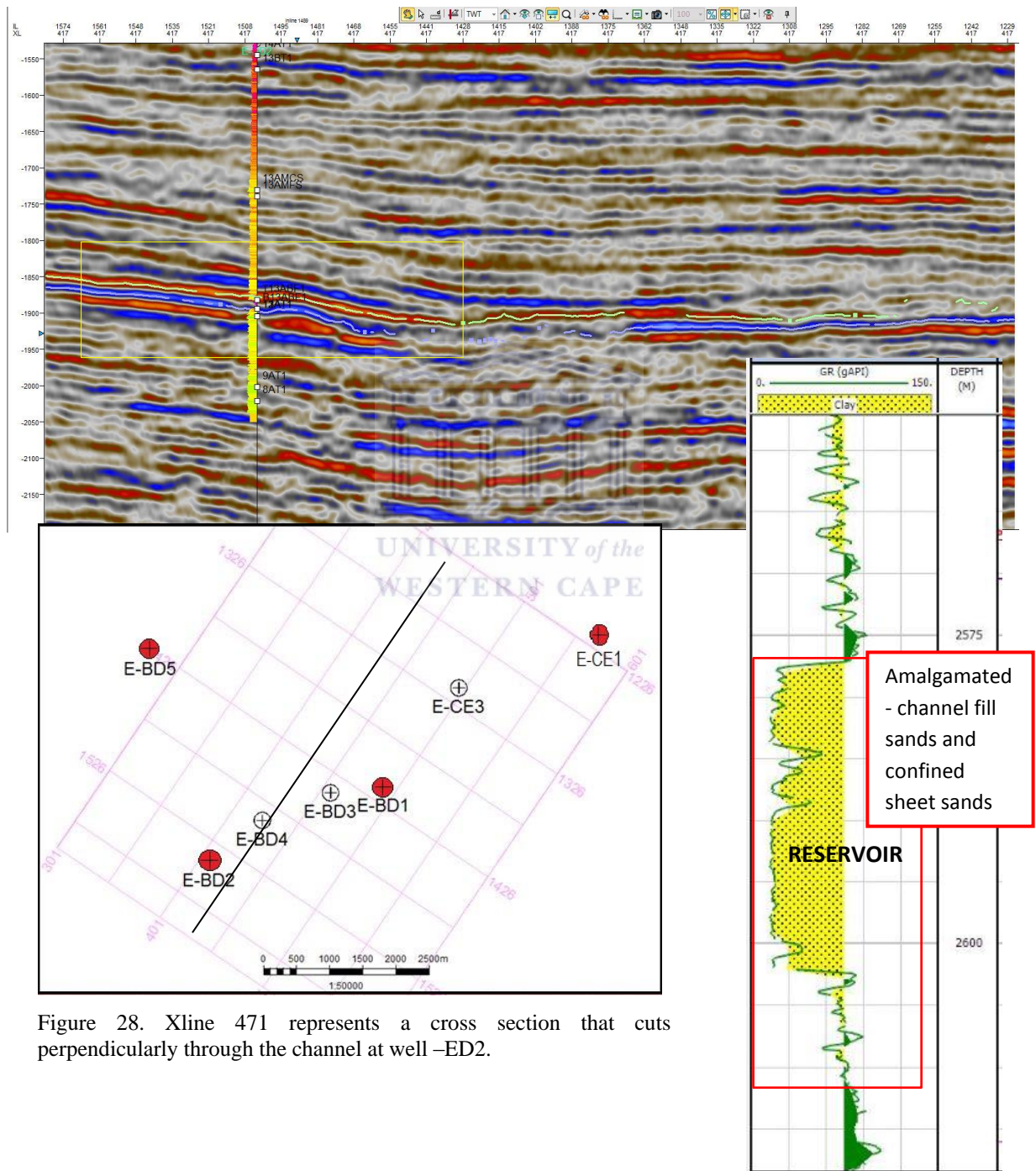

Figure 28. Xline 471 represents a cross section that cuts perpendicularly through the channel at well –ED2.

As seen in Xline 417 which cuts perpendicularly through the channel at well –ED2, the channel is highly confined. Its geometry is outlined in this proximal region by bright reflectors that define base and top reservoir surfaces. The axis of the channel is associated with a thickening of reflectors. The axis of the cannel is thicker than the off axis margins due to being sand rich, thus less compressible. The silt and mud sediments are draped alongside and over the thick sand accumulation in the axis of the channel. Some regions off the channel axis are associated with bright reflectors which could be interpreted as sand rich sediment which has flooded over the channel banks onto hemipelagic muds and subsequently sealed by hemeipelagic mud along witht the rest of the channel complex.

These channel over bank sands appear to have good communication with channel axis sands, a relationship marked by continuous but dimming and pinching of horizons between channel sands and overbank sands.

Well E-BD2 host sediments which exhibit various electro facies in the reservoir zone as well as the zones above and below the reservoir. The reservoirs base is dominated by 15m of irregular thin beds of alternating sand and silts (channel levee deposits). This 15m lower reservoir zone can be traced along a seismic horizon which is interpreted to be off axis channel deposits hosted on the over bank regions of the channel.

An overlying 25m thick clean sand accumulation exhibits a cylindrical electro facies pattern. This sand accumulation is associated with a seismic horizon that thickens due on axis channel fill sands deposited in a confined channel environment, before the channel take the left turn onto the basin floor.

The cylindrical gamma ray signal of the reservoir zone in well E-BD2 and the corresponding top and base seismic horizons, indicate a thick channel fil sand element that has been deposited in the confined environment of the erosive channel. This sand stone interval has predominantly been intersected by the well in the lobe axis, however sheet like sandstone from the off axis region off less confined sand rich deposits have also been tapped by well E-BD2. These sheet sands are found above and below the reservoir which is bounded at the top and base by prominent shale horizons. The reservoir zone itself also hosts sheet sand at its base which appear to be connect to the major lobe sand.

The presence of both massive and amalgamated channel fill sands is common when the feeder channels meander within the larger channelized region of the basin floor. Thus the reservoir in well E-BD2 hosts both amalgamated channel fill sands from the axial region of a deposit and the sheet sands from the off axis region of other feeder channels.
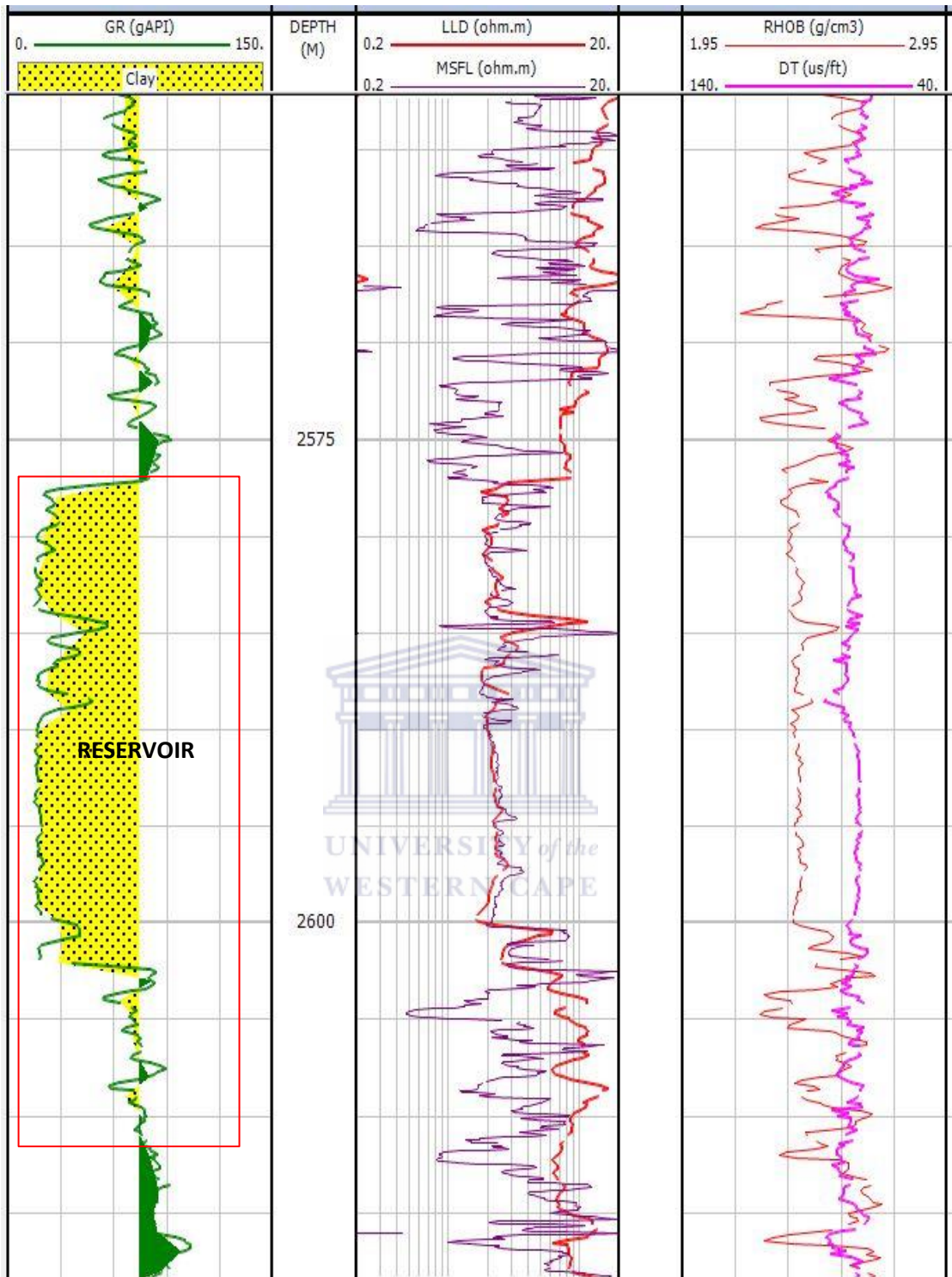
Figure 29. Well log analysis of well E-BD 2 using Interactive Petro physics.

4.6.2 BASIN FLOOR FAN CHANNEL-LOBE TRANSITION ZONE (CLTZ)

A significant sand rich zone of the Sable Fields reservoir is interpreted to arise in the channel-lobe transition zone (CLTZ) of the larger Basin Floor Fan system. This reservoir sandstone has been tapped by well E-BD1. Analysis of this reservoir zone is based on a collaboration of the 3-D seismic cube and well data in order to delineate the 3-D configuration of the reservoir. The seismic horizon in figure below represents the top of this sand rich reservoir zone. The accumulation of sand under investigation is outlined by the black ellipse. The ellipse encompasses a sand rich lobe which is interpreted to have been deposited at the base of the continental slope in a relatively confined channelized environment.
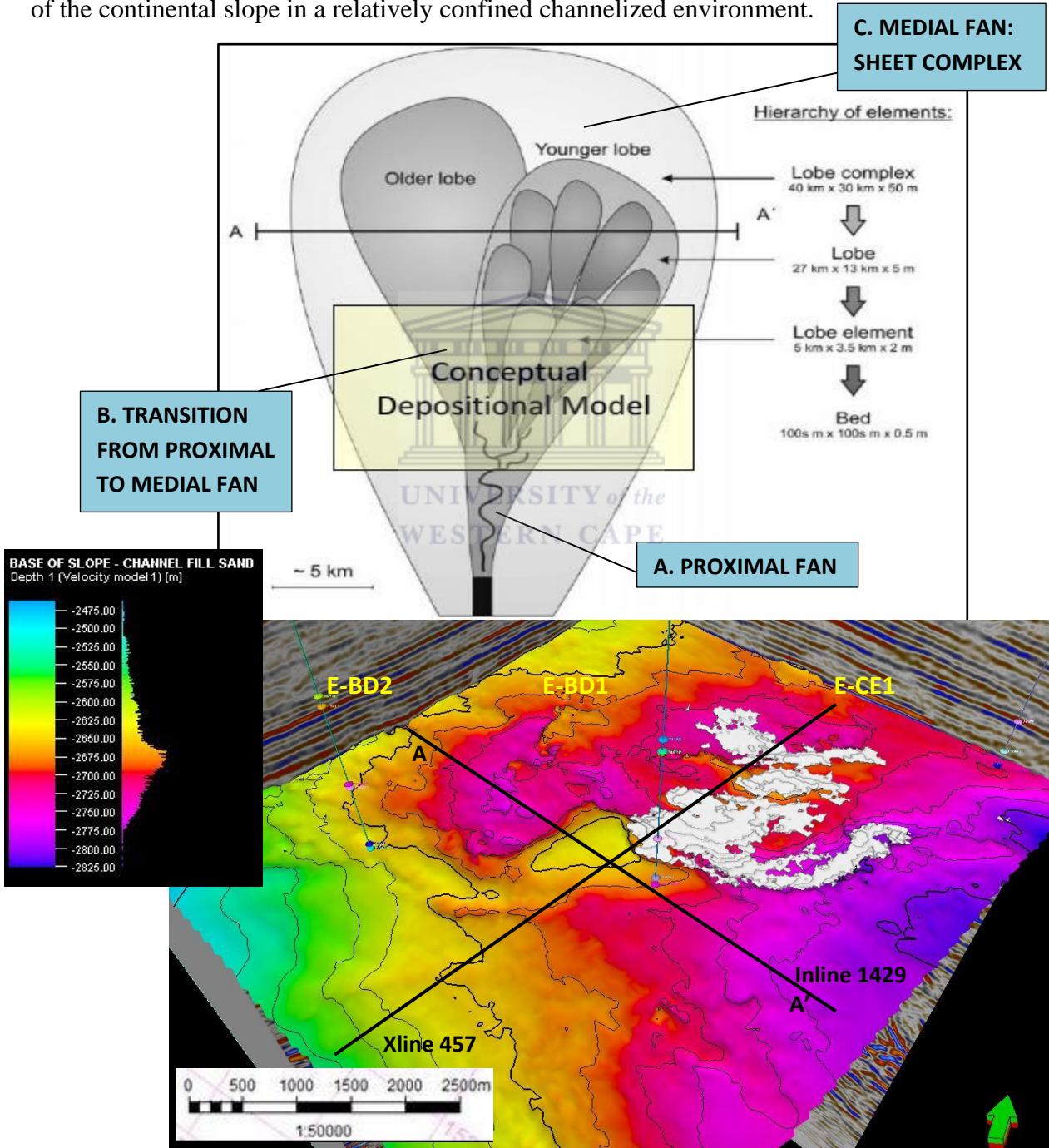

Figure 30. The Conceptual Depositional Model of a Basin Floor Fan systemis related to the Top surface for a sand package deposited at the base of the continental slope. Modified from Groenenberg et al., 2010 cited in Jiajie, 2012.

The sandstone reservoir tapped by well E-BD1 is interpreted to constitute a depositional environment which is referred to as the submarine channel-lobe transition zone (CLTZ). This region of the submarine basin floor fan marks the crossing point between up-dip channels and down-dip lobes. With respect to this study the CLTZ region is interpreted to be the base of slope region where sand has accumulated. The CLTZ functions as the connection between locally confined and unconfined conditions of sediment gravity flows. These gravity flows serve as the submarine fans building blocks (Jiajie, 2012; Gordon, 2014).

Sand was deposited in this region where the channelized slope environment progressed to a slightly less confined channel area close to the basin floor environment. This thick sandstone accumulation could have been deposited by back filling of sand in the larger channelized region of the basin. The sand rich lobe is elongated due to the steep topography of the Bredasdorp Basin as well as the confining nature of the channel base.

The CLTZ region tapped by well E-BD 1, governs sandstone connectivity between the channelized sandstone reservoirs (Tapped by wells E-BD5 and E-BD2) and the down dip lobes tapped by well E-CE1. This hydraulic communication only refers to a channel and lobe at the scale of an individual architectural element. The reservoir zone tapped by well E-CE1 however constitutes a different sand rich architectural element to well E-BD1. The lobes tapped by well E-CE1 are situated in a lower basin floor fan than the channelized lobe found in well E-BD1.

A turbidite system of the Ainsa basin in Spain serves as a good analogue example for the characteristics of the CLTZ which governs the reservoir found in well E-BD1. This turbidite analogue constitutes a ~4-km-long, paleocurrent-parallel transect which is continuous through a channel-lobe element. The base of slope sand deposit outlined in figure above by ellipse, has a width of about 2km at the channelized lobe, and a length of approximately 4-6 km along the paleocurrent-parallel transect through the channel-lobe element. There are a number of fundamental longitudinal changes which take place across the CLTZ in this depositional system (Wickens, 2014; Gordon, 2014). These changes are observed in the spatial distribution of the sandstone reservoir under investigation.

The spatial changes in the distribution of sand tapped by well E-BD1 is outlined using the seismic horizon interpreted in figure above as well as the transecting xline 457 and inline 1249 outlined below in figure … and … respectively.

The lobe elements and the lobe at large thicken in a down-current direction. This depositional phenomenon can be observed on inline 1249 below. The reservoir zone is delineated by the yellow window, where sand is transported and deposited from the left (up-dip) towards the right (down-dip) side of the window in figure below. The thickening of top and base horizons in a down dip direction is also the result of older proximal lobe bed-sets thinning and pinching out completely onto the erosive lower contact in an up-current direction (Wickens, 2014; Gordon, 2014). Based upon stratigraphic thickness measurements discussed in analogue studies, the CTLZ region of the BBF system is attributed to a base-of-slope depositional angle of approximately 2°.

The seismic horizons interpreted as the top and base of the reservoir correspond well with the reservoir zone outline in well E-BD2. The blue horizon pick is interpreted as the top of the reservoir. The upper part of the reservoir which constitutes a gas charged sandstone is

overlain by a 4 metre thick sealing shale. This rapid change in lithology and fluid content of the sediment has resulted in this bright blue seismic response. The seismic pic itself thickens in a down dip direction. This blue top reservoir horizon is however continuous both up dip and down dip.

The underlying red seismic pic is interpreted as the base of the reservoir. This horizon corresponds well with the base of the reservoir and it has the characteristics of deposition on an erosive channel base. This base reservoir horizon (red) is much thicker than the top reservoir horizon (blue). It also depicts considerably greater internal heterogeneity. This internal heterogeneity is outlined by thickening and thinning as well as brightening and dimming of the red horizon. This red horizon also indicates a highly confined environment due to its sharply discontinuous nature. The variation of brightness and continuity of this base reservoir horizon can be attributed to the nature of architectural elements within the channelized lobe structure.
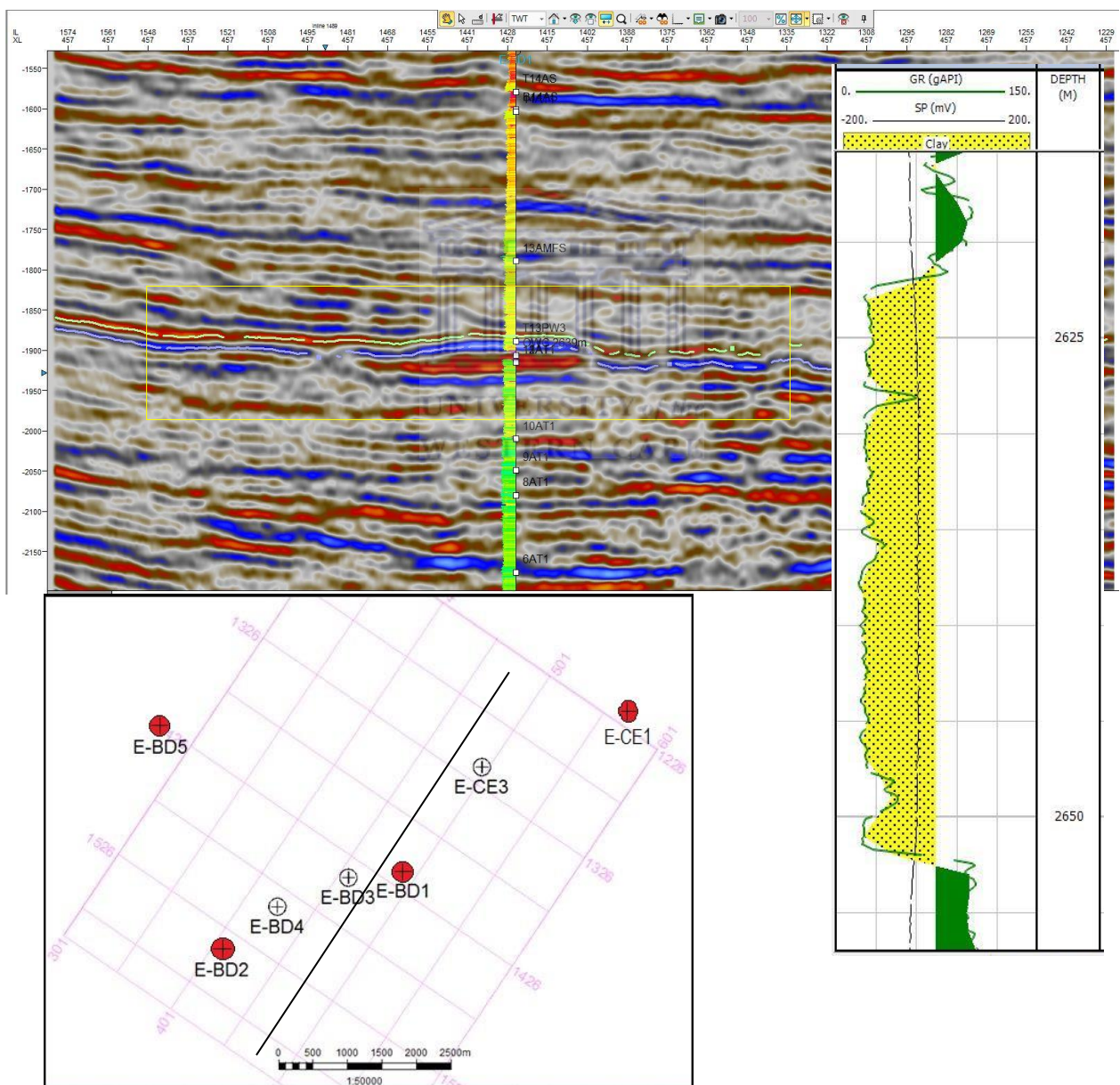

Figure 31. Xline 485 cuts parallel to the paleo current flow direction of the channel near well E-BD1. The well has intersected a reservoir zone which constitutes a thick amalgamated lobe complex deposited at the Base of the Continental slope in a relatively confined CLTZ.

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The CTLZ reservoir zone tapped by well E-BD 1 and its geometry away from the well bore has been interpreted with respect to the various analogues consulted for this study. Architectural elements within this sand rich zone constitute a transitional depositional style which increases the internal heterogeneity of the reservoir.

Since the CTLZ host a transitional depositional style, the nature of gamma ray responses at the well bore and seismic responses away from the well bore indicate a complex reservoir zone. This transitional style of deposition results in a reservoir zone which constitutes both channelized and lobe like architectural elements. The seismic response away from the well bore provides evidence for the presence of these architectural elements. Due to poor seismic resolution, the complex internal heterogeneity has not been fully captured.

The reservoirs internal heterogeneity has however been captured by well log response and core analysis. The gamma ray log response indicates that the reservoir zone is deposited on a relatively sharp erosive base, where architectural elements generally constitute constructional features such as: thick bedded sand sheets; thin bedded sand sheets; Amalgamated thick and thin bedded sand sheets as well as depositional feeder channels.

The amount of erosion at the base of the confined lobe like element tapped into by well E-BD1 generally decreases basin-ward. The sediment package also thickens basin-ward, where analogue studies have indicated that there is a basin-ward decrease in intra-element erosion and amalgamation surfaces. This can be observed within the base reservoir horizon which becomes brighter and less chaotic in a down dip direction. This can be attributed to less internal heterogeneity with the reservoir zone down-dip.

The base and top reservoir horizons as well as the thickness of the reservoir zone indicates that clean sandstone is extensively laterally continuous. There is thus Continuity of sandstone from the up-dip channel to the down-dip lobe. The CLTZ region of the basin floor fan system where well E-BD1 has tapped into provides a sand rich environment which could provide hydraulic communication between up-dip channels and down-dip lobes. This communication of various up-dip and down-dip sand rich depositional elements agrees with the analogues consulted for this study (Gordon, 2014).

With respect to the upper yellow window in figure… above, seismic and well data can be correlated to illustrate that the sub parallel horizons represent a massive succession of hemi pelagic mud which encases the sand rich reservoir. This hemi pelagic mud is found below and along the sides of the sand rich reservoir zone thus the entire spatial configuration of the sand rich BFF complex is trapped in hemi-pelagic mud.
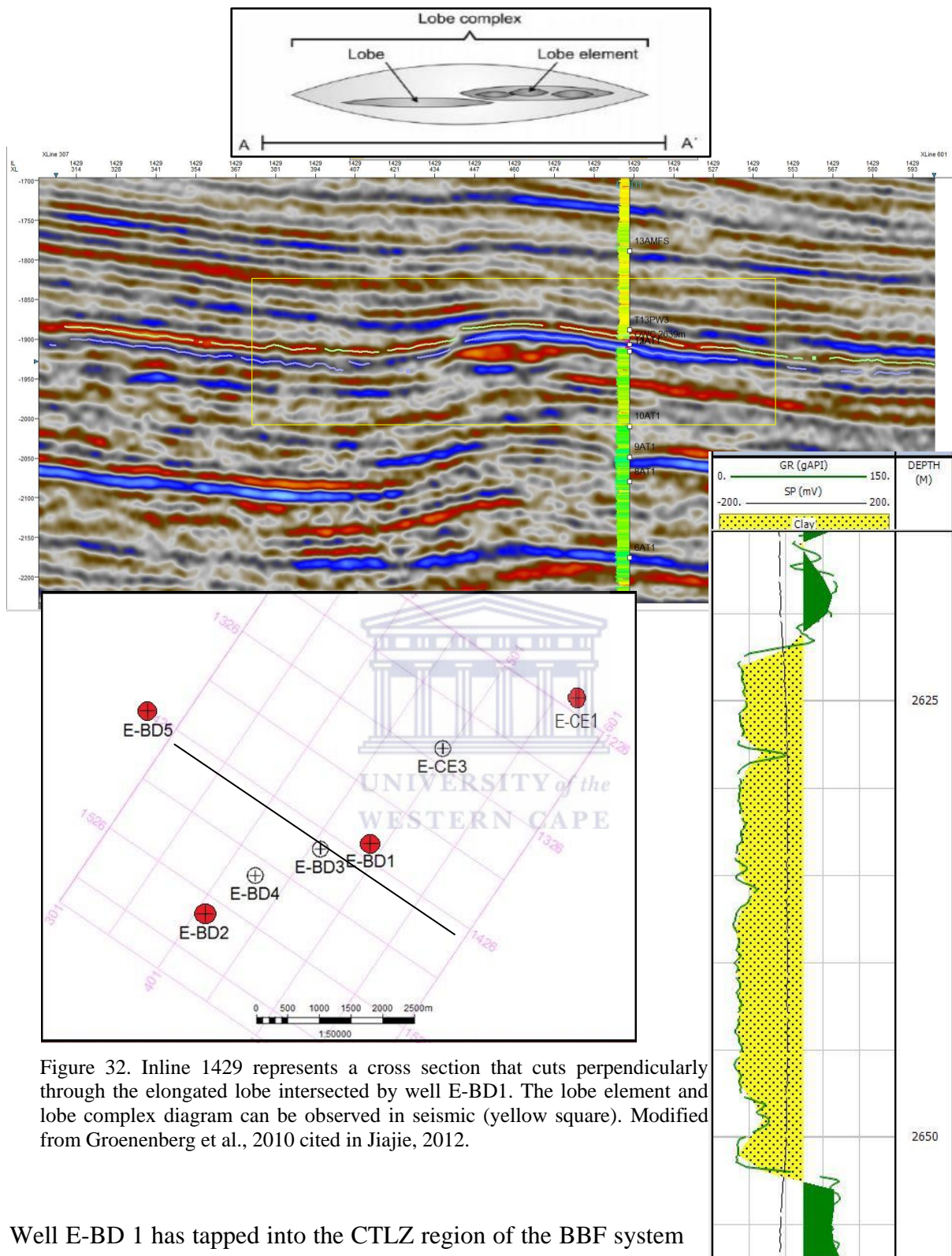
Figure 32. Inline 1429 represents a cross section that cuts perpendicularly through the elongated lobe intersected by well E-BD1. The lobe element and lobe complex diagram can be observed in seismic (yellow square). Modified from Groenenberg et al., 2010 cited in Jiajie, 2012.

Well E-BD 1 has tapped into the CTLZ region of the BBF system resulting in an extensively sand rich reservoir. This clean sand is attributed to the positioning of the well, which has intersected sands in the axial region of the larger basin floor fan system. This elongated lobe has been deposited at the base of the channelized slope, on the basin floor which is less confined than the channelized region of the BFF.

Figure 32 above outlines a perpendicular transect through the channel which depicts the confining nature of the depositional environment. The horizons interpreted as the top and base reservoir surfaces are thicker in the axis of the channel and pinch out towards the channel banks and outer medial fringes of the elongated lobe structure. As seismic resolution at depth of 2000m is roughly 20metres, the internal heterogeneity of individual lobe structures cannot be seen. The overall lobe complex can however be identified by the thickening of horizons in the lobe axis which host more amalgamated lobes element than the adjacent lobe fringes.
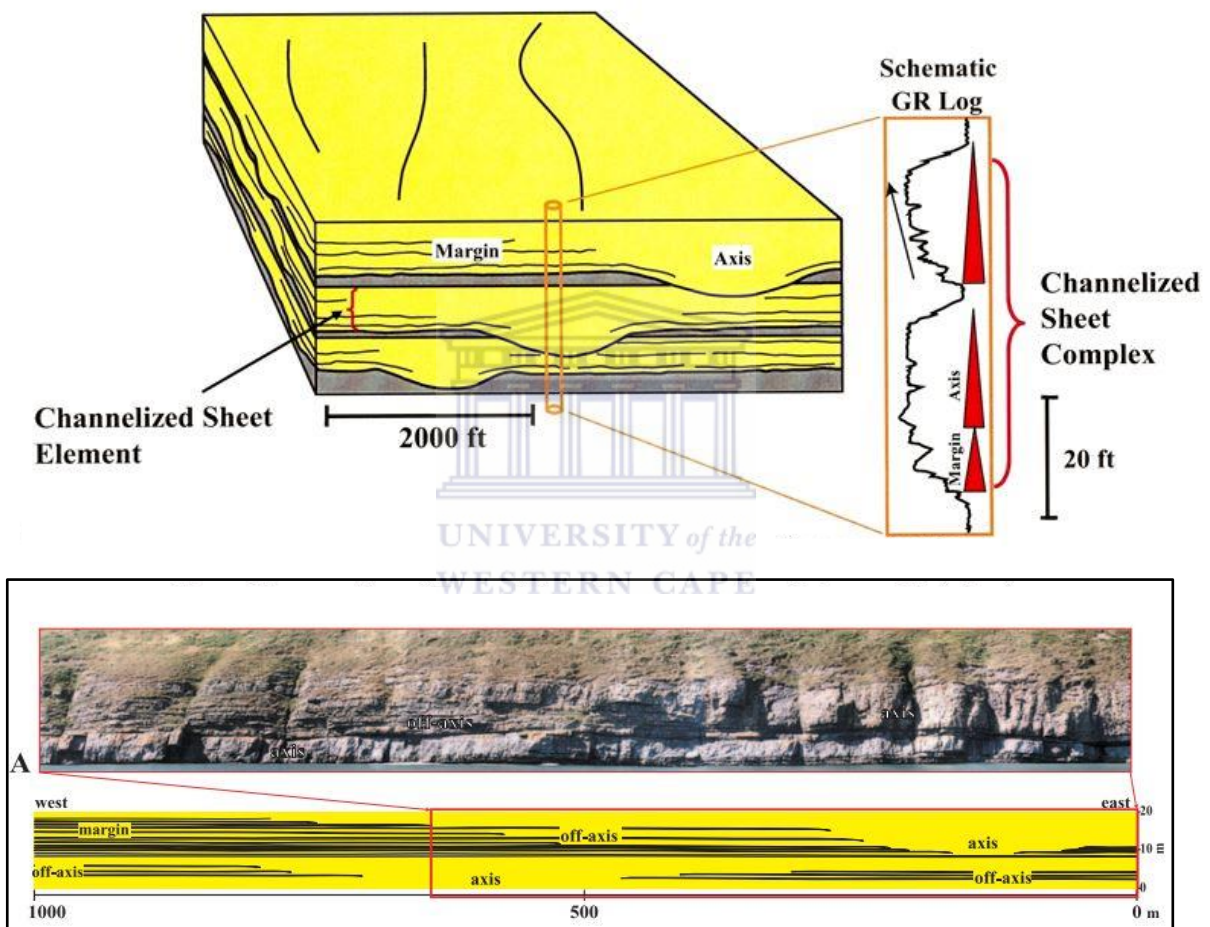

Figure 33. A diagram and photograph of the Channel Lobe Transition zone (CLTZ) of the Basin Floor Fan system (BFF). This region marks the transition from proximal (confined) to medial (unconfined) fan.

The axial region of the channelized sand sheet is associated with amalgamated thick bedded sheets as well as depositional channels. This axial region exhibits a prominent thick with the drapping of horizons towards the banks of the channel and the outer fringes. Outer fringes are dominated by pulses of overbank sand which are in possible hydraulic communication with the main channelized sands. The off axis region of the channelized lobe predominantly constitutes sheet sands which are inter-bedded with silt and discontinuous shale horizons.

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The axial portion of the channelized sheet predominantly hosts constructive features with minor erosional confinement at the base of some sand pulses do arise. This erosional confinement constitutes the axis of the channel which host amalgamated thick sand sheet deposits, while the off axis region host channelized thin bedded sheet sands.

The CLTZ region of the BFF system constitutes branching sand-filled shallow channels which are generally < 2 m deep. There is however cases where the axial portion of channelized sheets exceed 2m in depth, which is the case with the CTLZ region tapped by E-BD1.

The red pic seismic horizon which represents the base of the channel exhibits a seismic response of laterally switching and stacking of the axial portion of the amalgamated channelized sheets. The axis of the sheet constitutes brighter and thicker sections of seismic horizons which pinch out rapidly towards the fringes of the axial region. The fringes most likely constitute thin bedded sheets sands which are not sufficiently captured due to seismic resolution.

This transitional environment commonly hosts channel levees which are generally less than a meter in high, if present at all. Theses levees are associated with sandy overbanks deposited in the inter-channel area.

With respect to the perpendicular transect through the channel outlined in figure…. Above, a number of reservoir characteristics can be observed. Seismic responses outline characteristics away from the well bore, however with poor resolution. Seismic responses correlated with gamma ray log responses at the well bore depict spatial reservoir characteristics which shed light on reservoir behaviour near and far from the well bore.

The medial fan of this study which is tapped by well E-BD1, exhibits a reservoir with an extensively high aspect ratio (width vs thickness). The reservoir zone constitutes an uninterrupted 30m thick sand rich zone. Seismic responses away from the well bore indicate that this sand rich reservoir zone is extensively laterally continuous. There is however a rapid change in sand rich architectural elements the axis of the channelsed sheets elements to the marginal off axis sand deposits.

Analogue studies of the medial fan region exhibit a moderate net to gross of approximately 65-80% (Wickens, 2014). Well E-BD 1 has intersected the axis of the channelized sheet complex thus the net to gross of the reservoir zone is above 90%. No shale sediment exist in the reservoir zone, however minor silt sheets exist between amalgamated thick bedded sheet sands.

The reservoir zone hosts no erosive contact and it is bounded above and below by prominent massive shale beds which are uninterrupted by pulses of sandy sediments. The reservoir exhibits moderate vertical continuity, with minor silty breaks between amalgamated sheets which add to the internal heterogeneity of the reservoir zone. The reservoir has high lateral continuity (Wickens, 2014). This lateral continuity can be observed as top and base reservoir horizons which constitute. brightness and thickness changes. These geophysical changes are due to internal heterogeneity that arises when architectural elements progress from the axis to margins of the channelized sheet sands.

Grain-size analyses and point counting reveals that the CLTZ (tapped by well E-BD1) and lobe sandstones (tapped by E-CE1) are generally better sorted and finer-grained than channel sandstones. This change in the quality of reservoir sandstone is the result of different combinations of depositional processes which operate in the locally confined (channel) domain and the unconfined (CLTZ and lobe) domain (Gordon, 2014).

These depositional processes produce various architectural elements which contribute to the reservoirs internal heterogeneity. As in seen in figure… below, well E-BD1's reservoir constitutes a combination of architectural elements which include, amalgamated thick bedded sand sheets and depositional channels. These depositional processes have taken place in the base of slope region which constitutes a relatively steep confined environment. This relatively confined region of the Basin floor has been the depo-centre for the 30m thick sand succession.
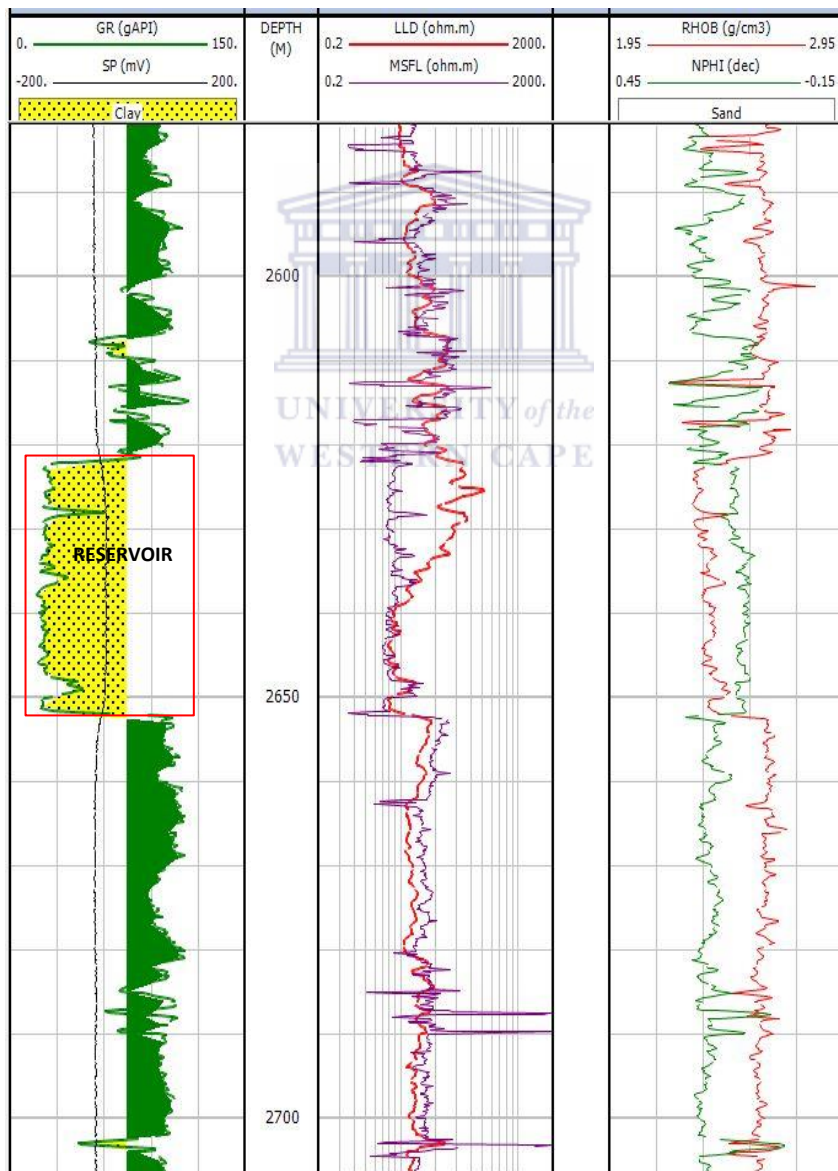

Figure 34. Wireline Log analysis of well E-BD 1 using the Interactive Petrophysics software. The reservoir zone constitutes a massive amalgamated lobe and channel sand complex (30m thick), deposited at the base of the continental slope.

4.6.3 DISTAL FAN REGION

Well E-CE 1 has tapped into a sand rich zone which constitutes the lobe region of the sub-marine BFF system. The extensively unconfined region is situated on the basin floor, approximate 3km away from the channelized sheet sand tapped by the up-dip well E-BD1.

Gamma ray logging of well E-BD1's reservoir zone exhibits cylindrical log responses. These GR patterns are interpreted as clean sheet sands which constitute laterally extensive lobe. The lobe structures constitute amalgamated thick and thin bedded sheet sands. There is an extensive feeder channel system associated with the sheet sands. These feeder channels are observed on seismic to reach the edge of the amalgamated lobe.

The lobes comprise of amalgamated thin and thick bedded sheet sands and depositional feeder channels which constitute a 50 metre thick reservoir interval. The reservoir hosts a sharp base which is not erosive. A rapid change in lithology is the result of a rapid sand pulse influx into the basin, which overlies hemi-pelagic muds. The influx of clean sand is the result of turbidity flows where sand flowed of the rise which overlies the Agulhus Bank. The onset of sand influx is associated with the low stand system tract that originates due to sea level transgression. The reservoir zone is bounded above and below by prominent hemi-pelagic shale successions which indicate sea level fluctuated considerably. Low sea level resulted in the deposition of clean BFF system sands which are eroded off the continental shelf. A subsequent rise in sea level resulted in the deposition of sealing hemi-pelagic muds which also constitute a possible good quality source rock.

With respect to seismic interpretation, the geometry of the lobe elements are relatively unique compared to analogue studies. Architectural elements which construct the amalgamated lobes are elongated instead of cylindrical. This is due to the steep topography of the bredasdorp basin at the time of deposition. This steep topography is also the cause of considerably deep feeder channels reaching to the edge of the amalgamated lobes. These feeder channels observed on seismic are quite large due to the fact that they are visible with respect to seismic resolution. The feeder channels are also prominent because the seismic cube constitutes the up-dip portion of the elongated lobe complex tapped by well E-CE 1. Feeder channels are broad. They exhibit a laterally switching and stacking depositional pattern.

Seismic interpretation has consulted well log responses thus the 50metre reservoir zone is observed on seismic as extensively laterally continuous lobes. The top reservoir is represented by two horizons (blue pick) which constitute gas charged lobe elements. These horizons represent two amalgamated lobes which are laterally continuous; however they do pinch out towards the fringes of the lobe complex. The well has intersect perfectly in the axis of the lobe where amalgamated thick bedded sheets and depositional feeder channel sand dominate. The reservoir is thus entirely fabricated of clean sand which exhibit cylindrical GR log responses.

The sheet complex tapped by well E-BD1 constitutes broad layered sand sheets which have a highly amalgamated axis (Wickens, 2014). This amalgamated axis has a relatively basic internal heterogeneity which is observed in well E-CE1. Seismic indicates that the reservoirs internal heterogeneity becomes more complex away toward the marginal of axis regions of the lobe.

The lobe which constitutes the lower portion of the reservoir has a thickness of 30m. This lower lobe can be clearly observed on seismic as a bright blue horizon (top of lobe) and a bright red horizon (base reservoir). This lobe is however not extensively continuous. The bright thick horizons pinch out rapidly as one moves away from the axis of the lobe. The axis is thus interpreted to be highly amalgamated thick bedded sheet sands and amalgamated depositional feeder channels. The off axis regions of this lower lobe are interpreted to be amalgamated thin bedded sheet sand sands. These sediments are represented by discontinuous seismic horizons which are less parallel than the amalgamated axis of the lobe complex.
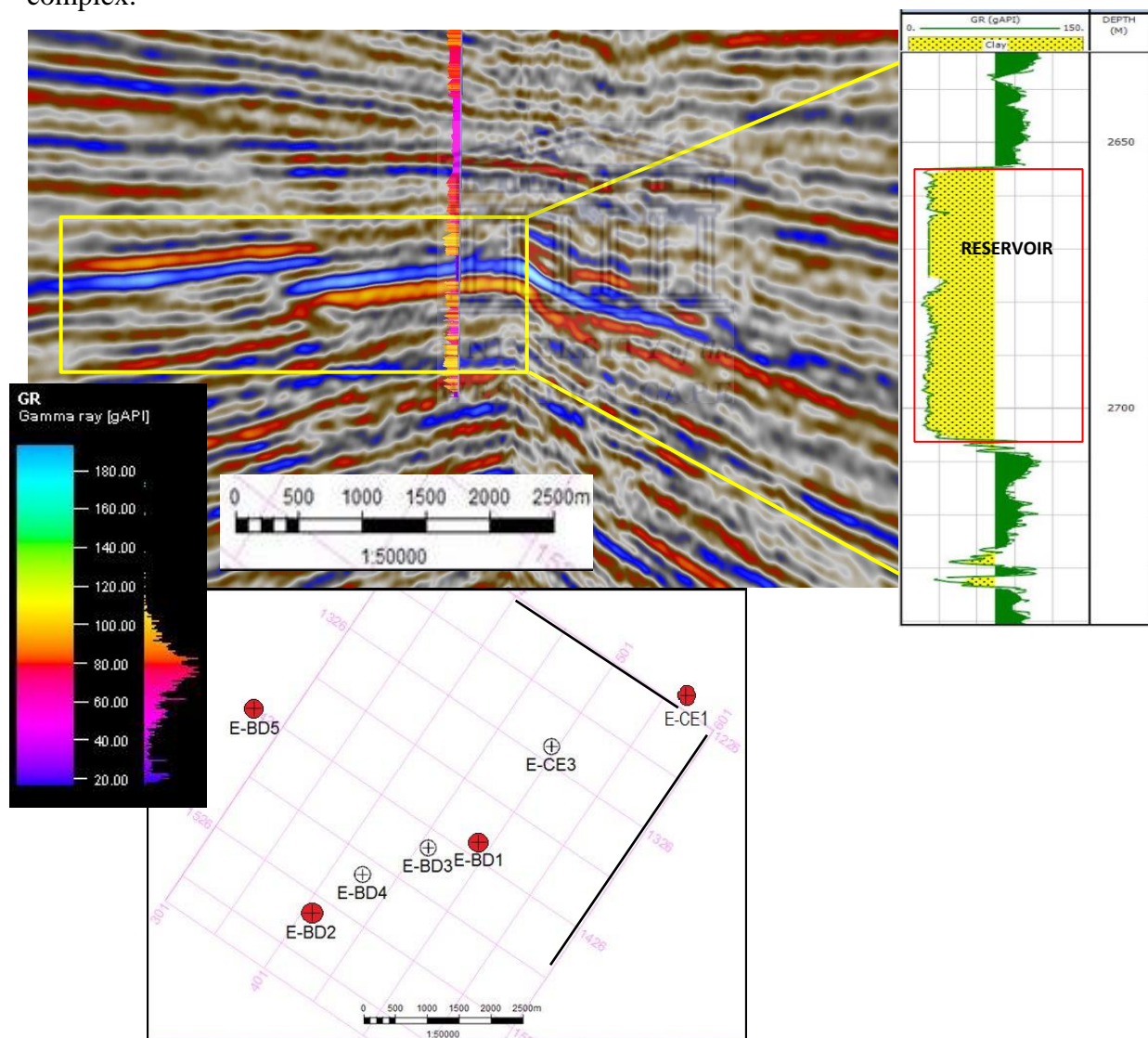

Figure 35. Well E-CE1 has intersected an amalgamated lobe complex (50m thick), deposited in the deeper waters on the basin floor. Amalgamated sheet sands and feeder channels are within the confines of seismic resolution thus these channel bodies are at least 15-20m thick. Unconfined massive lobe elements are spread out on the basin floor. These lobes elements are laterally continuous. Individual lobe elements are stacked together to form intricate lobe and feeder channel complex's resulting in laterally continuous zones of very good reservoir sand (4-5km wide).

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The upper portion of the reservoir zone constitutes two amalgamated lobes which are 12 and 8 metres thick. These two lobes are represented by extensively continuous horizons. These upper lobes are far more continuous than the lower lobes. They are thus interpreted as less confined architectural elements than the lower lobe, however they exhibit the same clean sand represented by cylindrical log responses. The horizons which correlate with the upper lobes are however less parallel and dimmer which could be associated with amalgamated beds which are slightly thinner than the lower reservoir.
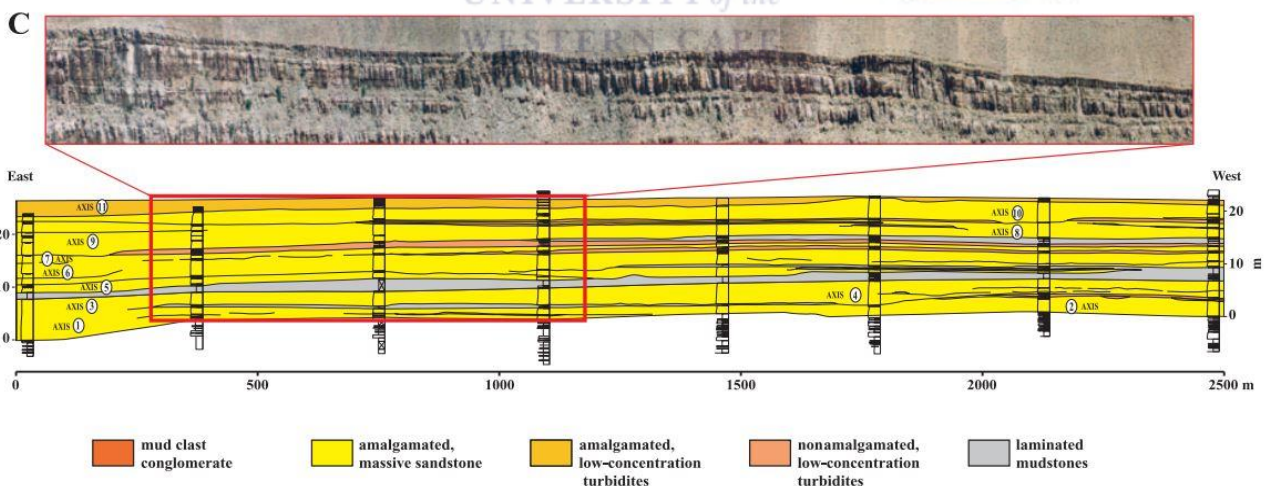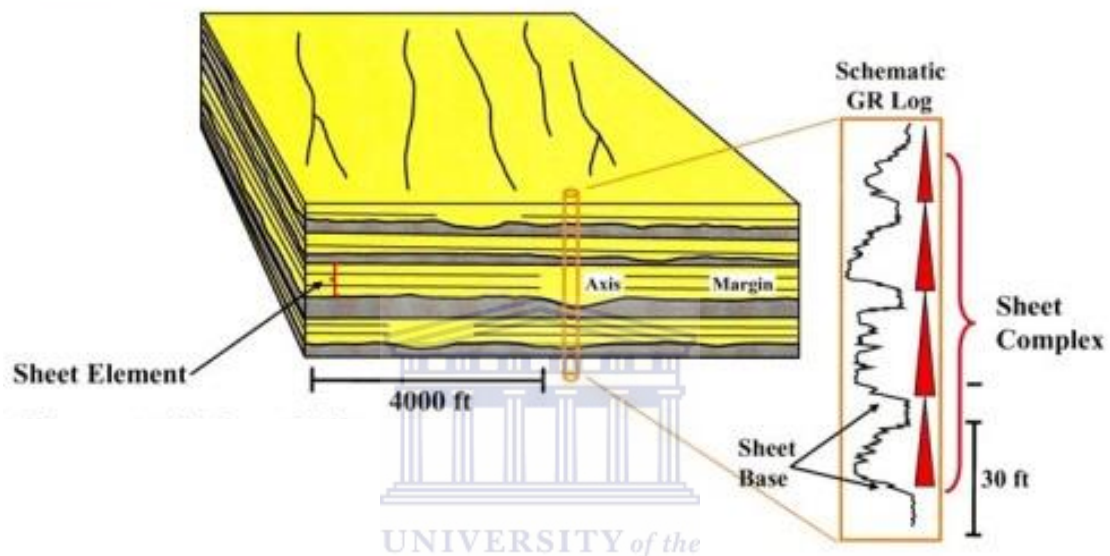

Figure 36. A diagram and photograph of the sheet like lobe elements and lobe complex's with respect to on axis and off axis sand deposits. Theses sheet are deposited on the unconfined basin floor.

The 12m thick lobe structure has a perfectly vertically continuous log response which could be attributed to an amalgamated massive sandstone deposited in a single pulse of sand influx onto the basin floor. This portion of the reservoir could also be a depositional feeder channel where its geometry is not entirely captured away from the well bore due to seismic resolution.

The Elongate lobes are generally composed of interbedded sand and mud. Well E-CE1 has however tapped into the highly amalgamated axis of the lobe, thus no mud lenses are visible

in the reservoir zone found in the well. These mud rich sediments arise as one moves further away from the axis of the lobe. Thus the reservoir net to gross of a single well varies considerably depending on where the well is placed in the larger lobe complex.

The axis is the best position to position a production well because it hosts the best quality clean sands. Its vertical and horizontal permeability is great due to the amalgamation of massive sandstone lobes. The axis is also the best place to link and tap into all extensively laterally continuous lobes with a single well. If good to moderate permeability is as extensive as the lobe complex itself the well will be able to drain a region as far as the off axis fringes of the lobes.

A number of shallow relic channels extend to near limit of fan, however observation is limited due to the extent of the seismic cube which doesn't expose the entire distal edge of the lobe complex. These channels flow this far onto the basin floor regardless of the fact that this depositional environment constitutes very low relief and gentle gradient. The depositional feeder channels and lobe elements do however exhibit a lateral switching and stacking pattern which is due to the structural control of lobe elements which were deposited prior to the subsequent lobes. This is an inherent structural control of the lobe complex environment. The lateral switching and stacking of lobe element can be observed in figure… below. The lower lobe tapped by well E-CE1 exhibits far greater stacking complexity of than the lobe which constitutes the upper portion of the reservoir.
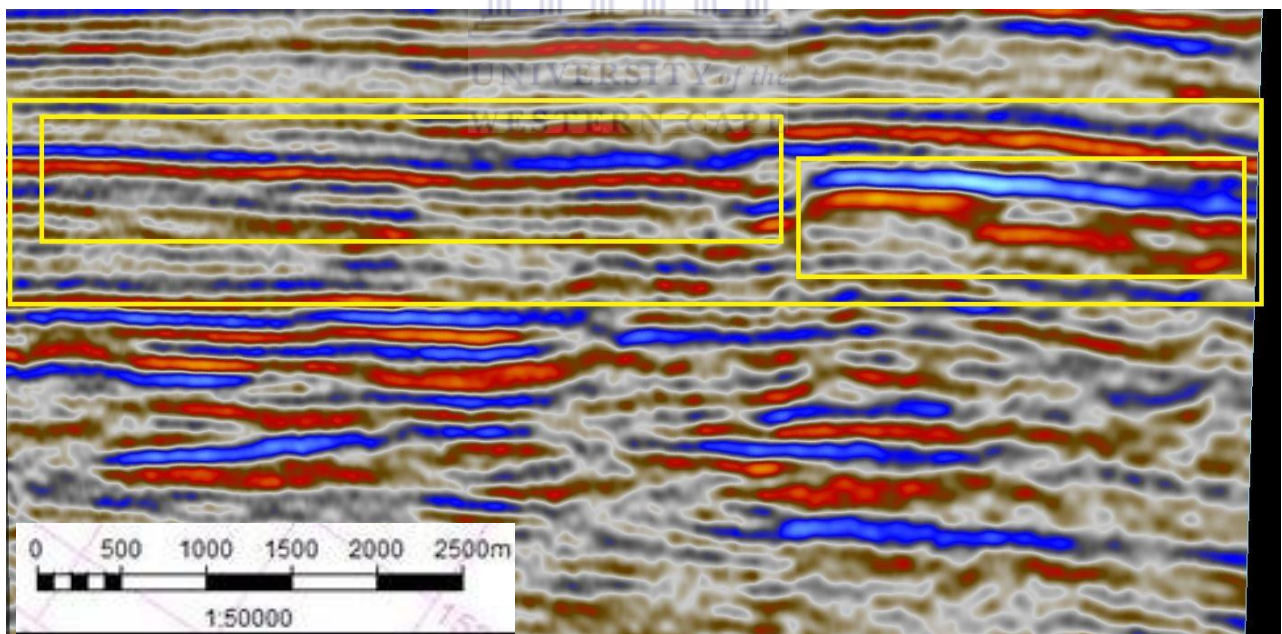

figure 37. Inline 1236 represents amalgamated laterally switching and stacking sandstone lobe elements in the axis of the lobe complex. These sand rich gas charged lobe elements are situated in the axis of channel complex (right yellow block), with flanking finer grained sheet sands, laminated shale and siltstone (yellow block on the left) found in the off axis region of the complex.

The reservoir zone as an entire amalgamated lobe complex has an extensively high aspect ratio. The lobe complex is more than 5km wide however the complex is no thicker than 50m at its axis.

Sub-parallel horizons are attributed to the thin bedded off axis portion of the lobe complex where the net to gross is considerably less than the highly amalgamated axis of the lobe complex. With respect to analogue studies the lobe complex has a moderate to good net to gross of 40-60%. The high aspect ratio of the lobe complex severely impacts the reservoirs vertical permeability, however horizontal permeability is quite good to the extensive lateral continuity of good quality sheet sands.

The highly amalgamated axis of the lobe has very good vertical permeability as well as horizontal permeability, to an extent that the lobe sand may be in hydraulic communication with channelized sheet sands situated up-dip.
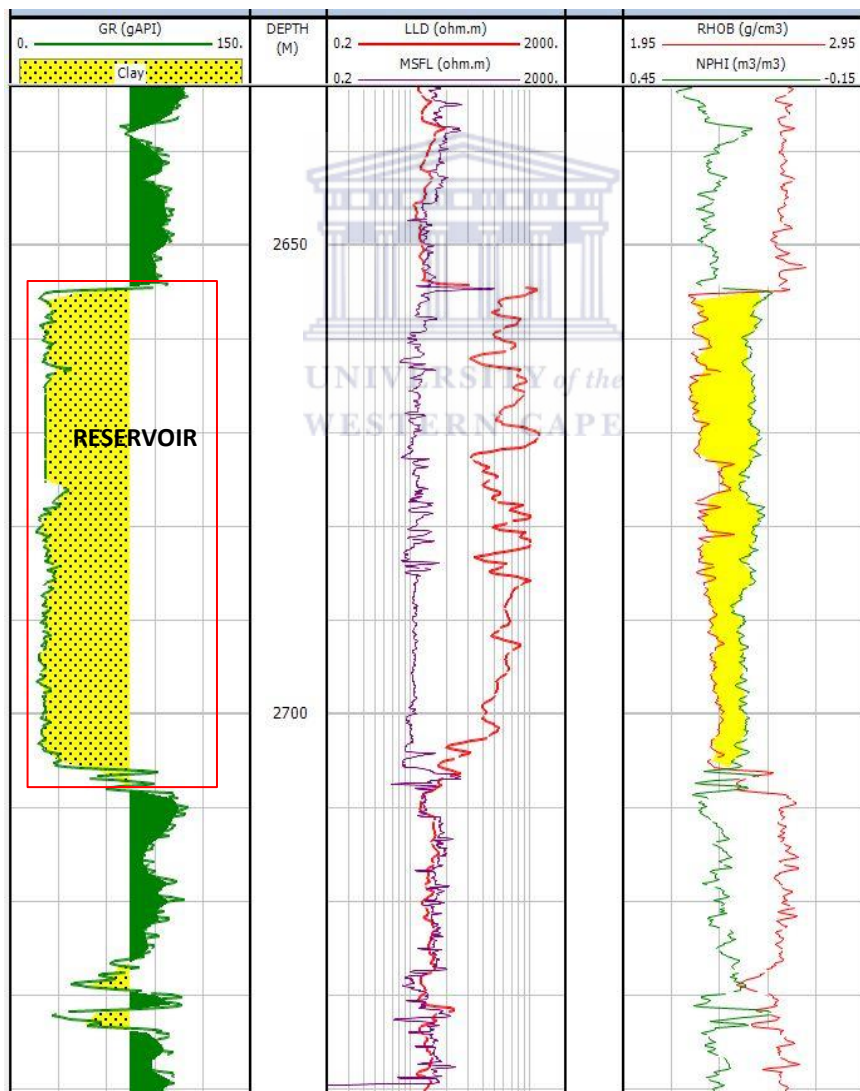

Figure 38. Wireline log analysis of well E-CE1 using the Interactive petrophysics software. The wells reservoir zone constitutes amalgamated laterally switching and stacking sandstone lobe elements in the axis of the lobe complex. The amalgamated, massive pure sand lobes have a thickness of 50m.

4.7 TOP SEAL ARCHITECTURE

The T13PW3 well top represents a perfect seal horizon. Moving from the reservoir zone upward, this top seal horizon represents the start of massive shale succession which seals the reservoir. With respect to figure 39 below this sealing horizon (red pick) is represented by the green line (seismic interpretation). This seismic horizon is extensively continuous and can be correlated in all the wells investigated in this study. This prominent shale horizon seals the up-dip proximal channelized reservoirs, the CLTZ reservoirs and the distal lobe reservoir of the BFF system.

The down-dip lobe reservoir tapped by well E-CE1 is not genetically related to the channelized sheet reservoir and proximal channel reservoir tapped by wells E-BD1, E-BD2 and E-BD5 situated up dip. These two individual BFF systems are probably not in hydraulic communication as the upper E-BD reservoir overrides the lower E-CE1 reservoir. This is observed by reservoir representing seismic horizons which pinch out.

This sealing shale does however seal both E-BD and E-CE reservoirs. This seal is equally think and prominent in all the wells. It is especially thick in well E-BD1 thus this well is used to illustrate this seal in figure 39. The seal does not comprise one massive 200m shale succession, instead it constitute layered sheet shales which are extensively laterally continuous. These layered sheet shales are however individually 5 to 10m thick. They can thus be characterised as massive layered shales which are hemi-pelagic in nature.

This type of hemi-pelagic shales also underlie the reservoir zone, however these underling shales are far more massive in nature. This indicates that the succession progressively becomes more thinly bedded after the sand pulse which constitutes the reservoir zone. This could be attributed to greater fluctuation in sea level rise and sediment influx into the basin.
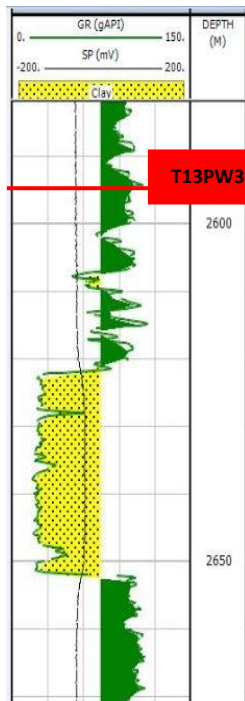
Figure 39. Top seal depicted in well E-BD 1

The T13PW3 horizon constitutes the mapped surface in figure 39 below. This top seal can be observed to drape over the axis of the BFF. The axis of the BFF system constitutes a sand rich zone which forms a prominent thick. This sand rick thick can be observed along the axis all the way from the up-dip channelized region to the down-dip lobe complex. The seal is also draped over the high which overlies the Agulhus Arch. This extensive lateral continuity of this hemi-pelagic shale can be attributed to a rapid rise in sea level or an increase in accommodation space associated with other factors such as tectonic activity and thermal sagging. The increase in accommodation space is also due to sediment load which has a great impact on post rift basin geometry and sediment influx.
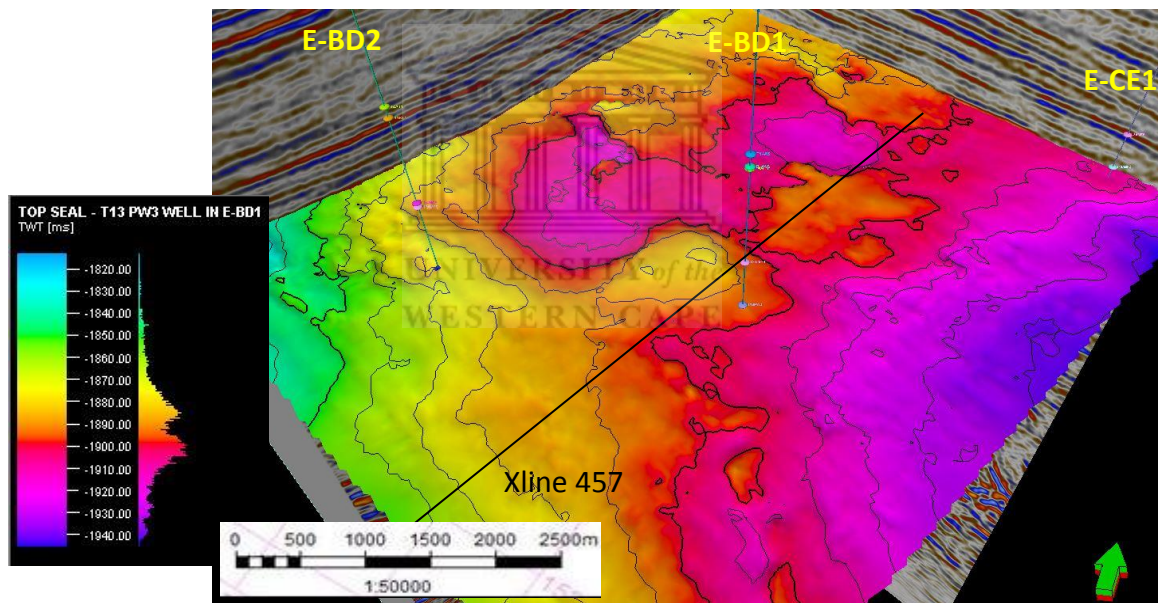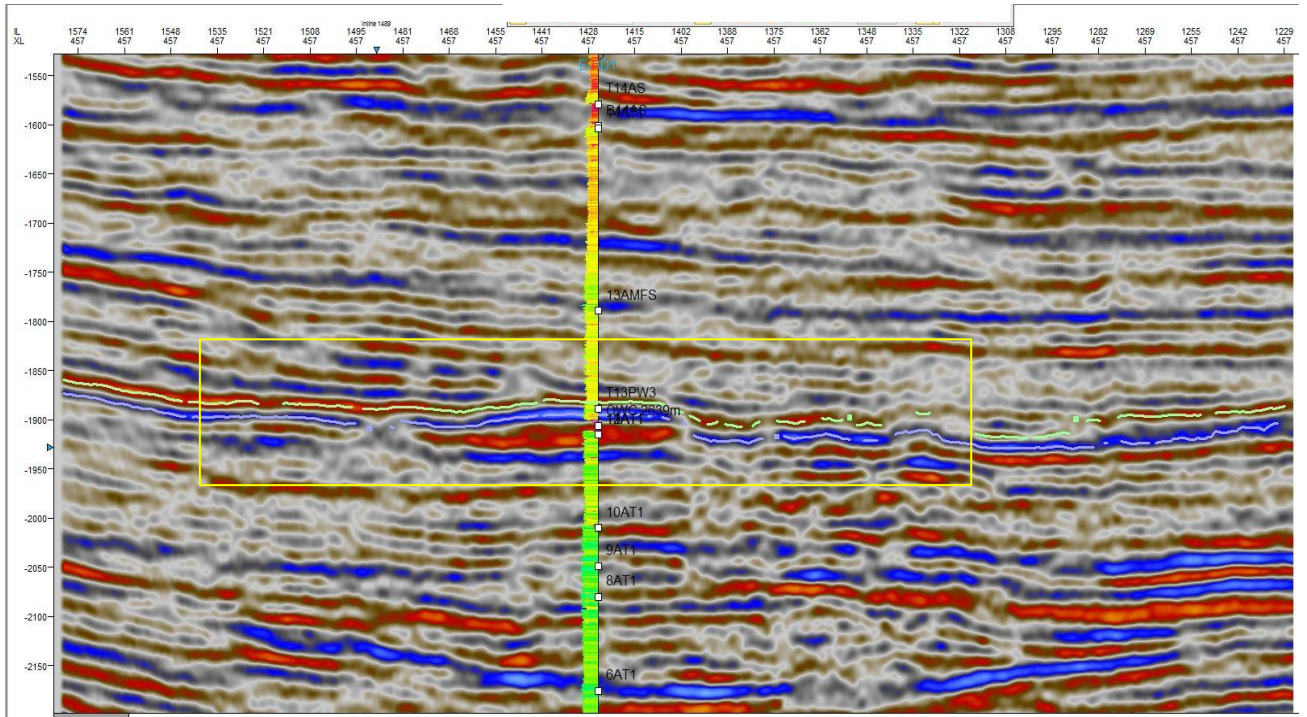
Figure 40. Xline 457 serves as a cross section that cuts parallel to the paleo-current flow direction of the channel. The mapped surface represents the top seal of the reservoir zone which is draped over the sand thick found in the on-axis sections of the BFF system. The seal is draped over the confined channel complex and base of slope sand package. It is also draped over the unconfined lobe complex in the down dip basin floor regions.

CHAPTER 5: RESEARCH CONCLUSION AND RECOMMENDATION

The Sable Fields reservoir has been deposited during the early post rift (Aptian) sedimentary fill of the Bredasdorp Basin. This Cretaceous reservoir zone overlies the 13AT1 early-drift unconformity. 3-D seismic mapping and surface generation, of Early-Drift sedimentation (figure 19. below) indicate a depo-centre towards the North Eastern section of the seismic cube. Sediment flows from the west as it is eroded off the shelf. This rise which overlies the Agulhus Arch constitutes high ground where the early-drift submarine channels transport sediment via turbidite flows, into the deeper waters depo-centre.

The depo-centre hosts a prominent thick of sediment, represented by parallel and sub-parallel horizons. These early drift sediments constitute reservoir sandstones. These deep water reservoir sands were deposited by turbidite flows during Aptian and Albian low-stands. These sand rich complexes host several small oil and gas fields with development potential.

3-D Seismic data from field analogues such as basin-floor settings offshore Indonesia, Nigeria, the Gulf of Mexico and outcrop analogues such as the the Tankwa Karoo outcrop reveal the extensive presence of gravity-flow depositional elements. Each depositional element constitutes a unique morphology thus they display different seismic expression. These depositional elements constitute a unique contribution to reservoir architecture. This contribution to reservoir architecture is a function of the interaction between three components namely:

(i) sedimentary process;
(ii) sea-floor morphology;
(iii) and sediment grain-size distribution

The wells investigated, namely: E-BD5, E-BD2, E-BD2, E-CE1; have tapped into these deep water sediments which are mainly subdivided into three depositional environments, namely:

i.   Channel complex reservoir sands that are back filled and into the large confined channel environment. E-BD5 and E-BD2.
ii. Basin Floor Channel (BFC) –E-BD1.
iii. Basin Floor Fan (BFF) complex E-CE1.

i.   E-BD5 and E-BD2

These wells have tapped into amalgamated depositional channel sands with a number of erosive channels. The channels meander in a larger confined environment in the lower regions of the continental slope, before the channel takes an 80° bend and flows onto the basin floor. The individual channels generally meanders down-dip, however this large channel systems makes a rapid change in paleo-current direction due to basin floor topography.

The amalgamated channels sands are deposited by laterally switching and stacking channel. The highly confined channels sands are deposited amongst massive channel fill sands that are

deposited in broader less confined channels. Sinuosity of these meandering channels ranges from moderate to high.

Turbidity-flows deposit fine grained good sands in meandering leveed channels. These sands constitute excellent lateral continuity and good vertical continuity which results in good quality reservoirs situated in the up-dip regions of the field. This channelized reservoir is at least 2km wide and 6km long. The stacked channel complex tapped by two wells, constitute a gross thickness of 76.2m (68.5m Net sand) in well E-BD5., and a gross thickness 25m (23m Net sand) in well E-BD2. Channel sands in well E-BD5 have an average porosity of 15% while the average porosity of channel sands in well E-BD2 (further down-dip) is 17%.

This channel fill constitutes a high net to gross with little to no lateral facies variations. This environment is dominated by amalgamated massive sands (on-axis) that are thinner bedded towards the banks of the channels (off-axis). A high degree of channel amalgamation has been interpreted in both wells, and extrapolated away from the wellbore by correlating top and base reservoir seismic horizons. The vertical and lateral continuity of the reservoir is generally excellent due to this high degree of channel amalgamation.

Channel-overbank sediments are associated with high-sinuosity channel elements. These sediments have been deposited in the proximal overbank levee setting. They are especially associated with the outer channel bends. These channel overbank sediments are found in the Sable Field over the outer bank of the major bend in the channel.

This up-dip channelised region of the Basin Floor Fan system results in high amplitude reflections. This common characteristic suggests that these features are sand filled depositional channels which are hydrocarbon charged. Bright sub-parallel horizons indicate confined channel architectural elements that are amalgamated and encased in hemipelagic muds (extrapolated from wells). These individual channel elements are at least 15-20m thick with respect to seismic resolution.

ii.   E-BD1

The well has tapped in relatively confined sands that are massive in nature and considerably thick. These amalagamated thick and thin bedded sheet sands have been deposited at the base of slope region.

The amalgamated sheet sand complex is entirely encased in hemipelagic mud. The reservoir sands tapped by this well are interpreted to be deposited in the Channel Lobe Transition Zone (CLTZ). This region is thus dominated by both channel complex and lobe complex elements. The reservoir sands are interpreted to have a transitional depositional style (generally channelized sheets). The reservoir constitutes a number of amalgamated elements such as; amalgamated thick and thin bedded sheet sands, broad thin amalgamated lobe elements, layered thick bedded sand sheets and deep broad depositional channels.

The amalgamated thick bedded sheet like lobes are found in the axis of the sand rich complex, where deep depositional feeder channels are abundant. The off-axis regions of the base of slope sand rich complex, is dominated by amalgamated thin bedded sand sheets. These deposited are associated with much shallower depositional feeder channel sands. The channel-margin levee constitutes a thickness which decreases systematically down-system.

The frontal splay and low-sinuosity distributary-channel complexes are found in the region where levee thickness is below seismic. The up-dip high-sinuosity channels feed the low-sinuosity distributary-channel complexes situated further down-dip in the base-of slope region. These low sinuosity distributary-channels and elongate lobe elements are expressed as lobate amalgamated sheets of sand which is up to 2-3km wide and 5km long and 30m thick (29.7m Net sand) at the well bore. These amalgamated thick bedded sand sheets, thin bedded sands and depositional channels constitute a reservoir zone which has an average porosity of 16.4%.

iii.	**E-CE1**

Well E-CE1 has tapped into a Basin Floor Fan complex that is built primarily with lobe elements. The Bredasdorp Basin has a steep topography thus these lobe elements and the larger lobe complex is elongated in shape.

Analogues of deep water turbidite sand rich deposits indicate that there stacking pattern of lobe and channel systems has an inherent structural confining ability. For example, according to the architectural framework of these deposits, the channelized portion of lobe will be structurally confined by its two neighbouring lobes. The Lobe complex of the Sable Field has also been affected by structurally confining factors such as basin floor topography and neighbouring lobe complexes.

The well has intersected a 50m thick reservoir (50m Net sand) which constitutes amalgamated thick bedded lobes which are massive in nature. The Axis of the lobe complex constitutes thick massive lobe elements. This laterally continuous hydrocarbon charged lobe elements result in bright seismic reflections where shale overlies reservoir sands. The reservoir zone has an average porosity of 14%.

The reservoir zone as an entire amalgamated lobe complex has an extensively high aspect ratio. The lobe complex is more than 5km wide however the complex is no thicker than 50m at its axis. Sub-parallel horizons are attributed to the thin bedded off axis portion of the lobe complex where the net to gross is considerably less than the highly amalgamated axis of the lobe complex. With respect to analogue studies the lobe complex has a moderate to good net to gross of 40-60%. The high aspect ratio of the lobe complex severely impacts the reservoirs vertical permeability, however horizontal permeability is quite good to the extensive lateral continuity of good quality sheet sands.

The highly amalgamated axis of the lobe has very good vertical permeability as well as horizontal permeability, to an extent that the lobe sand may be in hydraulic communication with channelized sheet sands situated up-dip.

Debris-flow deposits are found towards the distal edge of the Basin Floor Fan system. They comprise low-sinuosity channel fill sands, narrow elongate lobes and sheets sands. These distal sediments are characterized seismically by contorted and chaotic reflection pattern which have low amplitudes. Shale and silt constitute most of the distal regions and off axis region of the lobe complex. These sand rich sediments are ultimately overlain and draped by condensed-section deposits. These condensed hemi-pelagic mud-rich deposits constitute the top seal.

These distal deposits are characterised by transparent and chaotic seismic reflections which suggest that these deposits are silt and mud-rich. The outer edges of the lobe complex tapped by well E-CE1, constitutes debris flow deposits.

This succession of deep water Basin Floor Fan sediments can be attributed to a cycle of relative sea-level change. These sea level changes are associated with events at the corresponding shelf edge. Low sea level results in shelf sand being eroded and transported by turbidite currents to the deep water basin floor region. The deposition of a deep-water sequence is generally initiated with the onset of a drop in relative sea-level which is subsequently followed by a rapid relative sea-level rise which results in the hemi-pelagic mud rich seal

The seal constitutes a prominent shale horizon T13PW3 (8-10m thick) which is drapped over the entire reservoir complex. This top seal is extrapolated from the well and correlated with seismic facies in order to study the lateral continuity and thicknesss variations of the top seal. This shale horizon is draped over the axial portion of the BFF system which constitutes a thick amalagamated channelized complex and amalgamated lobe complex.

Post rift deposits that over lie the Sable Fields reservoir, plays a major role in the maturation of the source rock shales which encase the sand rich complexes. Tertiary post-rift events have been significantly influenced by the uplift of Southern Africa. They also have significant implications for the subsequent removal of a substantial amount of sediments from the Bredasdorp Basin during the tertiary.

The total lateral extent of the Basin Floor Fan complex could not be studied. Future studies of the Sable Field could investigate a larger seismic cube. The seismic cube should include regions further up-dip in order to study the geometry of the reservoir on the continental slope. The cube should also include the basin-ward region of the BFF complex which could facilitate outlining the total lateral extent of the lobe complex deposited on the basin floor where sand are entirely encased in hemi-pelagic muds. This sand rich lobe complex pinches out onto the basin floor in a dominant volume of shale.

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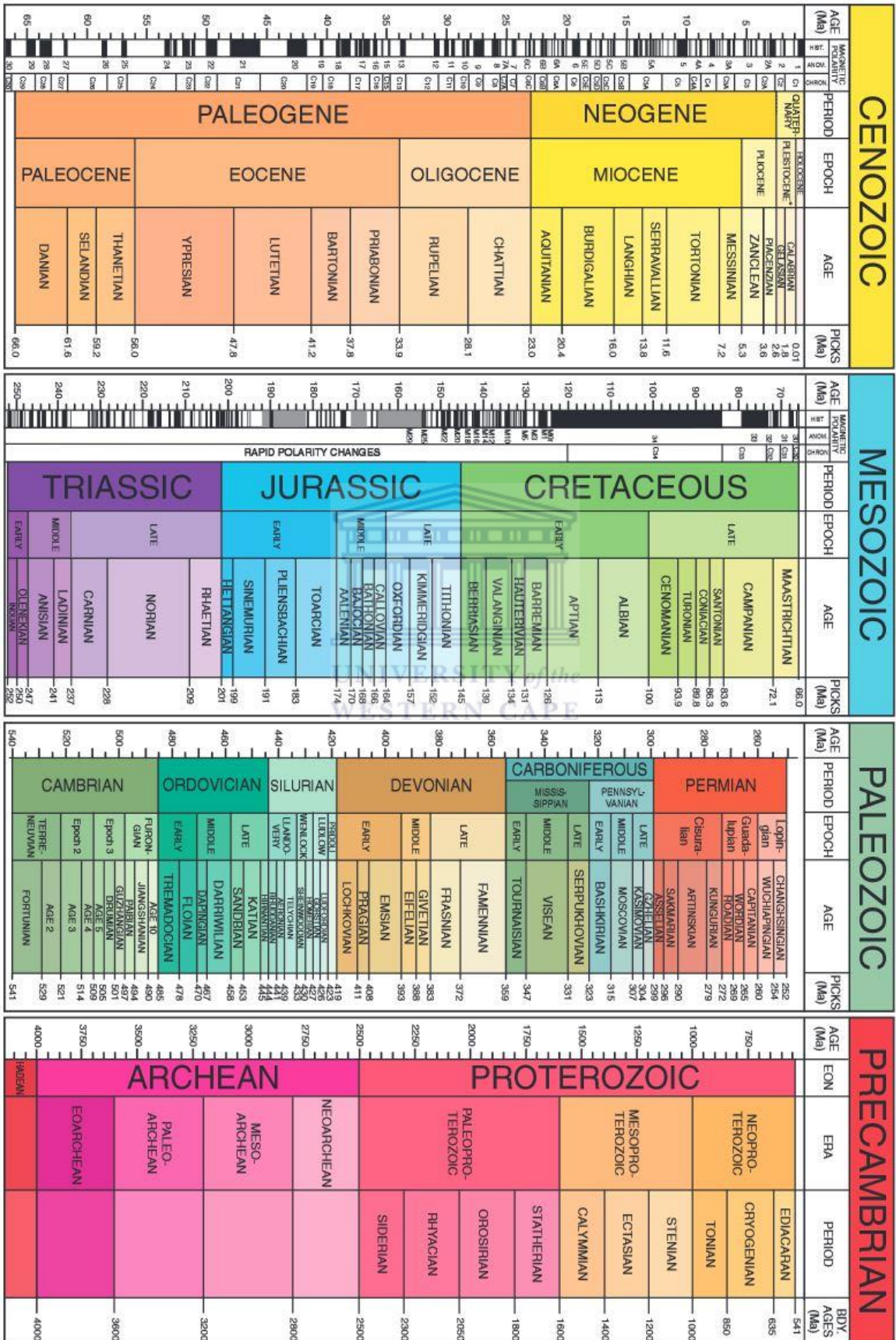
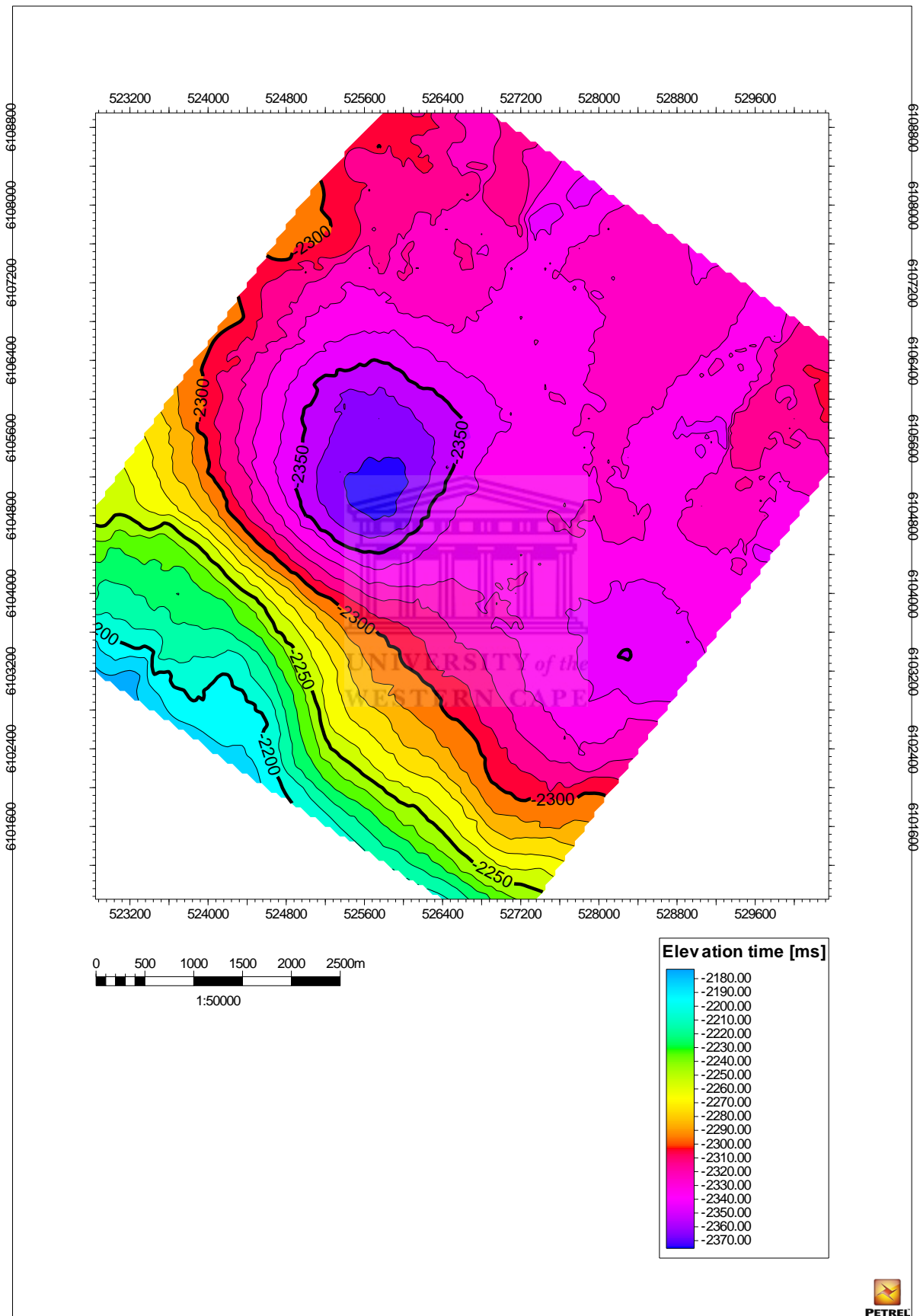# APPENDIX B: SYN RIFT HORIZON MAP
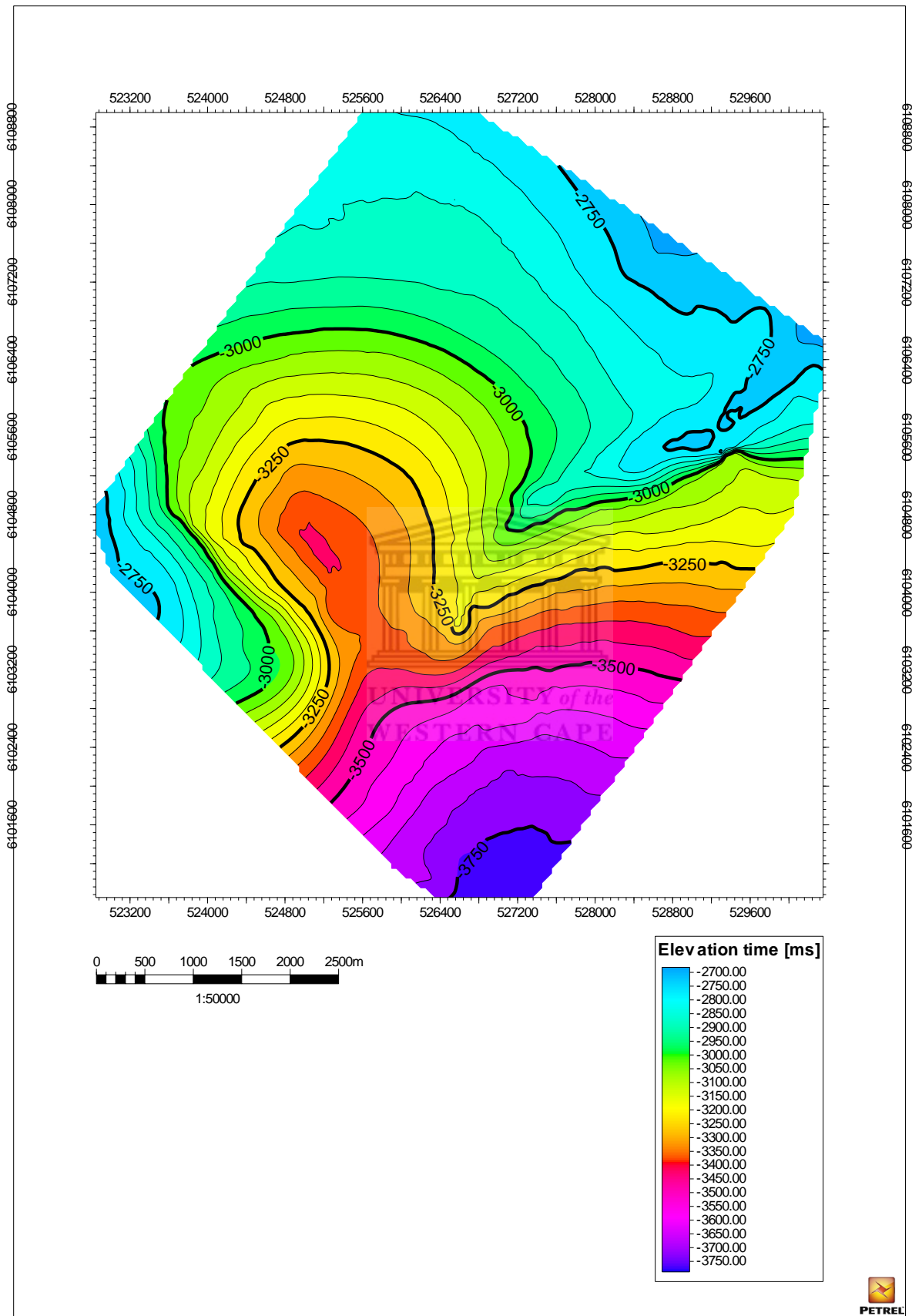
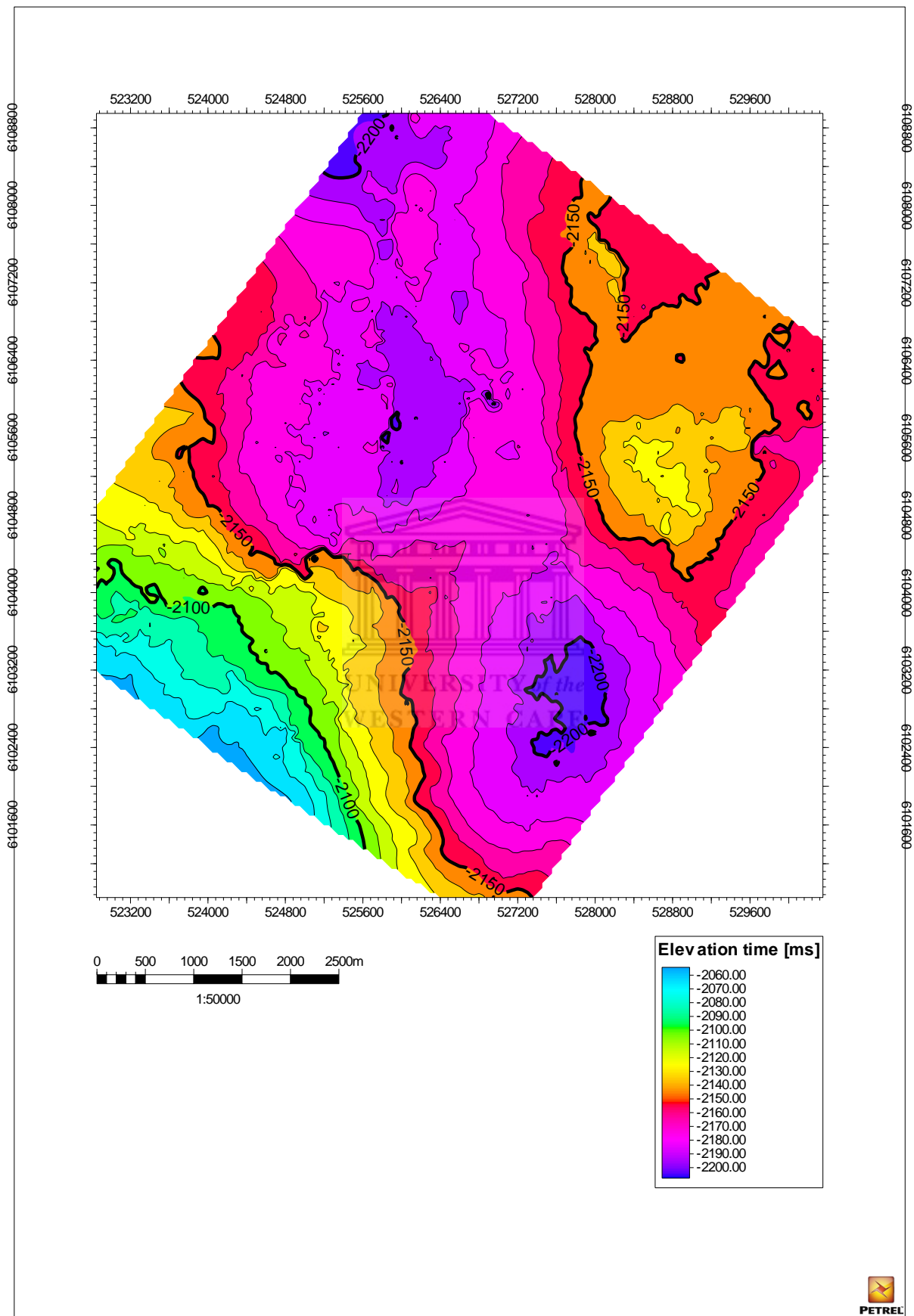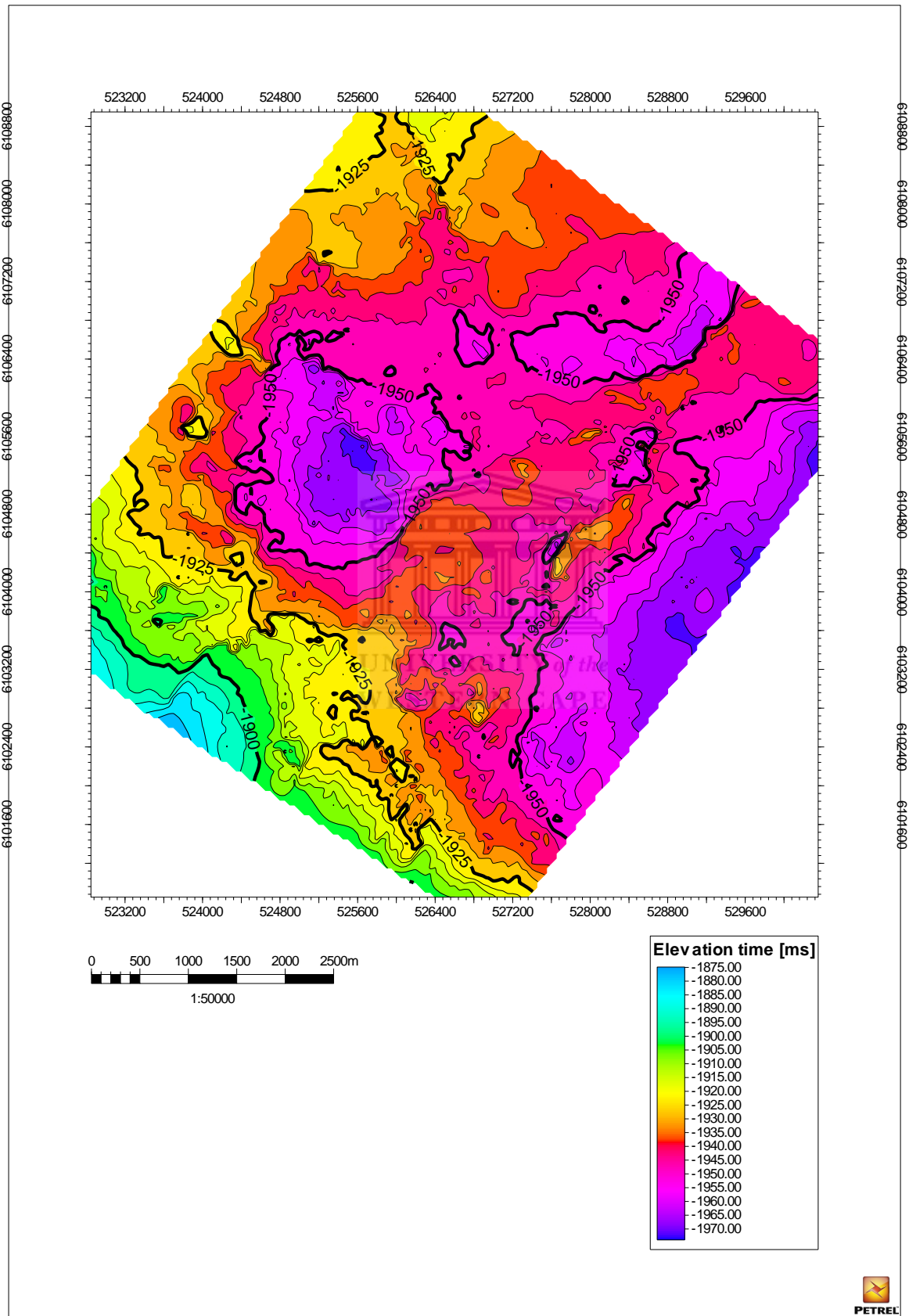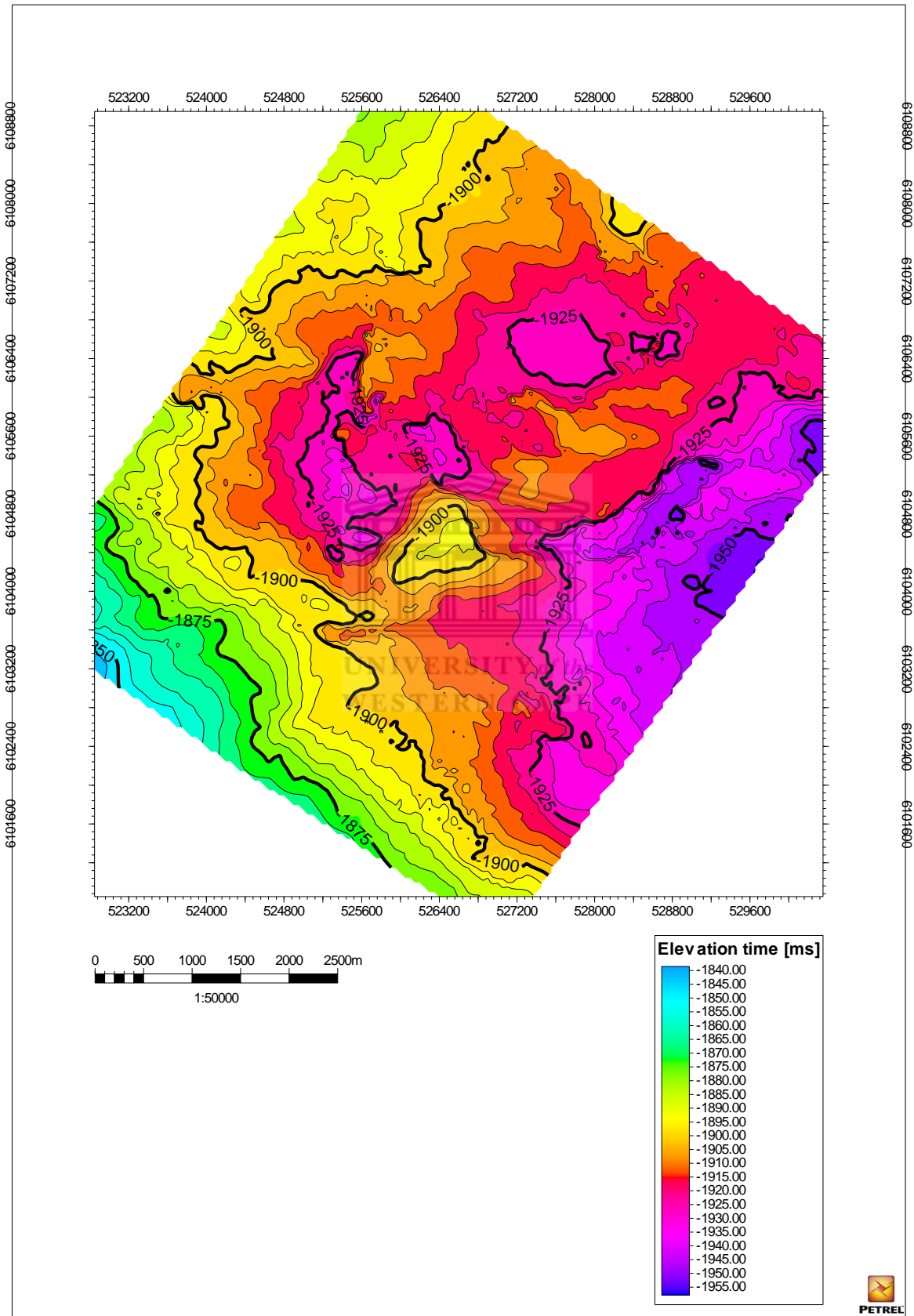## APPENDIX C: DRIFT UNCONFORMITY MAP

Figure 9. DRIFT UNCONFORMITY

APPENDIX D: TOP OF 6AT1 SAND MAP

APPENDIX E: BASE OF RESERVOIR MAP

APPENDIX F: TOP BASE OF SLOPE SAND PACKAGE MAP

APPENDIX G: TOP SEAL MAP