Foraminiferal Biostratigraphy and Depositional Environment of the Early Cretaceous Drilled Succession *in* Durban Basin, East Coast, South Africa

By

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Thesis submitted in fulfilment of the requirements
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Abstract

Durban Basin located on the eastern coast of South Africa has been a focus of interest for Petroleum Exploration for the last few decades. Only four exploratory wells have been drilled in this offshore basin without success. During the initial stage of its creation, the basin suffered major tectonic disturbance as evident from the presence extensional faults followed by intense igneous activities. This was followed by marine sedimentation in the late Mesozoic (late Jurassic-early Cretaceous). An attempt has been made in this work to understand the distribution of the rock in space and time for the early Cretaceous sediments considered most prospective for hydrocarbon exploration in Southern Africa. Temporal distribution of planktonic foraminifera helps in identification of the three early Cretaceous (Barremian to Albian) stages within the drilled intervals. Foraminiferal biostratigraphic studies integrated with sedimentology, log motif analysis and seismic data analysis helps to predict paleodepth and depositional environment during early Cretaceous in this research.

The integrated analysis reveals that during the Barremian-early Aptian stages graben filled sediments were deposited in a marine shelf in the northern part of the studied area (site Jc-D1) whereas, in the central and southern part finer clastics were deposited in middle slope (site Jc-B1 and Jc-C1). The thick claystone section and presence of minor limestone lenses and their benthic foraminifera assemblage in late Aptian-Albian stage in the northern area indicates possibility of submarine fan. Overlying succession dated between late Aptian to Albian and early part of Cenomanian interval in the three studied exploratory wells shows serrated log signatures. The dominant claystone lithology with intermittent siltstone/sandstone units and the benthic foraminifera indicates fluctuating distal marine slope environment with periodic shallowness in the entire area.

Keywords: Foraminifera, Durban Basin, South Africa, early Cretaceous, Well log motif, Seismic, Depositional environment

Declaration

I hereby declare that the research work entitled '**Foraminiferal Biostratigraphy and Depositional Environment of the Early Cretaceous Drilled Succession in Durban Basin, East Coast, South Africa**' is my own work, and it was not submitted before for any degree or examination in any other University. All data sources I have used or quoted have been indicated and acknowledged by means of complete references.

Joseph Mayala Nsingi 12 February, 2020

(Signature)

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Epayi ya Nzambe na pesi mapamboli: To God, I give glory.

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Chapter I

1. Introduction

1.1 Background

In the North-eastern part of South Africa there are two major sedimentary basins, southern extension of Mozambique Basin (on land and offshore basins) and Durban Basin (offshore). The basins came into existence after rifting and drifting followed by deformation episode of the East African margin during the initial breakup of Gondwana land (Broad et. al., 2012). The two sedimentary basins together cover an area of more than 31000km^2 and are comprised of north-south trending horst and graben structures. The Durban Basin is largely unexplored and only four wells were drilled so far and were not optimally positioned.

The rifting of the East African Margin controls the nature and distribution of the sedimentary fills in the two basins. In the Durban Basin the drift sediment overlies thick volcanoclastic rock of Jurassic age. Available seismic and well data show thick sediment fill ranging in age from early Cretaceous to Tertiary. The source rock in the early Cretaceous is found to be mature and reservoir and sills components are present in all the wells.

Till date only four wells, viz. Jc-A1, Jc-B1, Jc-C1 and Jc-D1 were drilled on the shelf margin. The large sedimentary thickness of the early Cretaceous remain untested and not studied in details for hydrocarbon potential and the depositional environment. In the present work an attempt has been made to understand the early Cretaceous stratigraphy of this basin with special emphasis to understand the depositional environment during early Cretaceous time using the marine microfossil group ‘foraminifera’. This particular fossil groups helps in demarcation of stage boundaries within the marine succession and are widely used in Petroleum Exploration throughout the world. Apart from assigning the stage boundaries this group helps to predict the depositional environment when integrated with the sedimentary rock characters.

In the present work an attempt has been made to understand the depositional cycles using the lithological characters as revealed by the well log signatures. This is integrated with the foraminiferal biostratigraphy (the main research aim) to track the paleo depositional changes took place in the early Cretaceous time in the Durban Basin.

All conclusions drawn from the sedimentological studies are based on well log characters as only one conventional core was cut in one of the four wells.

1.2 Limitation of the present work

As already mentioned, only four wells were drilled till date in the Durban Basin. The subsurface information viz. Well data (Well Completion Reports and Electrical logs), Seismic data and drilled samples (Core details and well cuttings) were available from the Core laboratory establishment of the Petroleum Agency of South Africa (PASA), Cape Town.

Conventional Cores are very important for sedimentological studies in subsurface drilled sections. However, only one Conventional core (CC#1; Well Jc-B1) was available for studies. The solitary conventional core top is represented by less than a one meter partially metamorphosed clastics and the rest is in the igneous intrusive rock. The lithological studies in this work is mainly based on megascopic analysis of drilled cutting samples, the original description available from the well reports and analysis of well log motifs. Foraminiferal data and integrated lithological analysis help to predict the depositional environment prevailed during early Cretaceous time in this area.

Due to some technical difficulties, cutting samples for many intervals were not available for biostratigraphic analysis. For biostratigraphic analysis minimum 20 grams of samples for each interval are necessary. As well cuttings were not available for many intervals and in sufficient quantity (20gms each), the precise demarcation of stage boundaries in most wells could not be made. However, overall faunal composition recorded in the subsurface sections helps to distinguish different stages within early Cretaceous epoch in Durban Basin.

1.3 Research aim and objectives

The research project aims to demarcate the stage boundaries encountered in the early Cretaceous sections of the Durban Basin with the help of the marine microfossil group ‘Foraminifera’ and predict the depositional environment prevailed during this period.

The main objectives of this study are:

- To demarcate various stage boundaries within the early Cretaceous using various planktonic foraminiferal suite. The last appearance datum (LAD) of age diagnostic planktonic foraminifera are used to identify different stages.
- To study the temporal distribution of foraminifera within the drilled sections and predict the paleodepth against each sample intervals. Important depth indicator benthic assemblages (especially the agglutinated foraminifera) helps in determination of paleo depth and reconstruct the sea level fluctuation curves.

- To integrate the biostratigraphic analysis data with all lithological information received from composite lithology description, megascopic and microscopic petrography and Geophysical data analysis (electrical log motif and seismic) for a meaningful understanding of the depositional environment during the early Cretaceous.

1.4 Location of the study area

The Durban Basin is located offshore on the East Coast of South Africa (Bhattacharya and Duval, 2016). It is limited by the Natal Valley in the South, the Zululand Basin to the North, by the Mozambique Ridge to the East and the continental margin to the South-West (Fig. 1.1). The studied area has an approximate extent of 10,000Km^2. Durban Basin is a structurally-rifted setting of Mesozoic which hosts a series of horst and graben structures (Broad et al., 2012). The Basin has a narrow continental shelf (Fig. 1.1) (Dingle et al., 1983; Broad et al., 2012). The opening of the Durban Basin is closely related to the breakup of Gondwana from Jurassic to Early Cretaceous (Fig. 1.1 & 1.2) (PASA, 2015). The Agulhas-Falkland Fracture Zone (AFFZ) northern termination delineates the Basin boundary against the Agulhas strike-slip fault at 2500m isobaths between the oceanic and continental crust (Fig. 1.1) (Broad et al., 2012; Bhattacharya and Duval, 2016). The basin fill is related to the breakup of Gondwana, followed by Indian Ocean development, then by the drifting of the East Gondwana (Fig. 1.2) (Salman and Abdula, 1995).

Two sedimentation phases have been identified within the Durban Basin: syn-rift and drift phases (PASA, 2015). The syn-rift sediments aged between Late Jurassic to Late Valanginian were correlated with the reddish quartzite of the Zululand Group of the onshore Zululand Basin (Visser, 1998). Yet, McMillan (2003) suggested that the Durban Basin was a depocenter around Mid-Campanian (late Cretaceous). Furthermore, the drift sediments were comparatively analogous to the West and South Coast basins of South Africa, linked to a series of highstands with deep-sea organic rich shale characteristics (Broad et al., 2012).

Tectonically, the development of the Durban Basin was complex with two volcanism activities on the margin (Bhattacharya and Duval, 2016). The presence of magmatic activity within the basin further contributed to the complex tectonic nature of the basin development. In addition, during the early Cretaceous the dextral movement of the Agulhas-Falkland Fracture Zone (AFFZ) affected Southern section of Durban Basin. Moreover, intrusive igneous rocks (sills and dykes) of Late Cretaceous or Early Tertiary have been identified within the pre-drift section of the Basin with dextral AFFZ associated with short rift margin (Bhattacharya and

Duval, 2016). Many volcanic rocks were intersected in wells which previously identified as poorly sorted sedimentary rock, diamictite. Moreover, the presence of the Tertiary Tugela Cone composed of steep-sided dome-shaped mounds at its base was noted. The cone, a deepwater fan system, extends eastward into the Indian Ocean from the continental shelf; and the progradation of the fan system into the Natal Valley is dated back to Early Cretaceous (Fig. 1.1) (Goodlad, 1986). It was formed as a result of tectonism at the continental shelf of the Durban Basin, and its growth is postulated to have taken place from major progradational sediment deposition during low sea-level stand (Goodlad, 1986).

Adding to the complex nature of the basin development, some syn-rift sediment deposition occurred synchronously with tectonic deformation within the graben; while drift sediments were deposited into one depocenter restricting further transportation of sediments into the Durban Basin (USGS, 2012; Bhattacharya and Duval, 2016). However, three Tertiary uplifts (Middle Oligocene, Miocene and Pliocene) were responsible for the loss of sediments into deeper water (Du Toit and Leith, 1974; Bhattacharya and Duval, 2016). Consequently, the location of the Durban Basin within the East Coast of South Africa was subjected to major tectonic activities during its development (Bhattacharya and Duval, 2016).

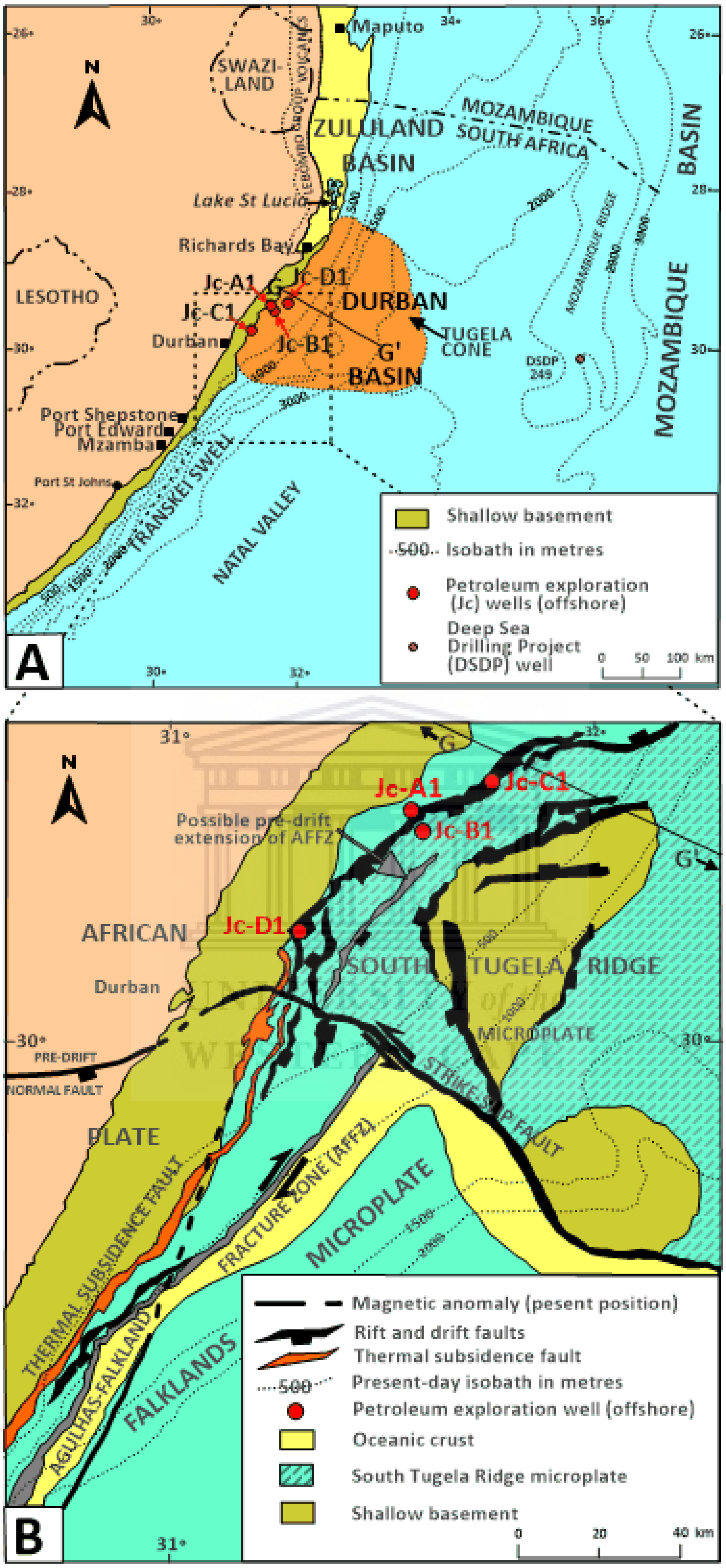


Figure 1.1 East Coast basins location maps and main features. A: Main features of the Durban and Zululand Basins, profile G-G' location and the Transkei Swell. B: Figure 1.2. The Durban Basin major structural elements including a reconstruction of early drift which led to the South American and South African plate's separation, and new oceanic crust emplacement area (modified after Kitchin, 1995; Ben-Avraham et al., 1997).

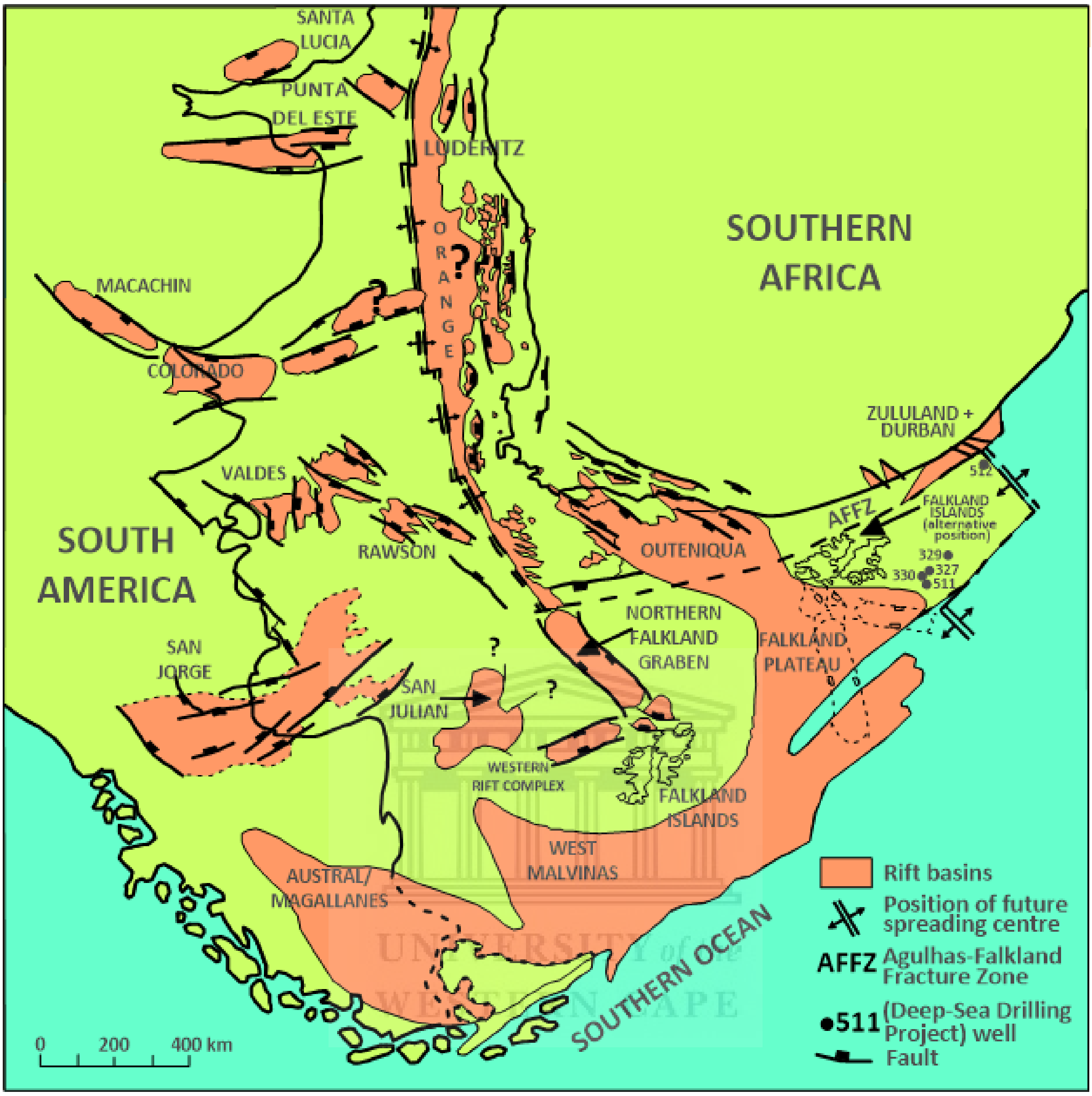


Figure 1.2 The reconstruction of plate tectonic within Southwest Gondwana with pre-break-up configuration for the rifted Late Jurassic to Early Cretaceous basins. Falkland Islands inverted North-East position showing the possible 180° clockwise rotations the Falklands microplate may have subjected to during continental breakup (modified after Jungslager, 1999a).

1.5 Hydrocarbon potential of the Durban Basin

Located on the east coast of South Africa, Durban Basin has attracted the attention of major petroleum exploration companies after discovery of hydrocarbon reported all along the eastern coast of Africa continent viz. Mozambique, Tanzania, Kenya and Somalia (Salman and Abdula, 1995; Bhattacharya and Duval, 2016). Durban Basin forms part of the Eastern African sedimentary basins which stretches from the horn of Africa, Somalia in the North to South African East Coast waters (South). This region represents a major frontier for hydrocarbon exploration (Salman and Abdula, 1995; Singh and McLachlan, 2003). Recent studies done by the US Geological Survey along the South African Coastal Province indicates future hydrocarbon potential along the East Coast (USGS, 2012). The study based on total petroleum system (TPS) found that the reservoirs are of Mesozoic-Cenozoic ages developed within deep water fan, graben and half graben, fault related structures from continental shelf to deep water (USGS, 2012; Bhattacharya and Duval, 2016).

Despite the Durban Basin geostrategic location within the East Coast of South Africa and being part of the major hydrocarbon frontier region of the Eastern Africa, it remains unexplored due to low density of wells drilled as per other Eastern Africa basins (Salman and Abdula, 1995; PASA, 2015; Bhattacharya and Duval, 2016). To date only four offshore wells have been drilled at the Durban Basin. Two of the four wells have minor hydrocarbon shows (Roux et al., 2004; PASA, 2015). One well presents a minor gas show while the other provides the evidence of an active petroleum system (PASA, 2015). Studies done by Roux et al. (2004) revealed that deep-seated source rocks of Jurassic age lie within the graben structures of the basin. Therefore, syn-rift sediments host hydrocarbon leads that are yet to be tested and prospected (PASA, 2015).

1.6 Previous work on the depositional environment of Durban Basin

During the last century, geologists have studied sedimentary rocks with focus on features characterization which assists in interpreting depositional environments (Scholle et al., 1983). The study by Bridge and Lunt (2006), for example, illustrates how braided river depositional models were used to interpret and characterize ancient and subsurface deposits. Moreover, sedimentary structures have been used exclusively in the past, in few cases, to analyse the depositional environment patterns (Scholle and Spearing, 1982). However, it has been argued that the recognition of a depositional environment is one of the complex procedures in stratigraphy as it requires the application of components such as tectonics, palaeontology, paleoecology, sedimentation, petrology and lithology (Tipsword et al., 1966; Hobday et al., 1975; Feng et al., 2017).

In terms of stratigraphy, clastic sediments of the Durban Basin were deposited on top of the Natal Metamorphic Province (NMP) basement (Fig. 1.3 & 1.4) (Marshall and Brunn, 1999). Adjacent to the Durban Basin, rocks between the Msikaba Formation, previously considered to be part of the Natal Group, and the Witteberg Group from the Cape Supergroup onshore have been a source of contentious stratigraphic-age correlation due to the complex nature of tectonics in the area (Kingsley, 1975; SACS, 1980; Marshall and Brunn, 1999; Liu, 2002).

Based on the work of Lock (1973), a Devonian fossil (*Lycopsid*) was found within the Msikaba Formation. Liu (2002) recognised this stratigraphic contention with age difference and proposed that more works need to be done to address the issue. He further recognized several formations identified offshore in Durban Basin, namely the Natal Group (sandstone) which overlies unconformably on the NMP; the Dwyka Group (tillite) which rests on top of the Natal Group, and the Ecca Group (shale and sandstone) affected by intrusive dolerites forming the extension of the Karoo Supergroup into the East Coast and overlies the Dwyka Group (Fig. 1.3 & 1.4) (Liu, 2002). Booth et al. (2004) indicated that both the Natal Group and the Msikaba Formation were not affected by the Cape Deformation Event and metamorphic activities. Later, the work by Kingsley and Marshall (2009) achieved lithostratigraphic correlations between sediments of the Msikaba Formation with those of the Witteberg Group rather than those of the Natal Group which it overlies unconformably. However, the recent stratigraphic and sedimentological works by Busakwe (2015) indicated the Msikaba could be correlated with neither the Cape Supergroup nor the Natal Group since it is a separate and younger formation (Late Devonian) which disagrees with Kingsley and Marshall (2009). This view has allowed for the revision of the depositional settings at the Durban Basin. Despite addressing the age correlation of the Msikaba Formation and Witteberg Group (Kingsley and Marshall, 2009), the latter work didn't cover (bio) stratigraphic framework (McMillan, 2003), time slicing and palaeoenvironments of the Durban Basin and its adjacent basins. McMillan (2003) work touched on the seven continental marginal basins of South Africa and Southern Namibia with Cretaceous drift infills using microfossil group foraminifera.

Additionally, stratigraphic correlation within the Natal Group has been a contentious topic on its own (SACS, 1980; Marshall, 1994; Liu, 2002; Kingsley and Marshall, 2009). Sutherland (1868) referred to today Natal Group as Palaeozoic Sandstone Formation. Thereafter, it had changed names from Palaeozoic Sandstone by Anderson (1901), Table Mountain Sandstone by Anderson (1904), Clairwood Sandstone by Schwartz (1916), and Table Mountain Series by Krige (1933). The correlation of presumed Early Palaeozoic sandstones despite its lithological differences within both Pondoland and KwaZulu-Natal by previous workers (Sutherland, 1868; Du Toit, 1920; Hobday and Mathew, 1974; SACS, 1980, Roberts, 1981) has contributed to the stratigraphic contention. Later, Rhodes and Leith (1967) presented the first stratigraphic subdivision of the Natal Group. Also, the lithological difference for the Natal Group in KwaZulu-Natal and Pondoland was documented by Kingsley (1975) for the Margate Facies (not correlating with Natal Group facies) and Hibberdene facies. However, Rhodes and Leith

(1967) Natal Group subdivision included units which were located within the Group such as the Upper Quartzite unit. Additionally, the inclusion of Hibberdene Sandstone Formation equivalent to Upper Quartzite unit (Rhodes and Leith, 1967) into the Hibberdene facies by Kingsley (1975) and SACS (1980) posed a problem as the formation should have been included into the Margate Facies due to paleocurrent indication (Marshall, 1994). Thus, Roberts (1981) proposed the stratigraphic subdivision of the Natal Group into two formations, the older Durban Formation and the younger Mariannhill Formation.

In terms of tectonic, it has been previously shown that no compressional folding was observed within the Cretaceous and Tertiary strata of the East Coast, while normal faults were present on the basement (Du Toit and Leith, 1974). In addition, these normal faults are parallel to the coastline, and the Cretaceous sediments terminate against these faults. More recently, Martin and Flemming (1986) analysed Holocene shelf sediment wedge in the South and East Coast of South Africa and found that the inner shelf Cretaceous rocks were faulted and folded, while younger rocks dip seaward. The Palaeozoic rocks of the later area form a South-East extension offshore (Fig. 1.4). Marshall and Brunn (1999) observed that the deposition of the older Durban Formation and the younger Mariannhill Formation are controlled by fluvial influence represents two distinct tectonic cycles supported by the upliftment of the source area followed by the restoration of drainage. Furthermore, volcanic activities have been traced to be contemporary to the deposition of the Eshowe Member sediments of the Durban Formation (Marshall and Brunn, 1999). The erosion affected the Natal Group for about 200 Ma toward the end of deposition to the onset of the Dwyka glaciation in the late Palaeozoic (Marshall, 1994).

In terms of sedimentological studies, Du Toit and Leith (1974) highlighted the different rates of Paleogene sediments input into the Durban Basin. Based on their studies, these rates occurred in three phases. First phase is characterized by the slow rate (approximately 15 meters per million years) of clay-rich particles deposited into a shallow water (prodelta) environment during the Palaeocene. Second phase is recognised by the high rate (61 meters per million years) of sediments input during the Eocene. The second phase has been interpreted as a subaqueous deltaic plain environment associated with upward coarsening sequence and regressive succession. Third phase deposition occurred into a deltaic marine transgressive environment for the Oligocene strata. This phase was characterized by a slow rate of approximately 23 meters per million years with lithological break from Eocene sediments. In agreement with Du Toit and Leith (1974), Bosman et al. (2007) have identified deposits bearing both deltaic and submarine fan features off the Thukela River. However, Hicks and Green (2016) had a different view to that of Du Toit and Leith (1974) regarding sediment input into the Durban Basin. Moreover, Bosman et al. (2007) pointed out the impact of ocean on the deposition process of sediments from shelf to submarine fan; and they have identified a total of eight sedimentary facies grouped into four facies associations on the shelf off Thukela River mouth. Each facies are related to a different sedimentary process. Two depositional sequences in the Devonian Msikaba Formation along the Kwa-Zulu Natal coastline relative to eustatic sea-level changes, namely the. transgressive and regressive sequences were recognized. The Msikaba Formation was deposited during Late Devonian and subjected to both fluvial and marine influences in the Southern part of the Durban Basin (Busakwe, 2015).

Furthermore, Green (2011a) pointed out a prolonged starvation periods and a subsequent high sediment input into the Durban Basin associated with tectonism. Consequently, the rate of sediments deposition into the Durban Basin was influenced by both tectonic and eustatic sea-level changes which were the result of the seafloor spreading (Du Toit and Leith, 1974). The latter was related to the opening of the Indian Ocean in the present Southern hemisphere during Late Jurassic (Salman and Abdula, 1995). Using 2D seismic reflection line and well logs, Hicks and Green (2016) profiled the Durban Basin depositional environment into six seismic settings. Each setting has a different type of sedimentation. Hicks and Green (2016) further elaborated on the complex sediments input into the Basin. They noted that fluvial sedimentation controlled the shelf formation, and a change in sedimentation style happened during Turonian from shelf to deep marine. The latter was followed by a change into shallow condition due to crustal upliftment (Goodlad,1986). Moreover, the sediments of the Ordovician Natal Group were deposited along the NE–SW direction under tectonic influence in the Natal Trough (a foreland graben) from subsequent subsidence around 490Ma (Marshall, 1994). This deposition occurred as a result of the Pan African Orogeny in the Southern Mozambique. Equally, the Natal Group is recognized as molasse deposit and was subjected to fluvial influence during its deposition (Marshall, 1994). Thus, in his study, Green (2011a) supported Du Toit and Leith (1974) suggestion that tectonism was a factor to be considered when analysing sediments input into the Durban Basin.

All the above-mentioned findings, eventually, explained the depositional environment construction and the biostratigraphic framework of the Durban Basin. Previous studies done at the Mid-Natal Valley have shown that the depositional style evolution depicts early rift basin fill and post-rift passive offlap fill. These two events resulted from an onlap fill through mixed offlap, onlap and onlap fill to offlap and sheet drape (Goodlad, 1986). Previous research works and publications on the Durban Basin (Du Toit and Leith, 1974; Singh and McLachlan, 2003; Bosman et al., 2007; Wiles, 2014; Hicks and Green, 2016; Bhattacharya and Duval, 2016; Hicks and Green, 2017) emphasised on the structural, tectonic and oceanographic complexities of its development. This spans from Palaeozoic Natal Group overlain by the Late Carboniferous-Early Permian Dwyka Group which is topped by the Jurassic Karoo Supergroup sedimentary successions.

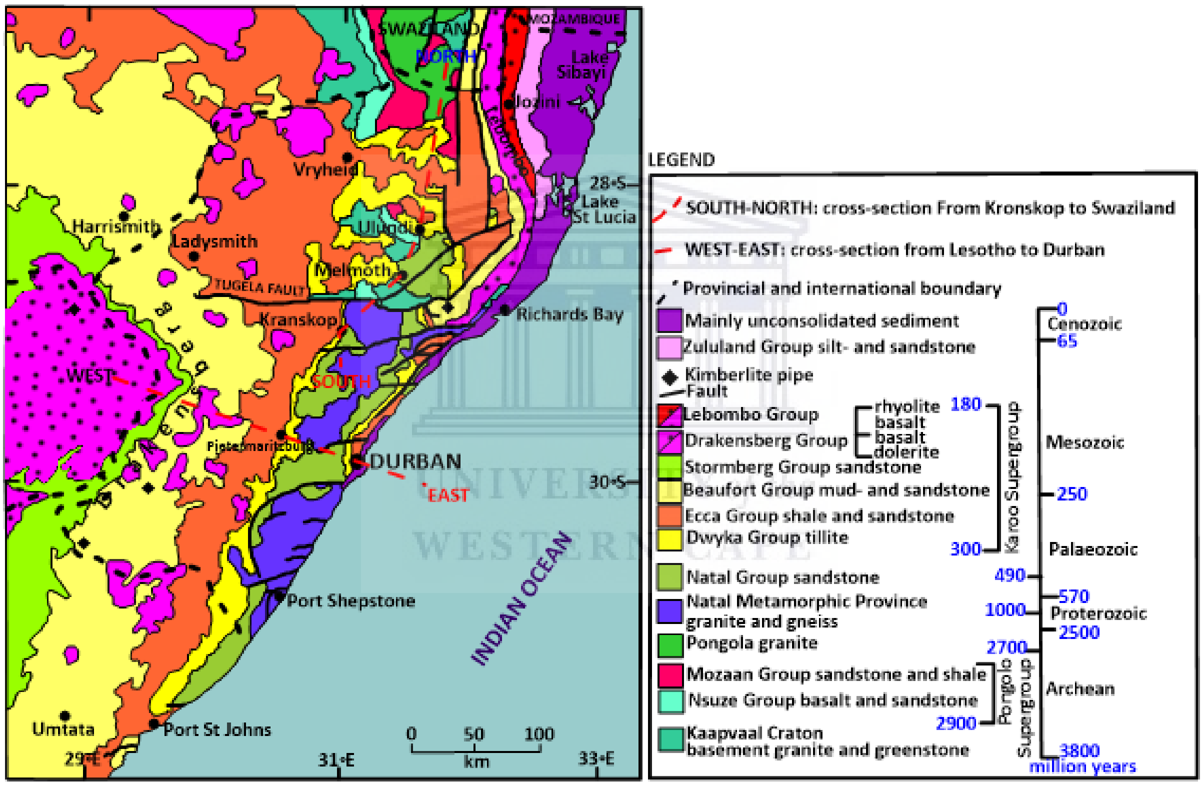


Figure 1.3 KwaZulu-Natal Geological Map: simplified and modified from 1:1000000 scale geological map sheets (Geological Survey, 1984, Pretoria, Government Printer, NE & SE sheets) modified after Geology Education Museum.

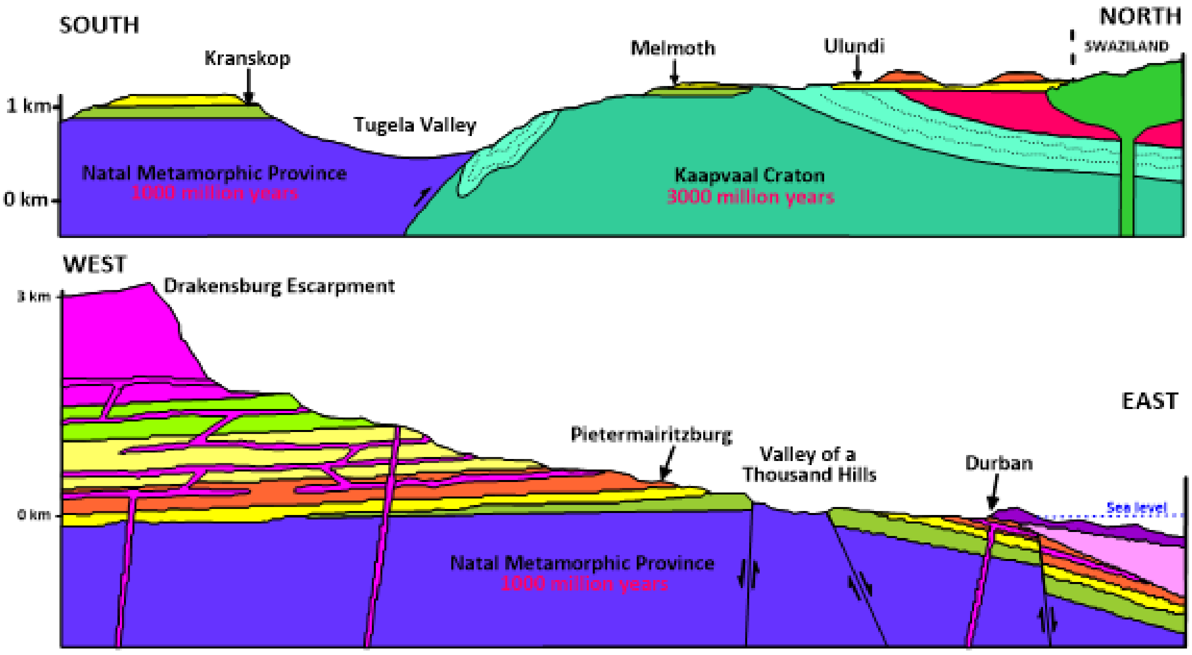


Figure 1.4 Geological cross-section from Kranskop to Swaziland (top) and from Lesotho to Durban (bottom). Refer to Figure 1.3 Legend modified after Geology Education Museum.

1.7 Motivation of the study

Based on previous studies, it can be concluded that the depositional environment of the Durban Basin is poorly understood. To date, only four wells have been drilled in the Durban Basin and detailed knowledge about the depositional environment and time slicing of the Mesozoic sediments for this basin remain uncertain. Therefore, for a proper understanding of the distribution of these clastic materials in space and time, the present research is carried out. All biostratigraphic information in the present work is essentially based on cutting samples examination available from the wells which helps in understanding the different stages within the early Cretaceous and to identify transgressive/regressive cycles and bathymetric changes within the early Cretaceous succession.

1.8 Problem statement

Previous geological studies conducted in the East Coast of South Africa involved sedimentology, palaeontology and stratigraphy (Du Toit and Leith, 1974; McMillan, 2003; Bosman et al., 2007; Green, 2011a; Hicks and Green, 2016). However, few studies have examined clastic sediments of the Durban Basin as previously described by Goodlad (1986). In addition, studies of the depositional environment in the East Coast of South Africa, especially within the Durban Basin have received little attention during the last two decades (Roux et al., 2004; PASA, 2015). The recent discovery of gas fields in the Mozambique Basin (located further north of Durban Basin) has generated interest for the petroleum companies to explore for hydrocarbon reservoirs in the Durban Basin (Bhattacharya and Duval, 2016). Although previous studies are significant, the depositional environment, the stratigraphy and tectonic settings of the Durban Basin are still poorly understood. This study is unique and uses an integrated approach that combines biostratigraphy, sedimentology and Geophysical information (from well logs and seismic data) for a better understanding of depositional environment. Early Cretaceous succession is known to be the most important target in all South African sedimentary basins as most of the important reservoirs are confined in this group of sediments.

1.9 Scope of the study

The present work aims at examining the subsurface stratigraphy and reconstruction of depositional environment prevailed during the early Cretaceous time in Durban Basin. In the present work foraminiferal distribution data was analysed mainly for stage boundary demarcation and was further integrated with sedimentological inputs (lithological information from the well cuttings), well log characters and seismic information data. However, the study is constrained by the following factors:

(1) The studied area covers around 10000km^2 of the Durban Basin.

(2) Only four wells have been drilled in this basin. Therefore, the drilling density is too small compared to the area.

(3) Importance of Conventional cores for laboratory analysis is very important. However, only one conventional core was cut in the four wells. This core CC#1 from the well Jc-B1 have less than 1m thickness of clastic sediments and the remaining interval comprises of dolerite intrusive (igneous).

(4) Limited quantity of well cuttings for some intervals were available. Also for some intervals, no samples were available for megascopic analysis and biostratigraphic processing.

Chapter II

2. Regional geology and tectonic set up of Durban Basin

2.1 General tectonic history of the East Coast (eastern continental margin) of Africa

The Durban Basin is located off the East Coast of the Republic of South Africa (Fig. 1.1). It is bounded to the south by the Natal Valley, to the North by the Zululand Basin and to the East by the Mozambique Ridge. Durban Basin is a structurally-rifted complex Basin forming a narrow about 8kmn continental shelf (Fig. 1.1). The Durban Basin together with the Zululand Basin form part of the East Coast basin of South Africa (Dingle et al., 1983; Broad et al., 2006; PASA, 2015).

Most of the basins located along the East Coast of Africa, from Somalia to South Africa on the Indian Ocean form part of the passive continental margin of the Palaeozoic Gondwana supercontinent (Zhou et al., 2013). The effects of the plate tectonic re-organizations within Gondwana affected the tectonic history of the East Coast of Africa. As a result, sedimentary rocks formed following major structural features development on the continental margins. The plate tectonic reconstructions impacted greatly on the global climate patterns through structural features such as micro-continental plateaux, submarine rises, ridges etc. which today act as barriers to the flow of the North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) (Hartnady et al., 1992). The offshore basins of this region owe its origins to the tectonic account of the African-South American-Antarctic triple junction reconstructions (Hartnady et al., 1992).

Prior to the Gondwana breakup, the Karoo-Ferrar volcanics were emplaced in the southern hemisphere between Early to Mid-Jurassic (Fig. 2.1) (König and Jokat, 2010). From Early Palaeozoic, the Gondwana northern margin acted like the present passive margin (e.g. along the Atlantic Ocean coast), subduction was active in the southern limit, and the supercontinent interior was landlocked. Around Mid-Palaeozoic, its stability began to weaken leading to its sequential break-up (Fig. 2.1) (de Wit et al., 1999).

The development of rifts within Gondwana resulted from regional extension around Early Permian; and large extensional faults evolved into rift system along the African East Coast (Erlank, 1986). The propagation of rift system moved from Madagascar to the region of Falkland Plateau in a south-westward direction (Erlank, 1986). The propagation is further attested by the presence of marine fossils in both Africa and South America (Erlank, 1986). Moreover, the subsequent drifting of Madagascar prime location relative to Africa and the occurrence of seafloor spreading centres in the region are the elements to consider when reviewing the development of sedimentary basins along the East Coast of Africa before, during and after the breakup of Gondwana (Salman and Abdula, 1995).

The formation of the first oceanic crust between Africa and Antarctica in the Riiser-Larsen Sea/Mozambique Basin occurred approximately during the Kimmeridgian stage (155Ma) (Jokat et al., 2003). The rifting/formation were accompanied with volcanic activities for about 80Ma prior to the seafloor spreading development (de Wit et al., 1999). These activities included magmatic intrusion and extrusion such as Karoo basalts (between 220-130Ma) in southern Africa, Ferrer dolerites (between 180-160Ma) in Antarctica, Parana basalts (120Ma) in South America, Deccan Plateau basalts (65Ma) of India; overlapping with the breakup of Gondwana (Erlank, 1986). The initial episode of rifting between Antarctica and Africa along the East-West orientation commenced during Tithonian (König and Jokat, 2006). This was followed by the second rifting phase north of the Riiser-Larsen Sea/Mozambique Basin along the N-S orientation (König and Jokat, 2006). By the end of Jurassic, the Gondwana supercontinent had broken up into many microplates separated and drifted away (Kennedy, 1964). The breakup of Gondwana led to the establishment of new seaways and the destruction of old land-bridges between continents impacting the distribution of marine fauna, changing seawater temperatures and climates (Kennett, 1982).

The open up of the Indian Ocean toward the end of Mesozoic era paved the way for the formation of various marginal sedimentary basins along the eastern margin of Africa such as East Coast basins of South Africa (Durban and Zululand basins, Natal Valley), Mozambique (Mozambique and Ruvuma basins), Madagascar, Tanzania, Kenya and Somalia (Bourget et al., 2008). The drifting phase of former Gondwana plates during Valanginian was followed by the deposition of major sediments in the Durban Basin (Hartnady et al., 1992). Thermal subsidence controlled the formation of large seaward-dipping fault as a result of the Gondwana plates drifting (Ben-Avraham et al., 1993). Moreover, thermal subsidence fault was reactivated following further deposition of sediments which occurred during Cenomanian stage (Goodlad, 1986). During Tertiary, two major upliftments characterized the Durban Basin tectonics. The uplift of the African craton during Oligocene was the first to occur, followed by marine regression. The Neogene uplift along the shelfal section of the East Coast basins was characterized by the introduction of modern sediments from the Tugela River (Ben-Avraham et al., 1993).

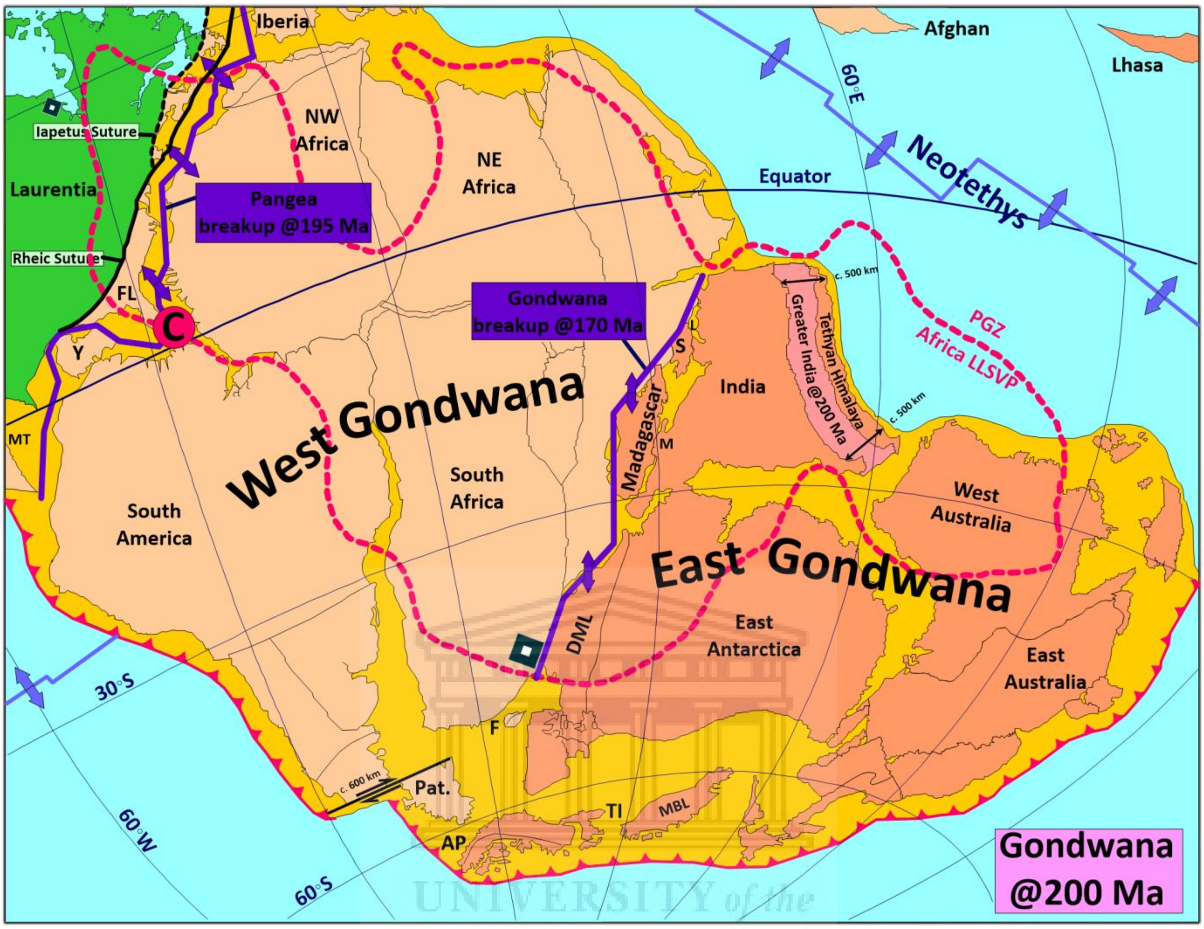


Figure 2.1 Representation of West and East Gondwana along with other adjacent sectors of the Pangea (200Ma) marking the boundary time between Triassic–Jurassic Period. The palaeolongitudes at 30° intervals obtained from the Pangea position over the Africa Large Low Shear-wave Velocity Province (LLSVP) from (Torsvik and Cocks, 2013) modified after (van Hinsbergen et al., 2012).

2.2 Tectonic history of the Durban Basin

The formation of the Durban Basin is closely related to the breakup of Gondwana (PASA, unpublished report, 2000). The East Coast of South Africa (offshore), where the Durban Basin is located, was subjected to complex and lengthy tectonic activities from Jurassic to Cretaceous. These activities included marginal rifting, shearing and drifting in addition to submarine volcanism (Wiles et al., 2014). Volcanic lavas intruded the continental crust extensively during the rifting phase of Gondwana before the final separation of South American plate from African plate (Goodlad et al., 1982). Following the rifting stage, the drifting phase made way for the development of the mid-oceanic spreading centre along the lines of weakness associated with the oceanic crust upwelling around 121-117.5Ma (Martin and Hartnady, 1986; Broad et al., 2006).

The Agulhas-Falkland Fracture Zone (AFFZ), a transform fault, lies along the South African south-eastern continental margin. The right-lateral (dextral) strike-slip movement formed when South American plate moved obliquely from the African plate during the Early Cretaceous break-up of West Gondwana (Broad et al., 2012). The AFFZ prevailed as a major tectonic feature for approximately 65Ma (between 130 to 65Ma.) where it was subjected to size reduction of about 180km ridge-ridge offset due to a ridge-jump event leading up to the annexation of South American plate to the African Plate oceanic part (Broad et al., 2012).

The strike-slip movement of the AFFZ started in the Early Cretaceous at the early stages of drifting with its ridge-ridge offset of about 1200km in length today (Dingle, 1993). The contemporary transform fault is active on the Mid-Atlantic Ridge and splits the Agulhas Fracture Zone (the African plate) to the Falkland Fracture Zone (South American plate) (Dingle, 1993). The clearing of the Agulhas Arch tip from the trailing edge of the Falkland Plateau led to the connection of the Indian and South Atlantic oceans during the Late Albian. The Natal Valley on the East Coast and southern coast are the two major spreading centres connected by the AFFZ (Martin and Hartnady, 1986; Dingle, 1993; Ben-Avraham et al., 1997; Broad et al., 2006).

The continental shelf of the Durban Basin has been postulated to be much narrower, approximately 18km, than the world shelf average (~50km) (Shepard, 1963; Ben-Avraham et al., 1997). The basin shelf break is estimated to be approximately 150m in depth and located at the top steepest part of the slope, and it corresponds to the sea-level lowstand during the Late Pleistocene glacial epoch (Ben-Avraham et al., 1997). Moreover, seismic profile R-74-6 from the Durban segment presents a structurally different steeper upper continental slope to the lower continental slope (Ben-Avraham et al., 1997). Kitchin (1995) postulated that the abrupt change observed at the upper slope base holds information of the seaward-dipping thermal subsidence fault position which separates the thickened and thinned layers of the upper crust. In addition, a relation may have been established between the landward-dipping faults and the up-slope boundary of the continent-ocean transform's crustal rollover structures (Kitchin, 1995). Moreover, the offshore faults delineate a deep rift below the Tugela shelf considered as a prominent landward and wide basement high (Kitchin, 1995). An asymmetric half-graben structure is present at the Tugela shelf bordered by a fault to its southeast margin, and the unconformity extends further to the top of the outer-shelf basement high across the graben (Ben-Avraham et al., 1997).

Detectable positive gravity anomaly association is present at Tugela shelf with large magnetic anomaly (Goodlad, 1986; Sandwell and Smith, 1992). Both gravity and magnetic anomalies have been accordingly used to determine the source of the basement block from the Jurassic (180Ma) flood-basaltic formations which rifted away from the Lebombo mainland (Ben-Avraham et al., 1997). The Tugela Cone exhibits a steep, west/east orientated southern flank, while the eastern flank has a more moderate gradient and hummocky surface (Wiles et al., 2013).

2.3 Sedimentary infill in the Durban Basin

The continental margin and abyssal plains along the East Coast of South Africa where the Durban basin is situated hold sedimentary records resulting from series of plate reconstruction that had influenced its formation (Hartnady et al., 1992). These are postulated to be connected to the major tectonic-stress systems influencing continental margins and mid-ocean ridges. As a result, the sedimentation pattern of the Durban Basin is closely related to the tectonic history of the southern hemisphere from Gondwanaland (Hartnady et al., 1992).

The Durban Basin sedimentary infill histories commenced in the Late Jurassic into Tertiary following the initial separation of Gondwanaland into East-West compartments (Hicks, et al., 2014). Two main sedimentation phases characterise the basin in addition to the Tertiary sediments formed during the progradational phase: the syn-rift phase aged between late Jurassic to early Cretaceous (late Valanginian) and the drift phase around mid-Albian (Fig. 2.2). The deposition of syn-rift phase sediments commenced in the late Jurassic and continued into the early Cretaceous. Moreover, the syn-rift phase is related to the active rift tectonics of the East Coast and linked to the early stages of continental break-up (Broad et al., 2012; USGS, 2012). Second phase, the transform-drift-passive margin phase began in the Late Albian and continues into the present time (USGS, 2012). The drift phase relates to the post-rift of thermal subsidence which developed due to the cooling and subsidence of the new oceanic crust, and the foundering followed by drifting of continents from the former Gondwanaland (Broad et al., 2012).

The thickness of the Mesozoic to Cenozoic stratigraphic section offshore province is estimated to be more than 5000m (Fig. 2.2) on the outer parts of the continental shelf (USGS, 2012).

Moreover, the thicknesses of sediments encountered within the drilled section of Durban Basin vary between 2300m (in well Jc-A1) to 3940m (in well Jc-B1), with Jc-C1 and Jc-D1 wells having intermediate thicknesses (PASA, unpublished Well Completion Reports). These sediments dated between Kimmeridgian to Late Valanginian are of syn-rift phase intersected at wells Jc-B1 and Jc-D1 within the graben fill successions and at well ZU 1/77 of the onshore Zululand Basin (Hicks et al. 2014).

The deposition of organic shales occurred during the Aptian clearance of Falkland microplate from the southern tip of Africa within the East Coast basins (Durban and Zululand basins). This event is postulated to have occurred concurrently with the worldwide anoxic event (Singh and McLachlan, 2003). The Mid-Cretaceous was marked by the establishment of the submarine fan system and Tugela delta within the Durban Basin (Goodlad, 1986). Moreover, sediments loading reactivated thermal subsidence fault around Cenomanian (Goodlad, 1986); and by Tertiary, marine and delta-prone sediments were deposited in the Durban Basin (Ben-Avraham et al., 1993) (Fig. 2.2). In addition, the east-west trending faults of the Natal Metamorphic Province (NMP) basement controlled the lower Tugela River course (Singh and McLachlan, 2003). The Tugela River supplied a large volume of sediments between Late Cretaceous to Tertiary into the sea; and the sediment supplied favoured the formation of the Tugela Cone which is a large submarine fan system stretching seaward within the Durban Basin (Singh and McLachlan, 2003). Du Toit and Leith (1974) dated sediments intersected at Jc-1 well above the basal unconformity to Cenomanian age. Also, within the graben, the older sedimentary sequence was correlated with the inland northern Natal Barremian-Aptian strata (Goodlad, 1986).

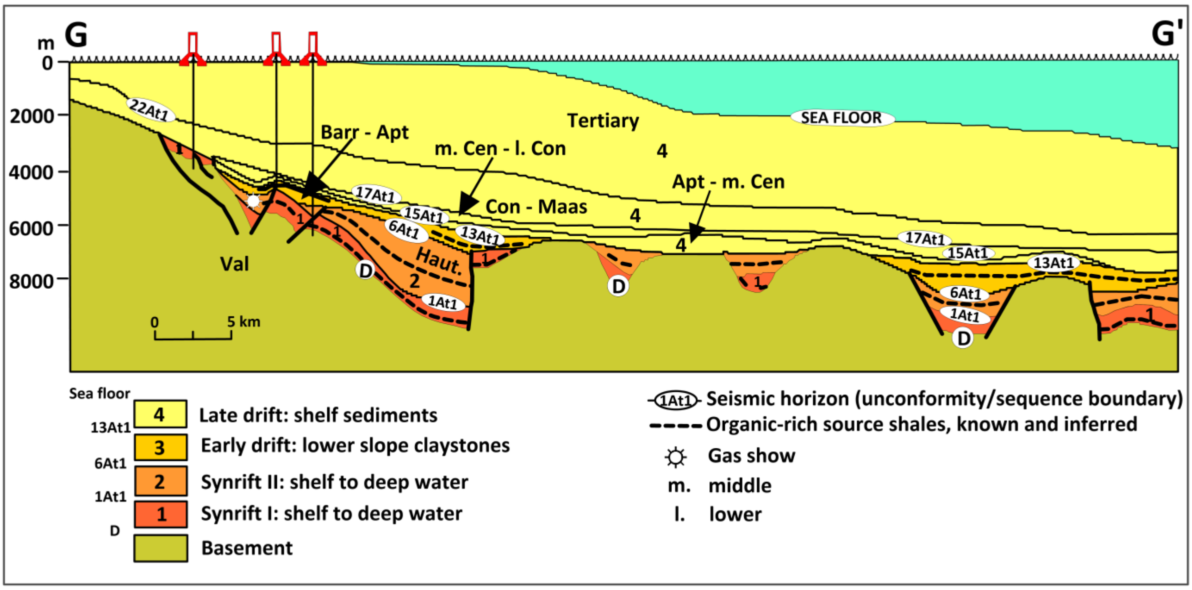


Figure 2.2 Geological profile G-G' across the Durban Basin from seismic analysis and well data illustrating main stratigraphic subdivision and structural features from Exploratory wells in projected locations indicated (modified after Broad and Mills, 1993; Soekor, 1994c).

2.4 Sedimentary succession of the Durban Basin

Several hundred thousand cubic kilometres of material eroded from the southern African continent since the initiation of the Gondwana breakup in the Mid-Jurassic and accumulated in the Durban Basin and other passive marginal basins which surround the South-African Plateau (Fig. 2.3) (Watkeys and Sokoutis, 1998; McMillan, 2003; Tinker et al., 2008a, b; Said et al., 2015). Moreover, the South-African Plateau as the most dominant structure in Southern Africa experienced tectono-morphic and erosional processes which favoured the deposition of continental sediments into the marginal basins (Said et al., 2015).

Today, the steeply-dipping Great Escarpment (Fig. 2.3) separates this interior plateau represented by a flat relief which stands at a high elevation between 1000m and 1500m from the coastal plain (Said et al., 2015). In addition, the plateau as part of the African surface was subjected to upliftment and erosional processes (Burke and Gunnell, 2008; Macgregor, 2010). The south-eastern Africa continental margin, during the Cenozoic Era, was susceptible to multiple epeirogenic uplift phases that resulted into the formation of the African planation surface, development of fluvial incision and accrued sediment supply to the coastal areas (Hicks and Green, 2017).

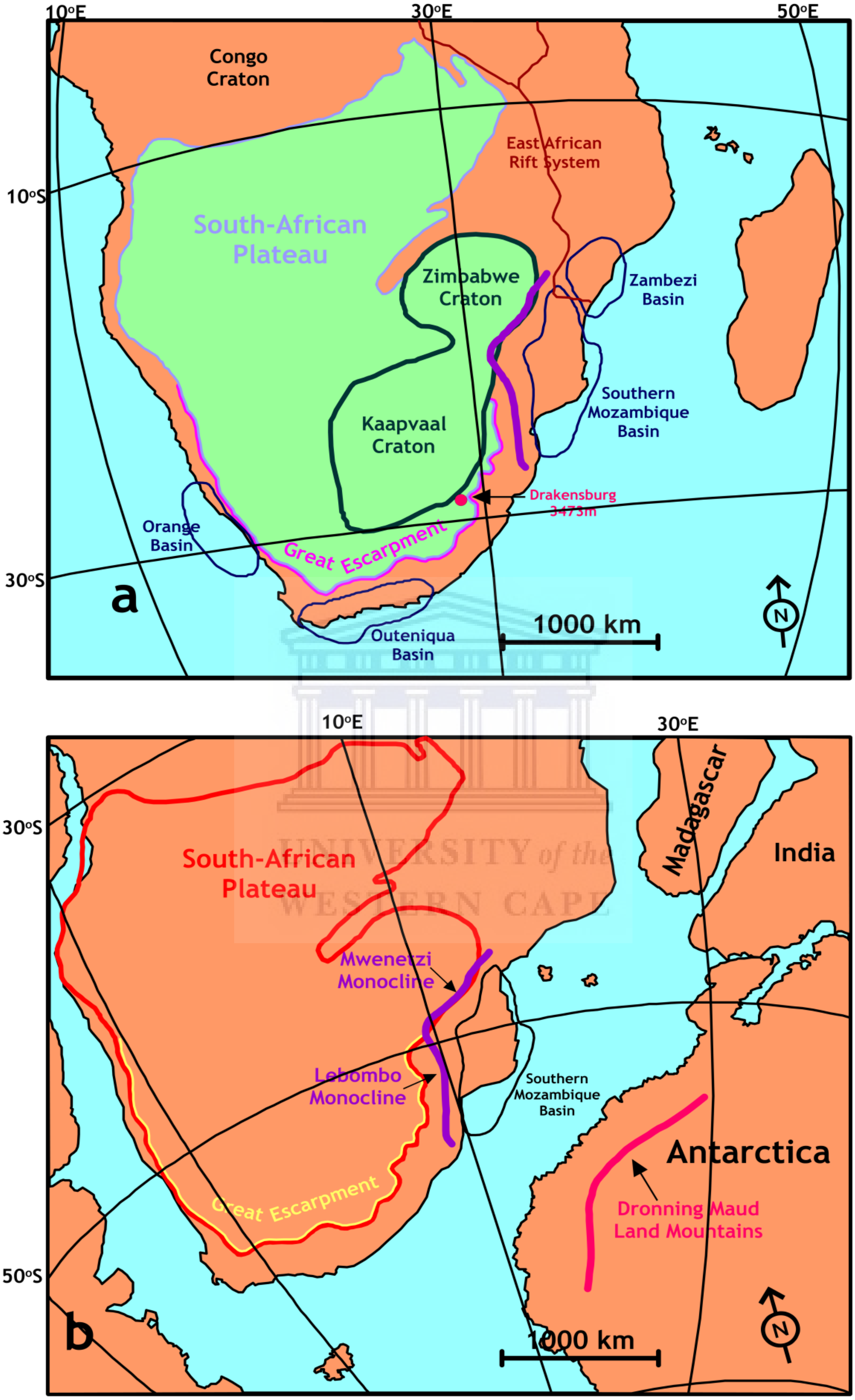
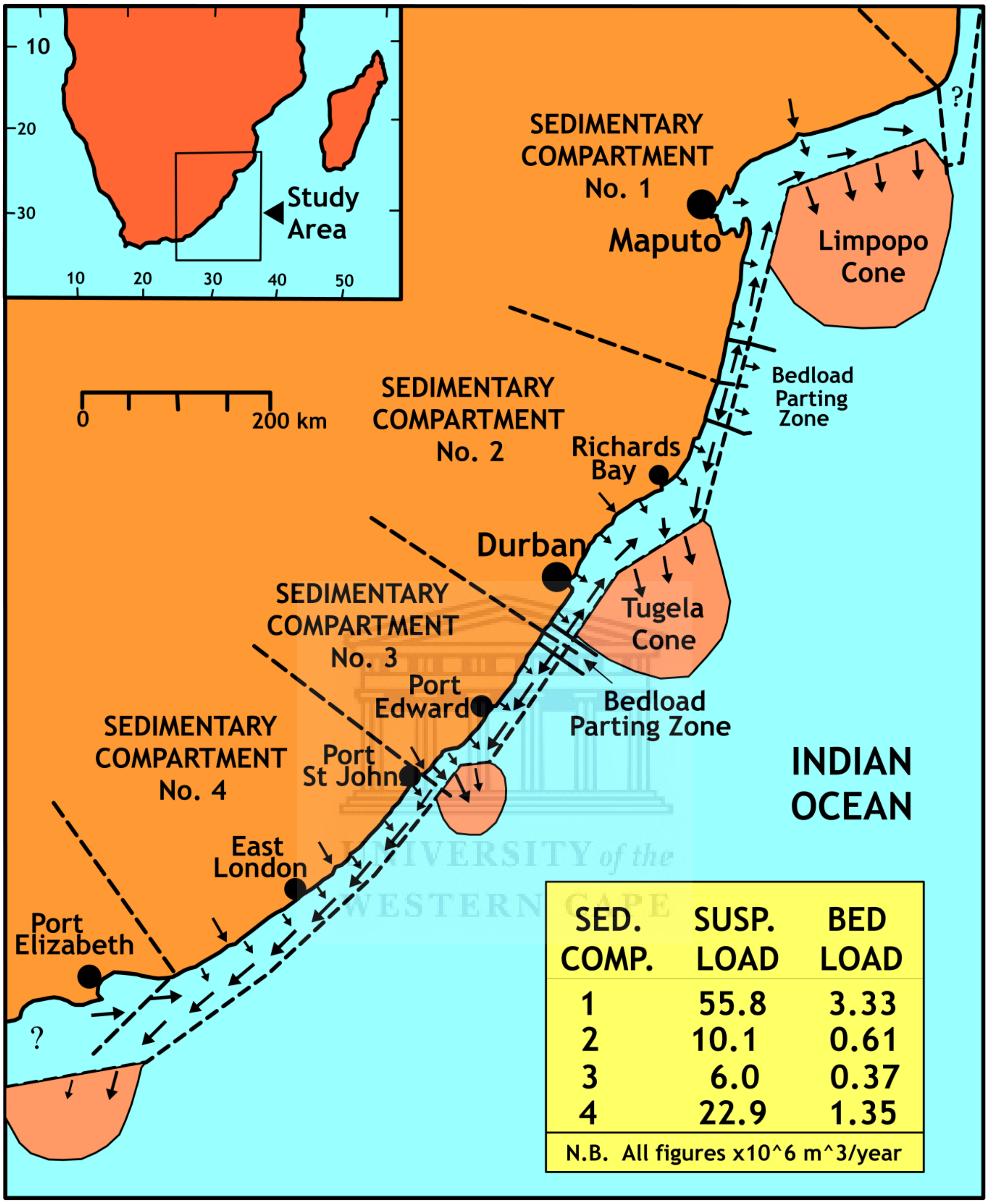


Figure 2.3 Southern Africa digital elevation model: (a) present day and (b) reconstructed at 150Ma based on UTIG model (modified after Lawver et al., 1998).

During Oligocene, the African craton uplifted as a result marine regression followed with deltaic and marine sediments deposition (Singh and McLachlan, 2003). The uplift of the shelf area during Neogene led to the deposition of modern sediments of the Tugela River (Singh and McLachlan, 2003). Two series of uplift during Neogene Period were suggested by Walford et al. (2005) which include the Early Miocene uplift with smaller-magnitude and the Pliocene uplift having a greater-magnitude although the uplift of the Oligocene has been identified as the most prominent of all three-event series. However, a series of moderate uplift and westward tilting events were registered within South Africa during the Early Miocene in addition to minor coastal monoclinal warping recording maximum uplift in KwaZulu-Natal along the Ciskei-Swaziland Axis (Partridge and Maud, 1987).

The Post-African I erosion surface development forms part of this episode along with sediment transportation to the coast through short and fast flowing river systems leading up to the development of Uloa Formation (Partridge and Maud, 1987). Hicks and Green (2017) propose an imbalanced sediment supply for the Durban Basin represented with sediment starvation in the southern portion of the shelf and abundant supply to the North of the Basin. However, the south-eastern part of Africa is postulated to be subjected to major drainage shift from late Cretaceous to early Palaeocene associated with intracratonic subsidence, flexural uplift along the Indian Ocean margin leading to development of the Kalahari Basin, an internally drained basin (Said et al., 2015). Furthermore, the Late Maastrichtian succession eroded prior to the deposition of the Palaeocene sediments in the southern African margin on the flanks of the Agulhas Arch. An indication of Agulhas Arch uplift commenced during the Late Cretaceous despite significant uplift is recorded from the Palaeocene to Early Oligocene epochs (McMillan, 1986).

A well-defined and shore-parallel zonation characterizes the East Coast of South Africa (Flemming, 1980a). The presence of inshore (50-60m isobaths) sediment wedge reaches 5km wide South of Durban (Flemming, 1980a). Moreover, large current-generated bedforms are absent at the nearshore zone, and the wave-dominated bedforms appear to be present due to high swell regime (Flemming, 1980a). The seaward margin of the sediment wedge merges with a current-controlled shore-parallel sand stream (Flemming, 1980a). Most of suspended load get expelled from the system, while wave action disperses materials discharged from adjacent catchments. The process is observed from distribution pattern of sediments (Flemming, 1981). And during less energetic periods, temporary deposition of thin mud layer from some of the suspended material occurs on the seabed (Flemming, 1981). A dynamic equilibrium is achieved between local wave action and the sediment profile along the seabed after the dispersal of bedload material within the nearshore zone (Flemming, 1981). Thereafter, the progradation of the nearshore sediment wedge occurs for the sand to be drawn in and transported by the flow after enough current strength is met (Flemming, 1981). Flemming (1981) postulated that the seaward boundary of the sandstream marks the outer limit of modern sand penetration across the shelf since material supplied to the sandstream is transported South by the current. The presence of sand-sized material beyond this boundary is less frequent and gravel lag deposits characterize the seabed (Flemming, 1981). This is attributed to the Agulhas Current forming an effective barrier that limits the penetration of modern sand into the shelf break along large parts of the outer shelf (Fig. 2.4) (Flemming, 1981).



SED. COMP.	SUSP. LOAD	BED LOAD
1	55.8	3.33
2	10.1	0.61
3	6.0	0.37
4	22.9	1.35

N.B. All figures x10^6 m^3/year

Figure 2.4 East coast of southern Africa, Regional sedimentary model adapted to the dispersal of bedload sediments (modified after Flemming, 1981).

2.5 Sediment supply

The presence of rivers along the KwaZulu-Natal coast favoured the input of sediments into the Durban Basin over the past 6Ma at ~4.9 x10^6 m^3/year. These rivers have been dated back to Mid-Cretaceous with the Thukela River being the most prominent. Moreover, the seasonal rate of sediment input stands at 4.405 – 106 m^3 (Flemming, 1980a; Dingle et al., 1987). The earliest syn-rift sediments found in the Durban Basin are postulated to be of lacustrine and fluvial in origin (Broad et al., 2012). These sediments are overlain by shallow marine and deltaic sediments in most basins of the East Coast; also, they are postulated to be associated with volcanic and volcaniclastics materials in some locations (Broad et al., 2012). Moreover, deep marine argillaceous sediments characterise the drift succession, and the basin floor fans are filled with sandy turbidites (Broad et al., 2012). The sandy turbidites deposited within the progradational/aggradational sedimentary sequences because of either eustatic sea level changes or local tectonics (Broad et al., 2012). Furthermore, Hicks and Green (2017) postulated an increase of sedimentation rate during the Oligocene across the S4 erosional boundary from 11.3m/Ma to 35m/Ma with a slight decrease in the Late Oligocene and Early Miocene, all within the Durban Basin. At Jc-B1 and Jc-C1 wells, the sedimentation rates indicate a sediment starvation for the Basin during Oligocene and Early Miocene to 5m/Ma sedimentation rates as compared to 38m/Ma for facies D2 and 23.8m/Ma for facies D3. From Late Miocene, an elevated rate of sedimentation (23.5m/Ma) is observed across the S5 erosional boundary indicative of a renewed sedimentation throughout the Basin (Hicks and Green, 2017).

2.6 Stratigraphy of the Durban Basin

The Durban Basin comprises of Early Cretaceous and Cenozoic sedimentary successions (Fig. 2.5) (McMillan, 2003). However, both successions have been reported to be absent along the coastal margin of KwaZulu-Natal Province, South Africa, (Dingle et al., 1983). The lacking coastal deposits is preserved in the northern KwaZulu-Natal within the onshore Zululand Basin (Maputaland) with an estimated succession thickness of 2000m (Shone, 2006). Palaeocene and Eocene successions are also missing along the coastal margin. However, sediments of the Early Miocene to Early Pliocene are present within the Uloa and Umkwelane Formations in the form of marine regressional package that overlie Cretaceous sediments in northern KwaZulu-Natal (Roberts et al., 2006). Within the Uloa Formation, aeolianite, calcarenite and decalcified red soils overlie an upward shoaling sequence of shallow marine coquina that describes the formation (Roberts et al., 2006; Porat and Botha, 2008). The chain of compounded hiatuses spanning from Late Palaeocene to Early Pliocene is responsible for the Cenozoic deposits absence along the KwaZulu-Natal coastline (McLachlan and McMillan, 1979; Dingle et al., 1983). Further north within the onshore Mozambique, substantial Cenozoic deposits along the coast have been correlated with individual hiatus periods with the Early Oligocene, Mid-Miocene and Early Pliocene epochs (Flores, 1973; Martin, 1984).

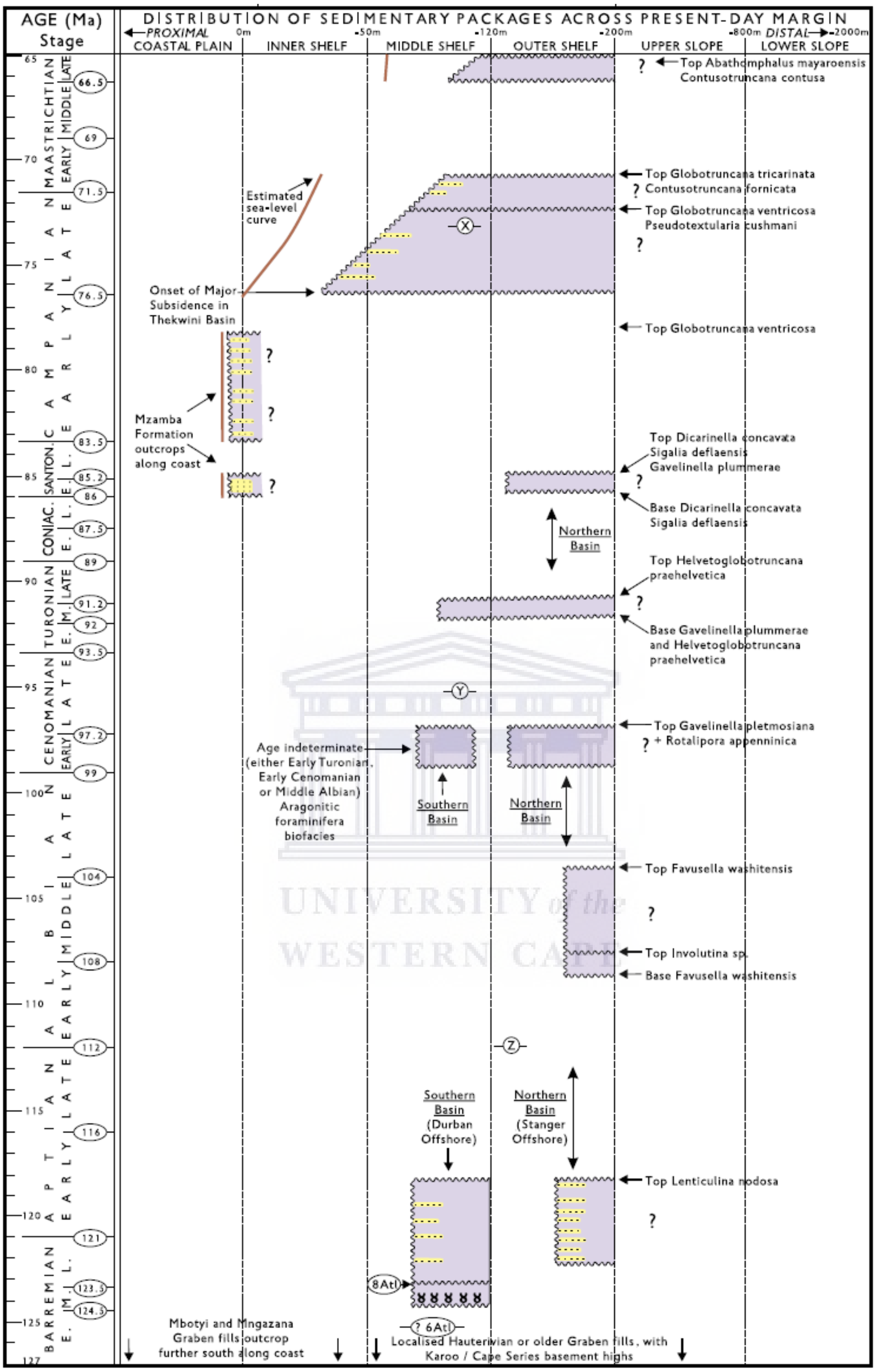


Figure 2.5 The Durban Basin interpreted chronostratigraphic and summarized lithostratigraphy of the Cretaceous drift succession. The north and south of the basin Early Cretaceous stratigraphy successions are very different and depicted in separate columns. Thick or massive sandstones indicated by yellow intervals and single lines of stipple represent sandstone stringers. Blue intervals designate claystones with distinguished major high-gamma claystones; "brick-work" symbol indicates carbonates and white areas being unconformities (McMillan, 2003).

2.7 Seismic and sequence stratigraphy

The drift successions found within the South African's offshore basins have been divided into unconformity-bounded sedimentary sequences as per sequence stratigraphic principles. The deposition of each sequence is linked to global (eustatic) sea-level change and the type-1 unconformity defines its base (Broad et al., 2012). The relationship between lowstand and high stand sedimentary packages of the southern African continental margin including the associated deposits agree since they indicate the rates of the continental margin subsidence changes and sediments input altered by processes such as tectonic, seismic and sea-floor erosion (McMillan et al., 1997). Within the drift succession of the Durban Basin, there are deep-water organic-rich shales reported present within the repeated highstands which bear similar characteristics of the South and West coasts drift successions (Broad et al., 2012).

2.8 Facies and facies associations on the Thukela Shelf

Bosman et al. (2007) recorded eight broad sedimentary facies types on the shelf off the Thukela River mouth and grouped them into four main facies associations namely: inner shelf facies association, Mid-shelf facies association, Outer shelf facies association and Submarine delta association, while assigning each facies association a sedimentary process (Fig. 2.6, 2.7 & 2.8; Table 2.1).

- In the *Inner shelf facies association*, the fair-weather processes are dominant, and all deposition is cited above the fair-weather base (FWB). Bosman et al. (2007) postulated the presence of 30m isobaths at the FWB junction between the well-sorted, fine-grained sand (Facies 3) and the poorly-sorted sand (Facies 4). In addition, there is no fining upward sequence (FUS) within the facies association as uniform; very well-sorted fine sand present in the sedimentary core (Facies 3) indicates the reworking of the Inner shelf by longshore currents and wave action.
- The *Mid-shelf facies association*, fining upward sequences (FUS) of 0.5m to 3m thick characterize the Mid-shelf (Facies 4). At the base of these sequences, the presence of gravel or shell lags was observed forming the scoured base; along with large floating clasts, this represents a storm-generated (tempestite) or density flows. Also, within facies, a mud horizon capping these FUS units in places is noted formed through suspension settling process of fluvially derived muds entrained in the gyre circulation during quiet periods. The symmetrical distribution of mud beds on the Inner and Mid-shelf (Facies 2) is reported with thickness ranging between 0.4m to 1.5m. Additionally, the less frequent coarsening upward units are present with basal gravel lag deposits which represent the surface erosion from which the

migration of sedimentary bedform took place. A prominent semi-continuous palaeodune cordon marks the Mid-shelf outer boundary (-60m) with a shelf slope increasing gradually. Moreover, these facies distinguish the Holocene sediment wedge seaward margin, an indicative of the modern terrestrial boundary for the deposition of sediment. Further observation points to the deposition of the Holocene wedge against the palaeodune ridge serving as a barrier to the movement of cross-shelf sediment into Outer shelf within this facies association (Flemming, 1978; 1980a; 1981; Martin and Flemming, 1986; Birch, 1996).

- The *Outer shelf facies association* sediment dispersal and sedimentary processes are influenced by the southerly-flowing Agulhas Current. Here, sand ribbons, relict carbonate-rich gravels and large southerly-migrating bedforms distinguish the sediments of the Facies 7 (Fig. 2.7) (Flemming, 1978; 1980a; 1981). Bosman et al. (2007) postulated that the unconsolidated sediment of this facies association is subjected to strong current action which continuously moves it over the shelf break edge and into present submarine canyons leading to the development of sediment-starved Outer shelf.
- A set of facies namely the Thukela mouth bar (Facies 1), Inner and Mid-shelf muds (Facies 2), sand-rich (Facies 5) and mud-rich (Facies 6) density flow deposits describes the *submarine delta association* of the Thukela Shelf delta system from the Mid- to Outer shelves. From Figure 2.7, the location of each facies is reported with Facies 2 extending northward and turning cross shelf then forms an offshore loop. Facies 5 splits Facies 4 (Mid-shelf) into two parts and proceeds down to Facies 6 (Mid- and outer shelf muds) which is the Thukela delta distal expression remarked Bosman et al. (2007). Facies 6 depicts the density flows deposition originating from the Thukela Shelf Delta Inner and Mid-shelf parts (Falhaber, 1984). The author (Bosman et al., 2007) contended that the Outer shelf mud (Facies 6) position on the shelf reflects its recent deposition within the setting as the Outer shelf (Facies 7) gravel or bedforms entrained within the Agulhas Current couldn’t buried.

Additionally, two distinct facies (Facies 2 and 6) of mud encountered in the study area represent two separate depocenters (Fig. 2.7). Forbes et al. (2002) postulates the occurrence of Inner shelf mud (Facies 2) in the Inner and Mid-shelf regions composed of pure mud that forms the well-known prawn-rich Thukela Mud banks as depocenter one. As for the Outer-shelf mud (Facies 6), there is a poorly-sorted sandy mud present on the Outer shelf and extends beyond the shelf break (Fig. 2.7) as depocenter two.

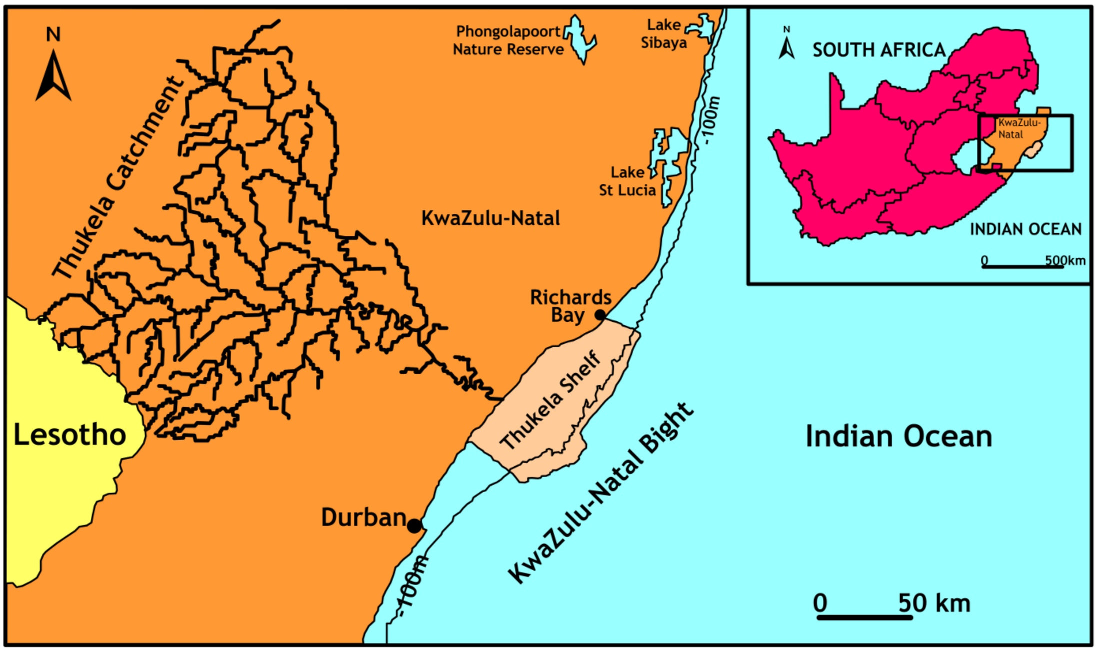


Figure 2.6 Both Thukela River drainage and Thukela Shelf location within the KwaZulu-Natal Bight (modified after Bosman et al., 2007)

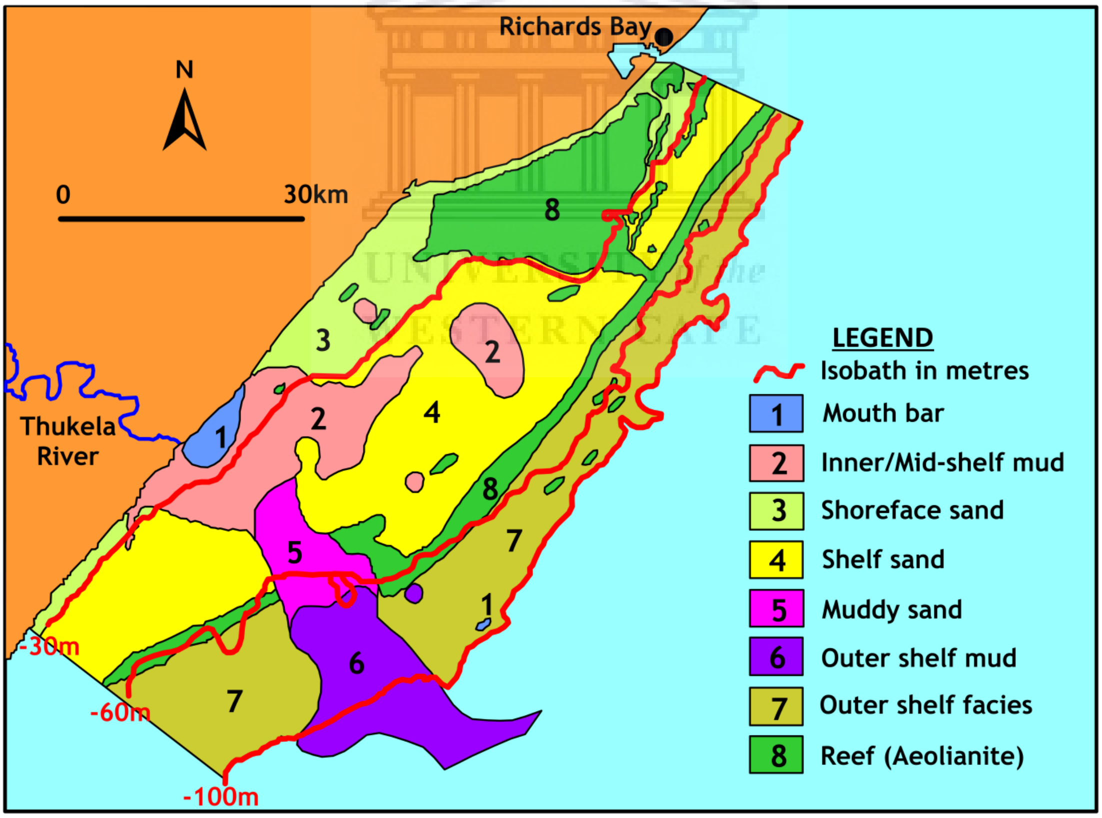


Figure 2.7 Thukela Shelf: distribution of eight recognized facies types. Each facies number is related to the table below. The -30, -60 and -100m isobaths are shown to define the Inner, Mid- and Outer shelf zones (modified after Bosman et al., 2007).

Table 2.1 Sedimentary facies, sedimentary environments and facies associations of the Thukela Shelf (after Bosman et al., 2007).

Facies	Sediment type	Sedimentary process	Facies association	Depth (m)
1	Poorly-sorted, fine, medium and coarse sand	Deposition at river mouth – mouth bar	Delta (Inner shelf)	<30
2	Mud (Inner shelf mud)	Fluvial suspension load settling controlled by current and gyre circulation	Delta (Inner and Mid-shelf)	0-50
3	Very well-sorted, very fine to fine-grained sand	Reworking of shoreface sands within the fair-weather wave base and by the longshore drift current	Inner shelf	0-30
4	Poorly-sorted, medium- to coarse-grained sand (frequently with fining up units)	Kwazulu-Natal Gyre transportation & storm-generated sedimentation	Mid-shelf	30-60
5	Poorly-sorted, medium-grained muddy sand	Sand-rich density flows originating from delta front	Delta (Mid-shelf)	50-70
6	Poorly-sorted, sandy mud (less clay than the inner mud) (Outer shelf mud)	Mud-rich density flows originating from delta front	Delta (Outer shelf)	70-100
7	Moderately-sorted, fine- to coarse-grained carbonate sand	Scouring and winnowing by the Agulhas Current	Outer shelf	60-100
8	Reef	Submerged palaeocoastal dune cordons	Reef (inner, Mid- and Outer shelf)	Any depth

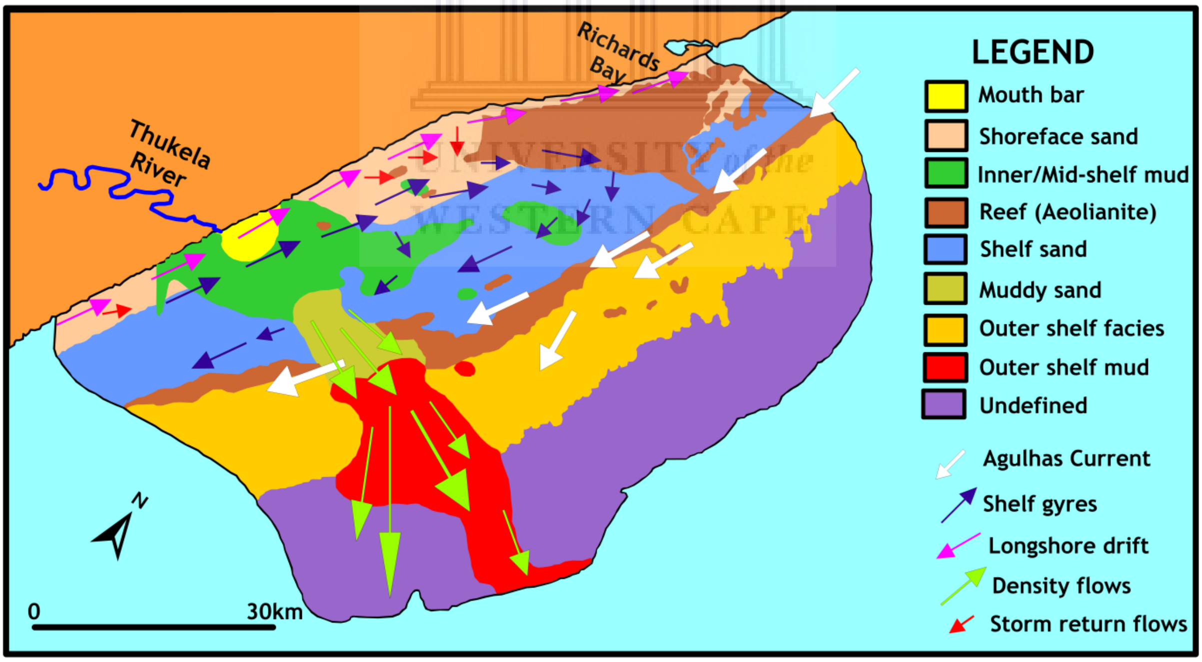


Figure 2.8 The Thukela Shelf 3D terrain model with shelf morphology, distribution of sedimentary facies along with oceanographic processes (modified after Bosman et al., 2007).

2.9 Morphology of the continental margin

A narrow shelf marks the continental margin of the East Coast of South Africa reaching 3km wide in some places to 40km in others below the world average of 75km with a very steep continental slope, 12°, higher than the world average between 3-4° (Shepard, 1963; Flemming, 1981). Submarine canyons within the Durban Basin dissect the shelf break intermittently with varying density of frequency (Flemming, 1981). The canyons penetration into the shelf is limited while their effects on the dispersal of sediments largely rely on the shelf width. With a relatively wide shelf reaching more than 10km, canyon heads at the Durban Basin are sited far off the coast. The shelf platform of the East Coast can be divided into two zones, a nearshore and offshore zone. Moreover, submerged and partly reworked Pleistocene sediment ridge separates both zones that stretch subparallel to the coastline between 40-60m water depths. Additionally, the sediment ridge is made of indurated coastal dune cordon remnants (Flemming, 1980b). The ridge is along most part of the shelf although being discontinuous (Birch, 1979; Flemming, 1981).

Several phases of canyon incision and fill underlying the canyon head had been revealed through the deep penetration multichannel seismic from the mid slope (Fig. 2.9) (Wiles et al., 2013). As such, three phases of canyon incision and fill can be distinguished which include the youngest canyon fill marked by onlapping drape relationship with palaeo-canyon walls. The series of drapes identified within the canyon hold the contemporary Tugela Canyon head. Wiles et al. (2013) detailed the down-canyon characteristics associated with canyon width, relief, margin and gradient for the multibeam bathymetry covered areas at Table 2.2. The canyon relief and width highlighted from the up-canyon and down-canyon limits to illustrate the canyon profile. The Tugela Canyon presents on overall increasing trend with respect to width and relief while the distance increases relative to both the continental shelf and water depth; and the canyon floor gradient exhibits some variation that generally decreases with increasing water depth and increasing distance from the continental shelf (Table 2.2).

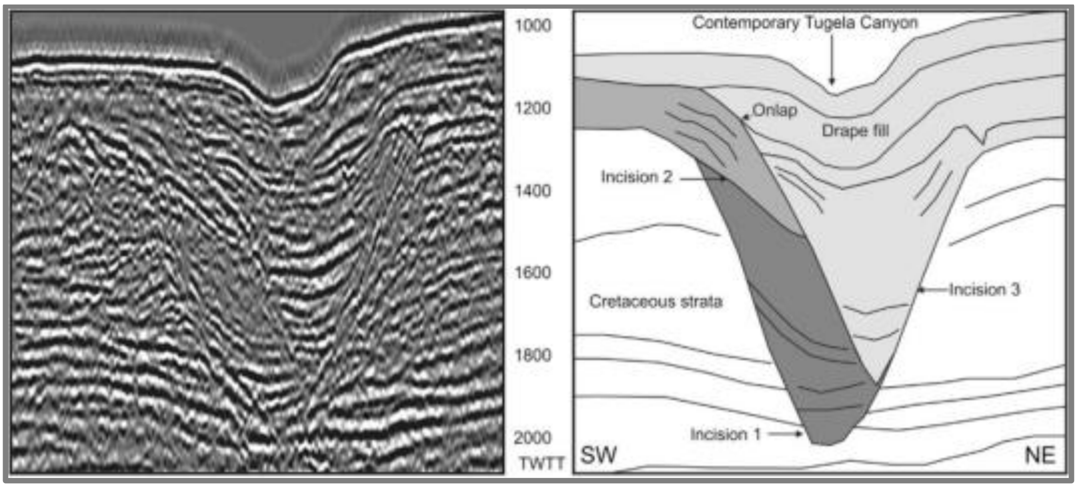


Figure 2.9 A multi-channel seismic record and interpretation from the mid-slope portion of the Tugela Canyon along the strike. The three stacked paleo-canyons while an onlapping drape fill dominates the youngest. The canyons stacking pattern with the contemporary Tugela Canyon position within the low point of the drape succession (Wiles et al., 2013).

Table 2.2 Down-canyon comparison of relief, width and gradient by Wiles et al. (2013)

Swath	**TC1**	**TC2**	**TC3**	**TC4**	**TC5**
Width (km)	3.1	6.4	11.5	12.2	18.3
Relief (m)	72	435	572	579	874
Width (km)	6	6.8	13	13.8	19.6
Relief (m)	260	458	599	615	1028
Margins (km)	Straight	Straight, divergent	Meandering, diverging	Meandering, diverging	Meandering, diverging
Gradient (°)	3.7	0.3	0.6	0.6	0.6

2.10 Oceanographic regime

The Agulhas current, the powerful southern hemisphere current, transports warm waters that sweeps the narrow continental margin of the East Coast, from the equatorial region of East Africa into the southern seas (Hartnady et al., 1992). The current is offset by the cold-eastward-bound waters at greater depths from either the North Atlantic Deep Water (NADW) or the Antarctic Bottom Water (AABW) (Hartnady et al., 1992). The Agulhas current drives a conveyor-belt process which carries excess sand onto the central shelf. Thereafter, the formed sandstream offloads its deposits on the upper continental slope due to the interruption caused by the structural offsets where the current overshoot the shelf break. Some distance downstream, the sandstream is regenerated where the current rejoins the shelf (Flemming, 1981).

The passage of the Agulhas current and the counter cold current NADW in this region plays an essential role in the transportation of sediments into the East Coast basins (Dingle et al., 1987). The current initiates a new sand stream at its northern limit sedimentary compartment while defining the southern limit of an eddy system at the same location. It is worthy to note that the development of bedload partings on the seabed indicates the boundary between southerly flow of the Agulhas Current and the northerly flow in the eddy systems (Flemming, 1981). Moreover, the partings are not stationary features as observed south of Durban and to the north of Richard’s Bay, but they constantly shift due to the long-term behaviour of the Agulhas Current. South of Durban, the bedload parting zone is about 10km wide (Flemming, 1981), and Flemming (1980a) established a relationship between the offset size and the associated eddy system intensity represented by the bedload parting zone size and the bedform development scale.

The dispersal of sediment along the East Coast of southern Africa is controlled by the Agulhas current which is one of the few fast-flowing ocean currents near the coastlines for appreciable distances as a result of narrow continental shelf (Flemming, 1981). The current is unsteady; and its unsteadiness creates a viable environment for large-scale sediment supply into the central-shelf sandstream (Flemming, 1980a). Both the orientation of the shelf break and current course has an impact on the dispersal of sediment along the East Coast of South Africa. The current passes near the shelf break. Since the flow momentum impedes an adjustment to sudden topographic modifications; the current overshoots the shelf break and follows the deeper-water path at each structural offset (Flemming, 1981). Furthermore, the southwest flowing surface Agulhas current sweeps the inner and outer continental shelf of the South African East Coast; thereafter it carries inbound sediments delivered from numerous streams and rivers such as the larger Tugela River into narrow continental shelf and deposits these sediments into well-developed submarine-canyon system heads (Goodlad, 1986; Boebel et al.,1998). Further deposition occurs above the thick continental-rise fans and abyssal plain sequences following turbidity currents (Flemming, 1981).

2.11 Previous biostratigraphy studies of the East Coast of South Africa

The seven sedimentary basins of South Africa the main hydrocarbon prospects are confined mainly within the late Mesozoic (mainly early Cretaceous succession) spread from the Indian Ocean on the East Coast through the South Coast to the Atlantic Ocean on the Western Coast. All the seven basins share some similarity in tectonic and sedimentary patterns as a result of rifting and drifting processes contemporaneously which affected the southern hemisphere during the Gondwana breakup (McMillan, 2003). The stratigraphic account of these basins reflects undisturbed Cretaceous and Cenozoic periods which allowed for the preservation of fossil records (McMillan, 2003).

From 1904 to the late 1950, the first attempt was made to biostratigraphically subdivide the southern African Cretaceous drift successions (Chapman, 1904, 1916; Ferreira and Rocha, 1957). It was up until 1958 and 1968 that the first Angolan and South African biostratigraphic subdivisions, respectively, were established using foraminiferal biostratigraphy to launch biostratigraphic records of well successions (Hoppener, 1958; De Gasparis, 1968). Furthermore, detailed studies of the continental margin were embarked on, and a comprehensive review of the offshore succession were established toward the end of 1970s (McMillan, 2003). But with increased oil exploration activities in South Africa around 1980s and the early 1990s reflect a period where both the integration and synthetization of well analysis were not regionally completed (McMillan, 2003). Deep Sea Drilling Project (DSDP) and Ocean Drilling Project Legs 25 and 26 were undertaken along the East Coast of South Africa, respectively Legs 40, 74, 75, and 175 on West Coast to understand the deep-water foraminifera assemblages of the southern Africa. Various DSDP sites (249, 361, 363, 364, 525, 527, 528, 529 and 530) were legs from which Cretaceous drift succession were traversed in the southern Africa. Foraminiferal biostratigraphy studies in South Africa received a boost between 1970s and 1990s with the improvement of drilling techniques used during oil exploration activities; this allowed for a better collection of cutting samples (McMillan, 2003).

Chapter III

3. Materials and methods

3.1 Introduction

This chapter outlines the methods and materials utilised during the course of this integrated research work (Fig. 3.1).

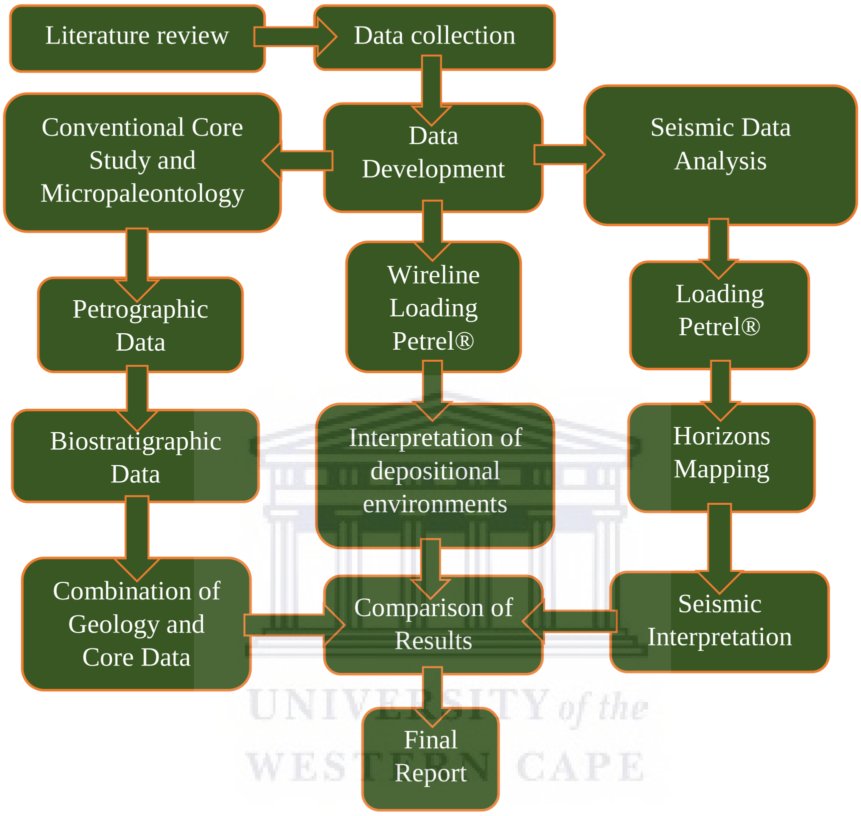


Figure 3.1 Research workflow

3.2 Data Collection

The following materials and data necessary for this research were collected from the Petroleum Agency South Africa (PASA):

- Geological well completion reports,
- Conventional Core Sample from CC# 1 of Well Jc-B1
- Well cuttings for biostratigraphic studies
- Well logs,
- Check shot data,
- Well tops,
- 2D seismic data.

All the four wells of the Durban Basin were drilled on the continental shelf offshore, east coast South Africa to test for hydrocarbon reservoirs as part of South Africa search for hydrocarbon (Fig. 3.2; Table 3.1). Very little information of the subsurface geology of Durban Basin and east coast basins existed before the Jc project's drilling phase (Leith, 1971). The first well (Jc-A1) was drilled in 1971 after the stratigraphic trap was identified as potential reservoir (Leith, 1971). Following the drilling of the first well, correct geological information of the continental shelf was then assembled for the east coast basins (Leith, 1971). The Second and Third wells Jc-B1 and Jc- C1 were drilled in 1983. The drilling of the last well (Jc-D1) to date in 2000 was supported by regional hydrocarbon potential, seismic stratigraphy and palaeogeographic mapping information (Halliburton/Sperry-Sun Drilling Services, 2000).

The wells are aligned parallel to the coast and the distance between the wells varies from 5836m (Jc-A1 to Jc-B1), 39632m (Jc-B1 to Jc-C1), to 61244m (Jc-C1 to Jc-D1) (Fig. 3.3).

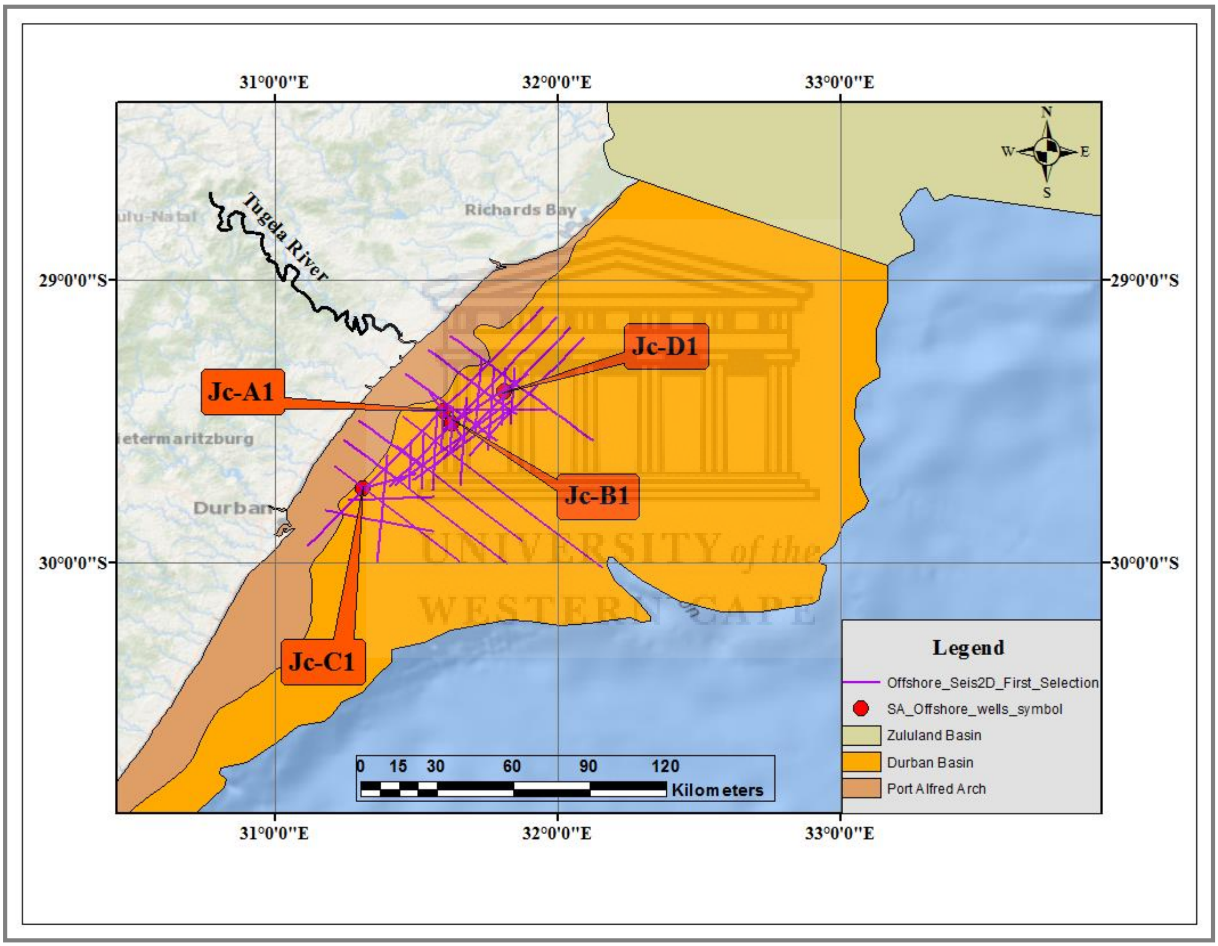


Figure 3.2 Durban Basin drilled offshore wells with selected 2D seismic lines

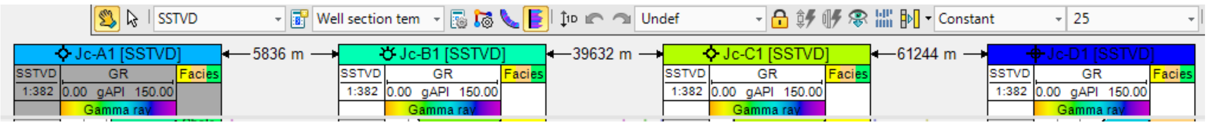


Figure 3.3 Durban Basin wells distribution

Table 3.1 Durban Basin well details

Name	Location	Classification	Symbol	Water Depth (m)	Total Depth (m)
Jc-A1	24km east of Stanger, offshore	Wildcat	Dry	71.6	2400
Jc-B1	80km NE of Durban	New field exploratory	Poor gas shows (minor gas)	80.4	3943
Jc-C1	28km ENE of Durban, offshore	Wildcat	Dry	97.7	3169
Jc-D1	91km NE of Durban	Wildcat	Plugged and abandoned	76.4	2900

3.3 Sample selection for biostratigraphic studies

Biostratigraphic data is the main source for dating the sedimentary succession and for paleobathymetric analysis. For marine sediments the microfossil group 'foraminifera' are considered to be most useful. Samples needed for foraminiferal studies are selected carefully through megascopic sample examination. The argillaceous sediments are always preferred for best faunal recovery. The microfossils are isolated from the sedimentary rocks through special laboratory processing techniques that involve several steps. The isolated foraminifera microfossils are studied carefully under high power binocular Stereozoom, placed under different morph groups by analysis test composition, wall microstructure. For this standard catalogues and reference books are used. This has been discussed in Chapter V.

3.3.1 Well cutting samples

Before selectin of well samples, the Geological Well Completion reports were studied in detail along with the composite log to select the sample. As already mentioned in the preceding chapters that four wells were drilled in this basin viz. Jc-A1, Jc-B1, Jc-C1 and Jc-D1. A total of approximately 4380 meters of samples interval was studied for the entire work.

Information available from the well completion reports indicates that cutting sample intervals were not collected in the drill site at a constant interval. In foraminiferal biostratigraphic studies usually samples are analysed at regular interval and also the argillaceous/ calcareous intervals are considered to the best for optimum faunal recovery.

3.3.2 Laboratory processing for foraminiferal recovery

A total of 78 well cuttings were selected for the present work. The samples are cleaned thoroughly with water to remove any drilling mud contamination and then dried. Caved particles (if any) present in the cuttings are separated manually. The washed cutting samples were studied for their lithological details (colour, texture, mineralogy, presence of oxidised/pyritised/carbonaceous matter and lithology percentage) prior to disintegration. The following steps were adopted in the present work:

i. All efforts were made to process 20g for each interval. For some intervals 20g samples were not available. The samples were cleaned repeatedly to remove any drilling mud present and kept in enamel bowls.

ii. Disaggregation phase: 30% Hydrogen peroxide (H_2O_2) was added to each bowl along a little washing soda to aid disintegration. Hydrogen peroxide helps to disintegrate the sediment matrix and isolate the microfossils.

iii. Boiling phase: the samples were boiled for about 15-20 minutes and then allowed to cool under room temperature.

iv. Washing phase: disaggregated samples were washed through sieves of 300 mesh size to remove the clay particles. The washed residue is allowed to dry in oven. The dry residue is properly kept in transparent container with a proper identification number (well name, depth interval, etc.)

v. Identification phase: The foraminifera microfossils were separated from the processed residue under a Stereozoom binocular microscope. The processed residue is spread in a special black metallic tray and by using a wet fine pointed brush (00, 000, 0000 size) and kept in micropaleontological slides for identification and preservation in repository.

vi. Detail account of identification, frequency etc. are discussed under biostratigraphy chapter.

3.4 Petrography

As only one conventional core was cut, the thin section petrographic studies was carried out from the top sedimentary segment. To understand the type of igneous intrusive few thin sections were also made. Petrographic studies from the only Conventional Core (CC#1, Well Jc-B1) was carried out using a binocular light microscope. Petrographic information viz. textural parameters, mineralogical composition and presence of any microstructures, biological contents and diagenetic features along, types of cements .and cementation textures. As only one conventional core was available for studies a total twelve thin sections from selected core intervals from clastic (five samples) and intrusive igneous materials (seven samples) were prepared and studied.

3.5 Information from Geophysical data

As only one Conventional core and limited well cuttings was available for the entire work, to bridge the data gap geophysical information (Seismic and well logs) were used. Use of Geophysical information to bridge data gap between core samples and well cuttings has been discussed by Kamgang (2013). The geophysical data used in this study includes well logs, well tops, checkshot and seismic data. The re-examination of well log and checkshot data was done for the well-to-seismic tie process. The interpretation of seismic delved on structural and Isochore maps analysis in addition to attribute extractions to generate the Durban Basin stratigraphic evolution.

The analysis, Modeling and interpretation of geophysical data were done using Petrel® 2018 Software Platform from Schlumberger. The software provided the methods such as well log analysis, integrated seismic well tie, sonic calibration, and synthetic generation.

3.5.1 Well logs

A well log is the recording of the measurement of a geophysical parameter plotted continuously against depth in the wellbore (Rider, 1996). In the present study the well log signature is used mainly for the interpretation of depositional environment within the early Cretaceous succession.

The followings are the common use of well logs:

- Gamma Ray log (GR) is used to distinguish the rocks type on the subsurface by recording the radioactive source intensity.
- Density log is used to calculate porosity by indirectly measuring the density of hydrocarbon if present.
- Sonic log measures rocks rigidity in drilled section by calculating the sonic wave’s velocity.
- Resistivity log is used to distinguish the types of fluid present in the drilled section. High resistivity values could indicate a formation which is porous and hydrocarbon-rich.
- Neutron porosity log measures the amount the amount of hydrogen in a drilled well section.
- Caliper log measures the well shape and diameter along the well depth. Moreover, it indicates the quality of the hole which assists assessing other logs data qualities. The ability to recognize the well caving state and mudcake content assists determine whether the readings of other tools (i.e. GR, Sonic, etc.) are reliable or not.

The well log data for wells Jc-A1, Jc-B1, Jc-C1 and Jc-D1 were loaded into Petrel 2018 in LAS formats, and the following logs were displayed: Gamma Ray, Density, Resistivity, Neutron, Sonic and Caliper (Table 3.2).

Table 3.2 Different well log used in this study

Logs	Abbreviations
Sonic	DT and DT24QI
Gamma ray	GR
Deep Resistivity	ILD
Neutron Porosity	NPHI and SNP
Bulk Density	RHOB
Caliper	CALI & CAL

3.5.2 Data cleaning

No data cleaning was necessary for all the wells.

3.5.3 Seismic data

The data is used to generate structural and static information for a reservoir such as its lateral extent and thickness, faults and porosity present, among other reservoir properties. Studied horizons have been selected based on their potentiality to host hydrocarbon reservoirs at sequence level along the costal margin of South Africa. Moreover, the incorporation of seismic data along with well log data can yield a more appropriate understanding of the lithological information (Chaki et al., 2014).

Four selected 2D seismic lines with each line crossing a well were assessed to recognize and delineate horizons of interest (Fig. 3.4).

The following steps were used to interpret the seismic horizons (Hutton, 2015):

- 2D processed seismic lines, checkshots and well tops were loaded on Petrel 2018 software;
- Checkshot data delivered information on velocity required to link encountered formations in the wells with seismic section reflections;
- Well to seismic tie was done through connecting wells and checkshot data;
- The formation tops provided assisted the picking of each horizon (Table 3.3);
- The seismic attributes (amplitude and phase) were used during the identification of seismic horizons.

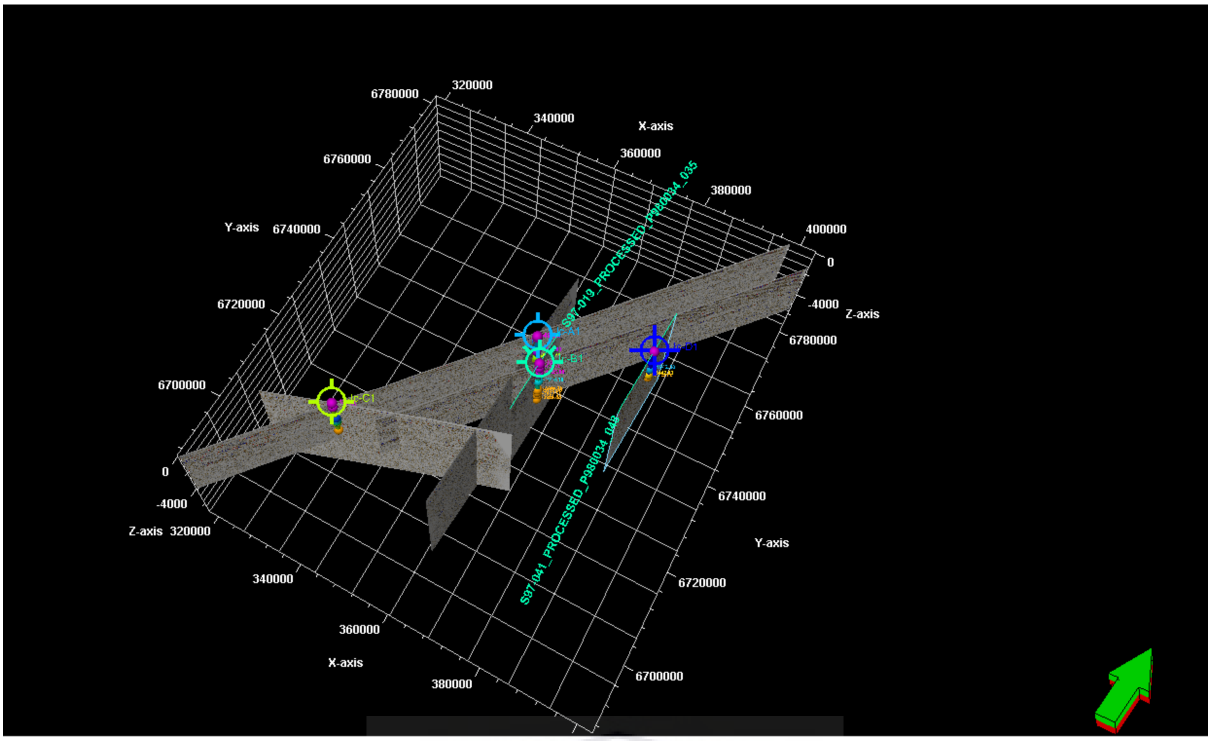


Figure 3.4 Study area in NE with all the wells and seismic lines

Table 3.3 Generalized Chronostratigraphy of South African basins

Standard Chronostratigraphy	**Age of the Unconformities in Ma**	**Major Unconformities**	**Stages**
LATE CRETACEOUS	67	**22At1**	Late Maastrichtian
	80	**17At1**	Campanian
			Santonian
			Coniacian
	95	**15At1**	Turonian
			Coniacian
EARLY CRETACEOUS	108	**14At1**	Albian
	124	**13 At1**	Aptian
	131	**6At1**	Barremian
			Hauterivian
	138	**1At1**	Valanginian
			Berriasian
LATE JURASSIC			Tithonian
			Kimmeridgian
			Oxfordian
PRE - JURASSIC	**ONSET OF RIFTING**		

These are the major seismic horizons / Unconformity surfaces recognised in the South African basins.

Chapter IV

4. Depositional environment from Seismic, well logs and petrographic analysis

An attempt has been made in this study to predict overall depositional environments using information available from Seismic interpretation, well log motifs (mainly Gamma Ray log) and petrographic analysis with the solitary conventional core. As only one conventional core was available the important lithological information available from the Well Completion Reports and megascopic descriptions available from the composite logs was widely used in this work.

Importance of lithological analysis using well cuttings, recording many associated components (such as presence of shell fragments, glauconite, oxidised minerals, pyrites and carbonaceous detritus helps in understanding the depositional condition. Glauconite is the product of shallow marine sediments early diagenesis. Stable under marine domain, it can be found among beach or deep-sea fan sediments due to transportation. If its grains are found in sandstone, marine environment is the likely domain of sandstone deposition. Among the carbonaceous detritus, plant and coal fragments are listed. They can be found both at continental or marine source. The presence of organic matters in rocks suggests a rapid deposition with minimal reworking and oxidation (Chow et al., 2005). Ideally, a detailed sedimentological and petrographic study of cores should accompany facies analysis. However, the limited number of cores at the Durban Basin renders this approach unachievable. Moreover, having one core cut out of the four drilled wells in the Durban Basin, this study interprets depositional environments based on Selly and Sonnenberg (2015) method.

4.1 Information derived from Seismic

Seismic interpretation was carried out to recognize the lateral distribution the sedimentary fill in the studied area of the Durban Basin to have a broad idea about the depositional environment. This was done by selecting appropriate seismic lines and followed by integrating it to the wells by generating synthetic seismogram for each of the four drilled wells from the four 2D seismic lines and then to correlate the seismic data and well log data.

Methodology: Sonic logs were calibrated with checkshots, and the wavelet was extracted from the seismic volume. The quality of the tie is verified by comparing the output interval velocity to the input interval velocity. Overall quality of the tie can be considered as good for all the wells (Fig. 4.1 & 4.2). Although, there is a minor velocity difference at Track 12 (lower and middle section of the log) between the output interval velocity vs the input interval. Also, there are some misfits observed between the well tops (depth-domain) and horizon picks (depth-converted) of the basin seismic lines. The misfits point to variations of velocity profile within the basin (Fig. 4. 3).

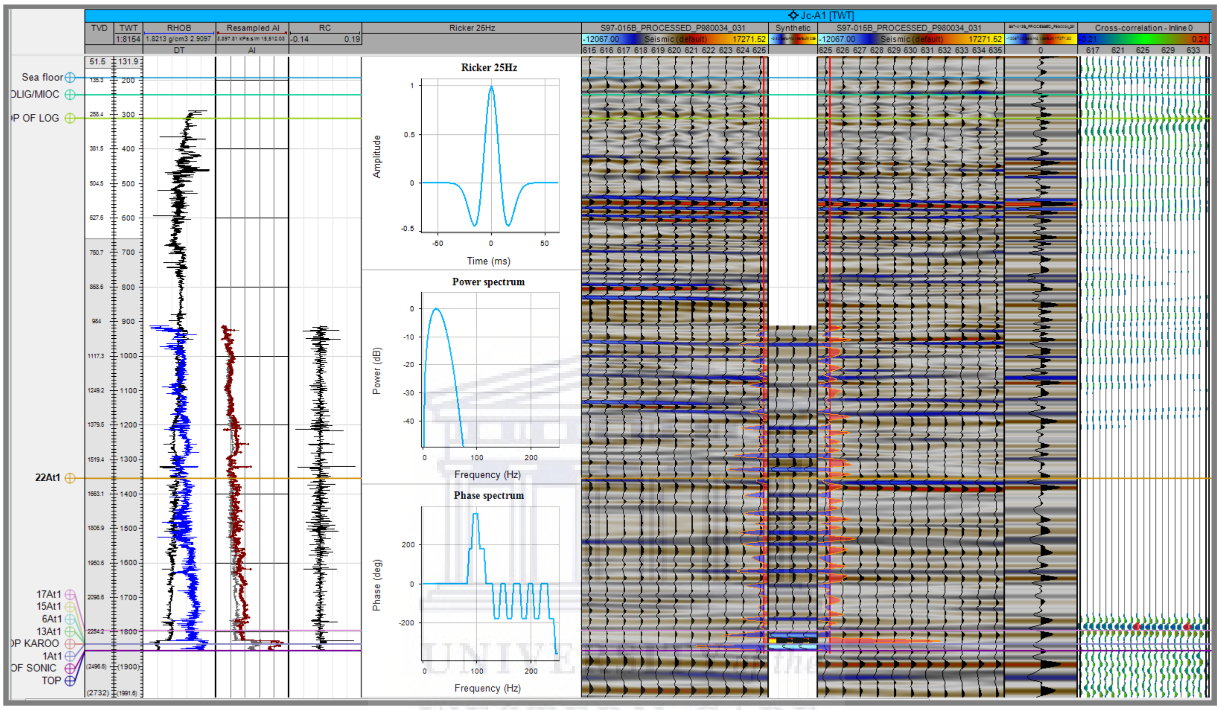


Figure 4.1 Well Jc-A1 well-tie. Track 1 is bulk density log in blue with calibrated sonic log in black. Track 2 is resampled AI log. Track 3 is reflection coefficient log. Track 4 is Ricker 25Hz, Power spectrum and Phase spectrum graphs. Track 5-7 display seismic data with generated synthetic seismogram at its centre (Track 6). Track 8 is processed line. Track 9 is cross-correlation – inline 0.

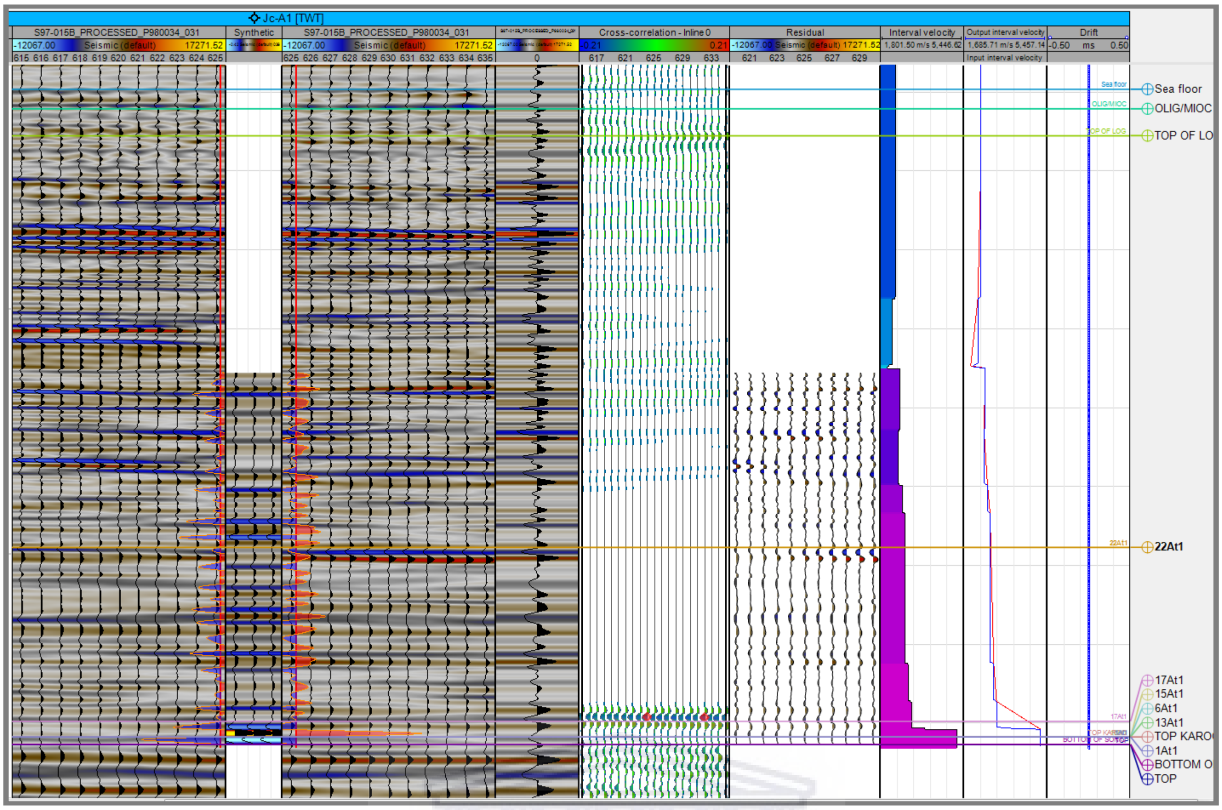


Figure 4.2 Track 10 from (Fig. 4.1) is residual. Track 11 is interval velocity. Track 12 is output interval velocity in blue and input interval velocity in red. Track 13 is drift curve.

4.1.1 Horizon description

The deposition of Cretaceous sediments in the South African sedimentary basins are marked by regional unconformities 6At1 to 15At1 (Broad et al., 2012). The regional unconformities 1At1, 6At1, 13At1 and 14At1 are usually recognized within the early Cretaceous in many South African basins. In the Durban Basin, the regional unconformities within the early Cretaceous intervals identified are 6At1 and 13At1 in wells Jc-B1 and Jc-C1 but not recognized in Jc-D1. The entire early Cretaceous is absent in well Jc-A1. Above 14At1 all other unconformities recognised are not included in the present studies but is presented in Table 4.1.

The lines (a, b & d) in Figure 4.3 were acquired along the south-north direction while line (c) along the west-east direction (Fig. 4.3). At Jc-A1, six seismic horizons are featured in the cross section passing through the well in different colours. Top & Bottom of Sonic horizons (orange) are overlain by Top Karoo, 15At1, 13At1, 6At1 & 1At1 horizons. 17At1 underlies 22At1. Top of Log and Olig/Mioc horizons ends the cycles at Jc-A1. At Jc-B1, seven seismic horizons are highlighted in the cross section passing through well in different colours. Bottom of Sonic & Top Volcanic horizons (purple) are overlain by 6At1 & 1At1 horizons (green). 13At1 & 15At1 horizons (pink) followed by 17At1 horizon. 22At1, Top of Sonic & Olig/Mioc overlie the earlier horizons. At Jc-C1, seven seismic horizons crossed the well in different colours. Lower horizons (Bottom of Sonic, 6At1 & Top Volcanic) are green coloured followed by 1At1 horizon in cyan. 15At1 & 13At1 horizons (in yellow) overlie 1At1. This sequence is followed by 17At1 horizon (purple) and Top of Sonic horizons (blue). 22At1 in orange is overlain by Olig/Mioc horizon in green. At Jc-D1, three seismic horizons featured in the cross section: 1At1 horizon in green overlaid by the 15A1 horizon in cyan followed by 22At1 horizon in yellow.

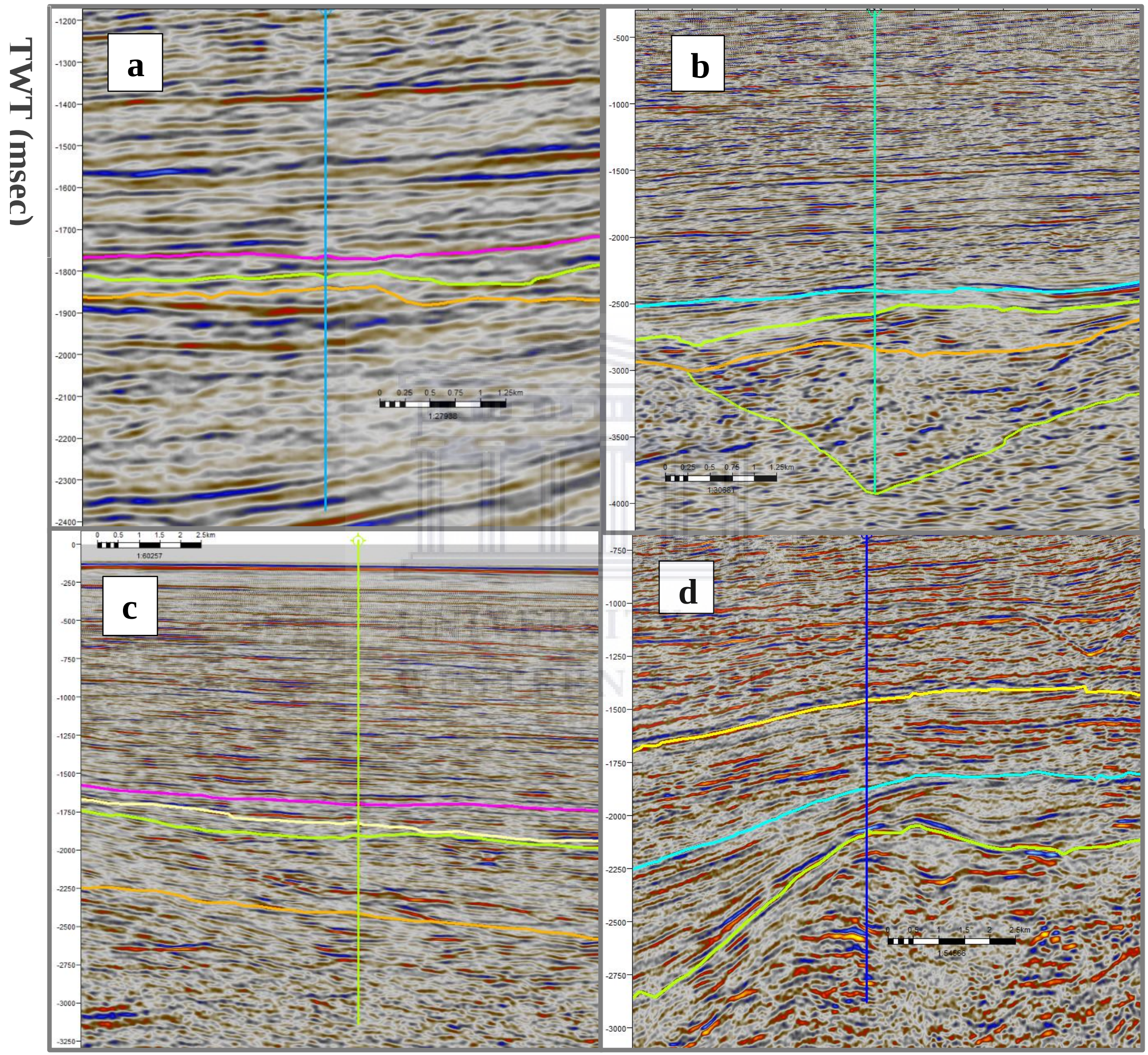


Figure 4.3 Seismic cross sections display the wells: (a) the line extracted along the south-north direction crossing the well Jc-A1, (b) the line extracted along the south-north direction crossing the well Jc-B1, (c) the line extracted in a west-east direction crossing the well Jc-C1 and (d) the line extracted along the south-north direction crossing the well Jc-D1. Each horizon is represented by different colours demarking formation boundaries.

Table 4.1 Seismic horizons (Formation tops) intersected by the four drilled wells with biostratigraphic age intervals studied

Well name	Seismic Horizons	Depth (m below Kelly Bushing)	# of horizons	Age as per Well Reports	Biostratigraphic Results (present study)
Jc-A1	17At1	2219	1	Turonian-Cenomanian	Not studied
	1At1, 6At1, 13At1, 15At1	2302	2	Upper Carboniferous	Not studied
	Top	2351,5			
Jc-B1	15At1	3110	4	Cenomanian	Cenomanian
	13At1	3137			
	1At1 & 6At1	3429	5	Late/Early Aptian	Barremian- early Aptian
Jc-C1	17At1	1965	7	Santonian	Not studied
	13At1 & 15At1	2114	8	Late Aptian/Albian	Cenomanian
	1At1	2257	9	Barremian-Early Aptian	Late Albian
	6At1	3115	10	Undefined	Barremian- Early Aptian
Jc-D1	15At1	2442	11	Cenomanian	Cenomanian
	1At1	2734	12	Late Aptian	?Late Aptian

4.1.2 Seismic Horizon interpretation

Twelve (12) seismic horizons with high amplitude were interpreted from four 2D seismic lines which have crossed at least one of the four wells (Fig. 4.3a-d). This was carried out following the methodology adopted in Mitchum et al. (1977) and Hicks and Green (2016). The mapped horizons have reflections characterized by good to moderate continuity; the reflections dip in general southward for lines acquired along the south-north direction (Fig. 4.3a, b &d) and eastward for the west-east direction (Fig. 4.3c). Few horizons show chaotic reflectors in all four lines (Fig. 4.3b-d). Moreover, the interpreted horizons show variation in thicknesses between horizons from -100msec (TWT) to -1400msec (TWT), in depth between -300msec (TWT) and 3700msec (TWT) across the surveyed horizons.

In the present work it was found that the entire early Cretaceous and the earliest part of late Cretaceous section in the location Jc-A1 was eroded and is represented by a major hiatus. Below the hiatus is the lower Devonian (Paleozoic) age group of sediments are present. Therefore, the sections under Top Karoo (Upper Carboniferous) and the early to earliest late Cretaceous horizons (*1At1, 6At1, 13At1 and 15At1* respectively) are converging. The seismic line was extracted along the south-north direction. This was followed by a hiatus of prolonged duration after which the late Cretaceous (Turonian) sediments were deposited age (Hicks and Green, 2016). The line shows a divergent reflection configuration pattern with divergent fill.

However, when zoomed in, a subparallel reflection configuration is present with chaotic reflectors (Fig. 4.3a; 4.4 & 4.5). This observation was further supported by foraminiferal biostratigraphic studies in the present work where the lowest fossiliferous assemblages indicates late Cenomanian to Turonian age (late Cretaceous affinity) and therefore the well Jc-A1 was not considered for biostratigraphic analysis.

Two early Cretaceous seismic horizons (*1At1 & 6At1* and *Top Volcanic & Bottom of Sonic*) intersected in well Jc-B1 appear truncated by features bearing incision characteristics (Fig. 4.3b). The seismic line was aligned along the south-north direction. Moreover, *Bottom of Sonic & Top Volcanic* horizon appears to pinch out against *6At1* & *1At1* horizon. The incision feature appears below the *Top Volcanic & Bottom of Sonic* horizon combined (Fig. 4.3b). Also, the reflection configuration pattern is strongly subparallel within the early Cretaceous horizons to slightly divergent in the younger horizons. Chaotic reflections are conspicuous below the *1At1 & 6At1* horizons. The fill seismic migrates from partly divergent within *1At1 & 6At1* horizon to chaotic fill at *Top Volcanic & Bottom of Sonic* horizon (Fig. 4.3b; 4.4 & 4.5).

The two seismic horizons within the early Cretaceous (*1At1* and *6At1*) were identified in well Jc-C1. The horizons bear some incision features (Fig. 4.3c). The seismic line was extracted in a west-east direction. No evidence of faulting was observed. Remarkably, the thickness of the layers between *13At1 & 15At1* and *1At1* horizons are very thin and the reflection configuration is subparallel throughout with subparallel-chaotic fill. The basement has chaotic reflectors with chaotic fill (Fig. 4.3c; 4.4 & 4.5).

One early Cretaceous horizon (*1At1*) was intersected by the well Jc-D1 (Fig. 4.3d). The seismic line was aligned along the south-north direction. The horizon *1At1* overlies the basement unit and is well defined with sharp reflector. Its surfaces have few signs of erosional features compared to the lines observed in well Jc-A1. The early Cretaceous horizon shows a hummocky clinoform reflection configuration pattern with divergent fill interior as it overlies a lenticular-configured basement. The basement reflectors are chaotic throughout with chaotic fill. The younger horizons above *1At1* carry divergent configurations (Fig. 4.3d; 4.4 & 4.5).

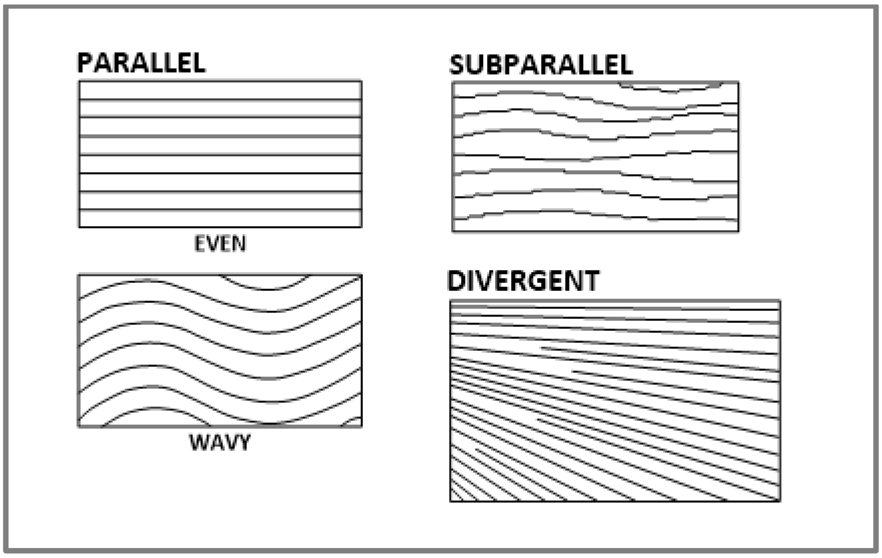


Figure 4.4 Diagram depicting parallel, subparallel, wavy and divergent seismic reflector patterns modified after Mitchum et al. (1977).

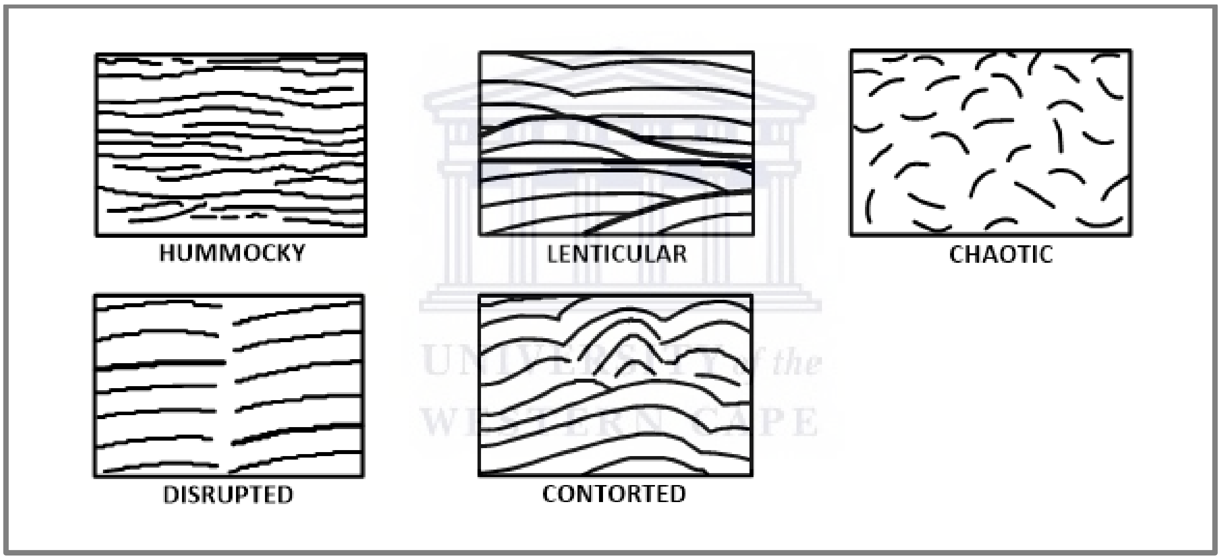


Figure 4.5 Diagram illustrating discontinuous seismic reflector patterns such as hummocky, lenticular, chaotic, disrupted and contorted modified after Mitchum et al. (1977).

4.1.3 Discussion

The interpretation of depositional process, paleo-topography and erosional surface is aided from the reflection configuration which contains the full stratification patterns. Moreover, Mitchum et al. (1977) define depositional sequence as a stratigraphic unit made of genetically related strata sandwiched by unconformities and their naturally-related conformities. They further refer to unconformity as reflection termination from a discontinuous surface. The early Cretaceous horizons interpreted have shown few discontinuous surfaces ending with chaotic reflectors. Dolson et al. (1999) postulate that chaotic reflectors may represent reservoir in a valley, whereas parallel indicates shale fill. Forming part of discontinuous reflector patterns, chaotic reflectors identified across all horizons could represent coarse-grained turbidite or fluvial channel fills. These horizons sediments were deposited under higher energy conditions. In term of transportation distance, a long distance could be postulated for fluvial deposits. For turbidite deposits depending on the site of deposition under marine conditions, a shorter distance for sediments deposited on the foot of a continental slope after as products of mass-flow process could be the case. Moreover, hummocky layers may represent discontinuous crevasse splay and point bar. However, the hummocky clinoform patterns observed in well Jc-D1 are not crevasse splay or point bar feature, but a progradational feature that was developed on a clinoform defined as inclined strata present over several spatial scales from delta front to continental margin slope. Accordingly, the well log results for this horizon indicated a progradational setting named prograding delta in agreement with Mitchum et al. (1977).

Divergent reflectors, as part of parallel reflector patterns, characterize depositional surface with progressive tilting or laterally varying depositional rates of sediments; whereas subparallel and parallel reflectors represent a uniform rate of deposition for surfaces that subside uniformly (i.e. basin plain or shelf). The basin plain environment identified from the serrated log motif at the well Jc-C1 supports the findings of the subparallel configuration found within the *Top Volcanic, 6At1 & Bottom of Sonic* horizon. Although few reflection discontinuities have been observed, most horizons have continuous surfaces. Continuous strata are represented by reflection continuities which in turn indicate the uniformity deposited strata. The incision features found from most horizons of the seismic lines which crossed wells Jc-B1, Jc-C1 and Jc-D1 could indicate period of fast erosion that characterized the Durban Basin during forced marine regression in southern Africa forming incision channels (Hicks and Green, 2016) and led to incision of the shelf sediments transported by the fast-moving Agulhas current (Flemming,1980a; 1981) and created paleo-canyons through erosional process (Wiles et al., 2013). The subparallel reflection configuration identified from well Jc-A1 and Jc-B1 *Top Volcanic & Bottom of Sonic* horizon which in Hicks and Green (2016) work separate Facies A1 and A2 shows incision features and they concluded that Facies A1 is an aggradational succession. Their observations in general are in agreement with well log and seismic results of this work where the horizon is an aggradational feature determined from cylindrical motifs to represent delta distributary channels and the reflector found to be subparallel.

4.1.4 Discussion and Conclusion

The seismic interpretation of the early Cretaceous horizons at the Durban Basin has shown that the quality of synthetic seismogram for the seismic lines to be in overall of good qualities after comparing the output interval velocity to the input interval velocity. Moreover, the seismic lines that crossed Jc-A1, Jc-B1 and Jc-D1 were acquired along the south-north direction and Jc-B1 along the west-east direction. All the studied early Cretaceous horizons were mapped and assigned different colours. They have varying thicknesses with depth across the surveyed horizons. Among the studied horizons, all have chaotic reflectors either within the horizons or at the basement unit with some discontinuous surfaces. The incision features observed indicate periods of forced marine regression coinciding with the fall of sea level around the southern Africa and formed channels on continental shelf through erosional process. Major reflection configurations found include subparallel, divergent, hummocky and chaotic. The basin plain environment determined at well Jc-C1 from the well log supported the finding of the subparallel reflector. The hummocky reflector found at well Jc-D1 relate to the prograding delta of the well log. Also, the subparallel reflector pattern in Jc-B1 agreed with the delta distributary channels found from the well log motif. Lastly, few horizons were thinner than most the horizons mapped.

4.2 Well Log analysis

Gamma ray log (GR) motif is characterized by grain size variation that shows the ratio of sand/shale contents at a given penetrated subsurface interval (Fig. 4.6). The relationship between the GR motif and grain size of sediments can be utilised to interpret depositional or which pattern of log motifs are used. From these relationships, five distinct log curve shapes (cylindrical, funnel, bell, symmetrical and serrated) derived to interpret the depositional environments. Moreover, the vertical description of grain size is represented by a gamma ray log; and an increase of shaly content in sandstone denotes simply a grain size decrease. Likewise, a gamma ray trend deflection indicates a decrease of clay content while sand content increases (Nazeer et al., 2016). Hence, the establishment of facies and rapid interpretation of related depositional environments (such as prograding, retrograding, aggrading, etc.) is made possible by analysing the GR curves, the nature of log motif contacts (progressive or abrupt) and curve behaviours (bell, cylindrical, funnel, serrated, and symmetrical) (Kim et al., 2012). Chow et al. (2005) and Odundun and Nton (2012) utilised GR log responses and well sample data to interpret the paleoenvironments of the Hsinyin and Pachanchi areas (SW Taiwan) and SMEKS Field (offshore western Niger Delta, Nigeria) respectively.

The five log motifs utilised in the interpretation of depositional environments as represented by Emery and Myers (1996) and Nazeer et al. (2016) (Fig. 4.6):

i. Cylindrical log motif is associated with aggradational sediment supply system and characterized by a sharp top and base with relatively consistent lithology.

ii. Funnel log motif is characterized by an abrupt top with a coarsening upward trend, grain size increase with rapid sediment deposition. The motif is associated with progradational sediment supply system.

iii. Bell log motif indicates an abrupt base with fining upward sequence and a decrease in grain size with depositional energy. The motif is associated with retrogradational sediment supply system.

iv. Symmetrical log motif represents a coarsening upward trend overlaid by a fining upward trend that have a near like thicknesses without a break between the two trends; and the motif is associated with progradational and retrogradational sediment supply system.

v. Serrated log motif is associated with aggrading sediment supply system and shows fluctuating gamma ray readings of high and low values on the well profile over short distance.

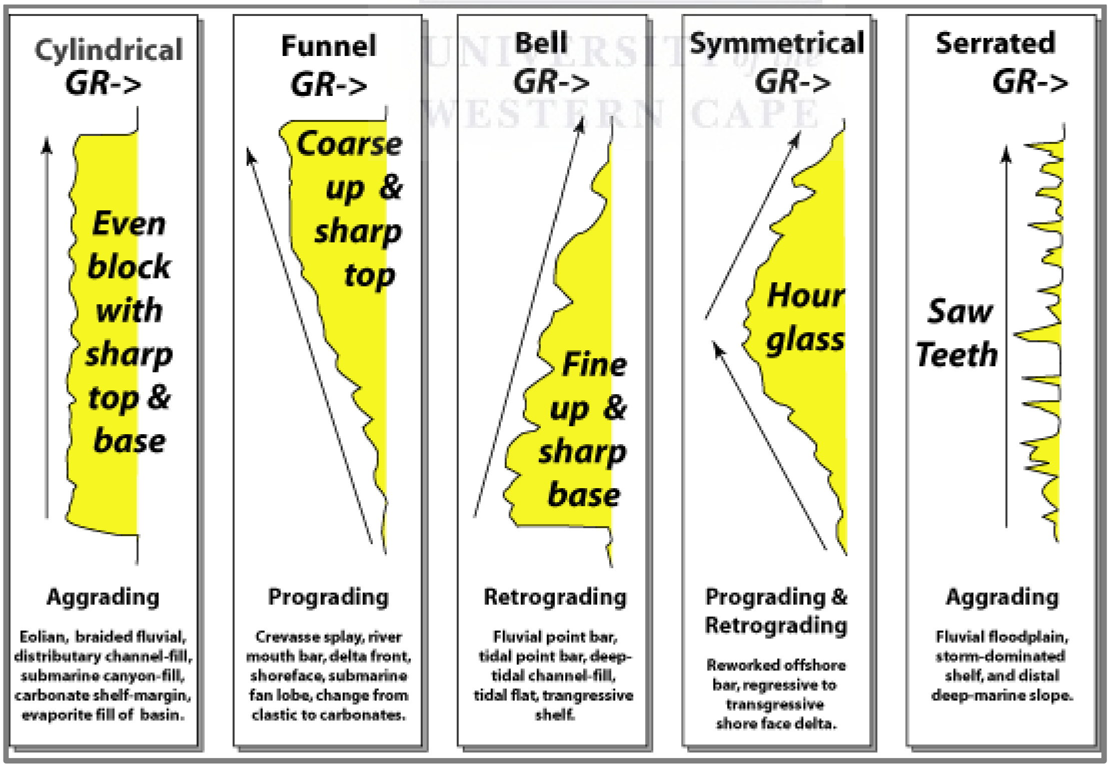


Figure 4.6 General gamma ray response to variations in grain size based on Emery (1996) model.

Furthermore, Daniels and Scott (1980) used the following well logs: density, water content, porosity, resistivity, natural gamma-ray radiation and electrical polarizability to identify and interpret the depositional environments of various lithologies in the Illinois Basin, Kentucky. In addition to Selly and Sonnenberg (2015) method, additional well logs such as density (RHOB), deep resistivity (ILD), neutron (SNP and NPHI), sonic (DT) and caliper (CALI) are used in this study to aid the interpretation of depositional environments and potential hydrocarbon reservoirs from the Durban Basin four wells (Jc-A1, Jc-B1, Jc-C1 and Jc-D1) (Table 4.2 and Table 4.3).

Table 4.2 Well logs calibrated readings

Log/wells	**Jc-B1**	**Jc-C1**	**Jc-D1**	**Scale of readings**
Gamma ray	GR	GR	GR	0-150Gapi
Neutron	NPHI	NPHI	-	-0.15 to 0.45m^3/m^3
Density	RHOB	RHOB	-	1.95-2.95g/cm^3
Resistivity	ILD	ILD	-	0.2-2000ohm.m
Sonic	DT	DT	-	30-140us/ft
Caliper	CALI	CALI	-	5-25in

Table 4.3. Matrix densities of common lithology (Schlumberger, 2009)

Lithology	**Matrix value (g/cm^3)**
Albite	2.6
Anhydrite	2.98
Calcite	2.71
Chlorite	2.81
Clay minerals	2.02-2.81
Coal	1.19
Dolomites	2.85
Glauconite	2.96
Halite	2.04
Illite	2.61
Kaolinite	2.55
Limestone	2.71
Muscovite	3.88
Orthoclase	2.57
Plagioclase	2.59
Pyrite	4.99
Sandstone (quartz)	2.65
Siderite	3.88
Smectite	2.02

4.2.1 Results and discussions

Well Jc-A1

The early Cretaceous horizon in this well is absent and therefore, no interpretation of depositional environment was possible for this well.

Well Jc-B1

In this well, fourteen intervals of about 812m thick of accumulated sediments were interpreted for depositional environments and identification of clastic reservoirs between 3100-3912m (Fig. 4.7). Due to non-availability of well cutting samples below 3150m, the samples between 3100-3500m were only studied for biostratigraphic analysis. However, for the interval below 3150m an attempt has been made to analyse the depositional environment using well-log characters and integrate with encountered lithology for which all necessary information viz. well cuttings analysis data and conventional core/sidewall core records were considered. The following log motif characters were seen within the intervals 3100-3516.89m of Well Jc-B1.

Interval 1: 3516.89-3402.69m

Cylindrical log motif is characteristic for this 174.2m this section. The main difficulties in interpretation on the basis of well logs in this interval is the presence of Dolerite intrusion at several stratigraphic levels. Claystone with frequent presence of fine-grained sandstones and siltstones (2-3m thick) are recorded. Presence of carbonaceous particles and pyrite grains are also recorded in the sediments.

Effect of the intrusion on the clastic sediments cannot be ruled out within this interval. However, the log characters indicate possibility of distributary channel within subaqueous delta plain. The presence carbonaceous detritus in some of the samples indicates possibility of delta distributary channel.

Interval 2: 3402.69-3100m

Serrated log motif is characteristics of this 302.69m thick interval. The entire interval is dominated by fine argillaceous lithology (mainly dark grey claystone) with frequent presence of siltstone / fine sandstone and rare calcareous lamination towards the upper part of this interval. The claystone is feebly calcareous. Pyrite grains are present mostly in siltstone units. The log motif indicates possible distal marine slope depositional environment for deposition.

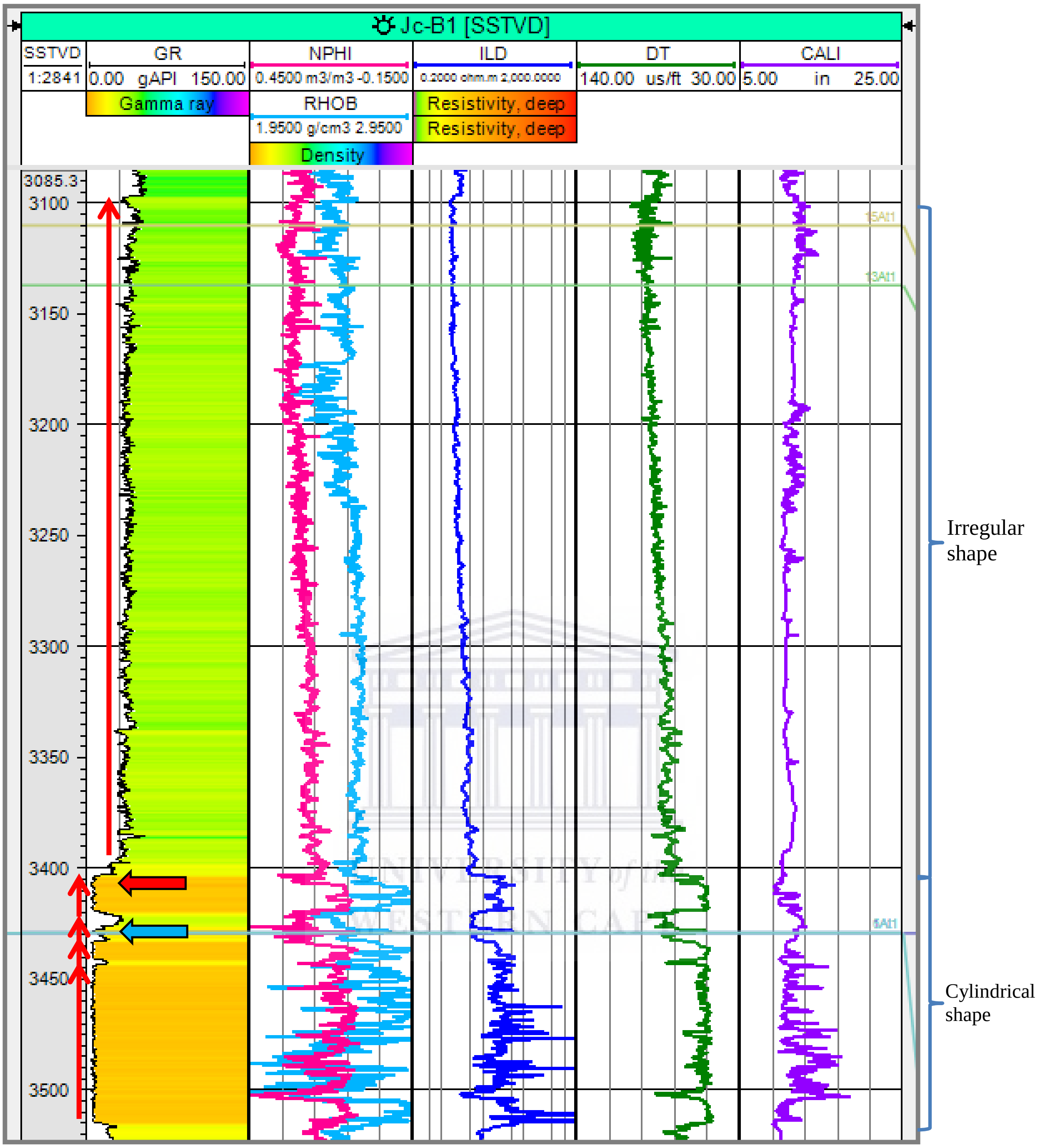


Figure 4.7 Depositional environment interpretation of well Jc-B1 early Cretaceous: GR log motif shows cylindrical, symmetrical and serrated motifs with NPHI, RHOB, ILD and DT logs. The blue arrow shows the location of the symmetrical motif. The red arrow indicates the location of the cored samples, both clastic and intrusive.

Well Jc-C1

In this well, the intervals between 2000m and 3200m was studied both biostratigraphic work as well as for analysis of well log motif. Within this 1200m interval three major log motifs were recorded (Fig. 4.8-10). The results of integrated lithological studies and well log motif analysis can be summarized as follows:

Interval 1: 3086-3200m

The log motif within this 114m thick interval is not reliable. This is mainly due the presence of dolerite intrusive in this interval. The sediments within this interval comprises of only claystone and any course clastics siltstone/sandstones are absent in the interval.

Interval 2: 2917-3086m

Bell log motif is characteristics. Claystone dominant interval with presence of thin limestone beds common between 2990-3086m. Transgressive shelf environment is environment is predicted for this interval.

Interval 3: 2917-3086m

Serrated log motif is typical for this interval. It is a very thick section comprises mainly of claystone with several siltstone and fine sandstone units throughout. This gives the possible serrated log motif in the big interval. Between 2500-2700m siltstones are very frequent indicating shallowness and highly fluctuating condition. Presence of shell fragments (marine bivalves are recorded). At some intervals thin limestone partings are recorded. The integrated result indicates a possible distal marine slope environment with frequent shallowness.

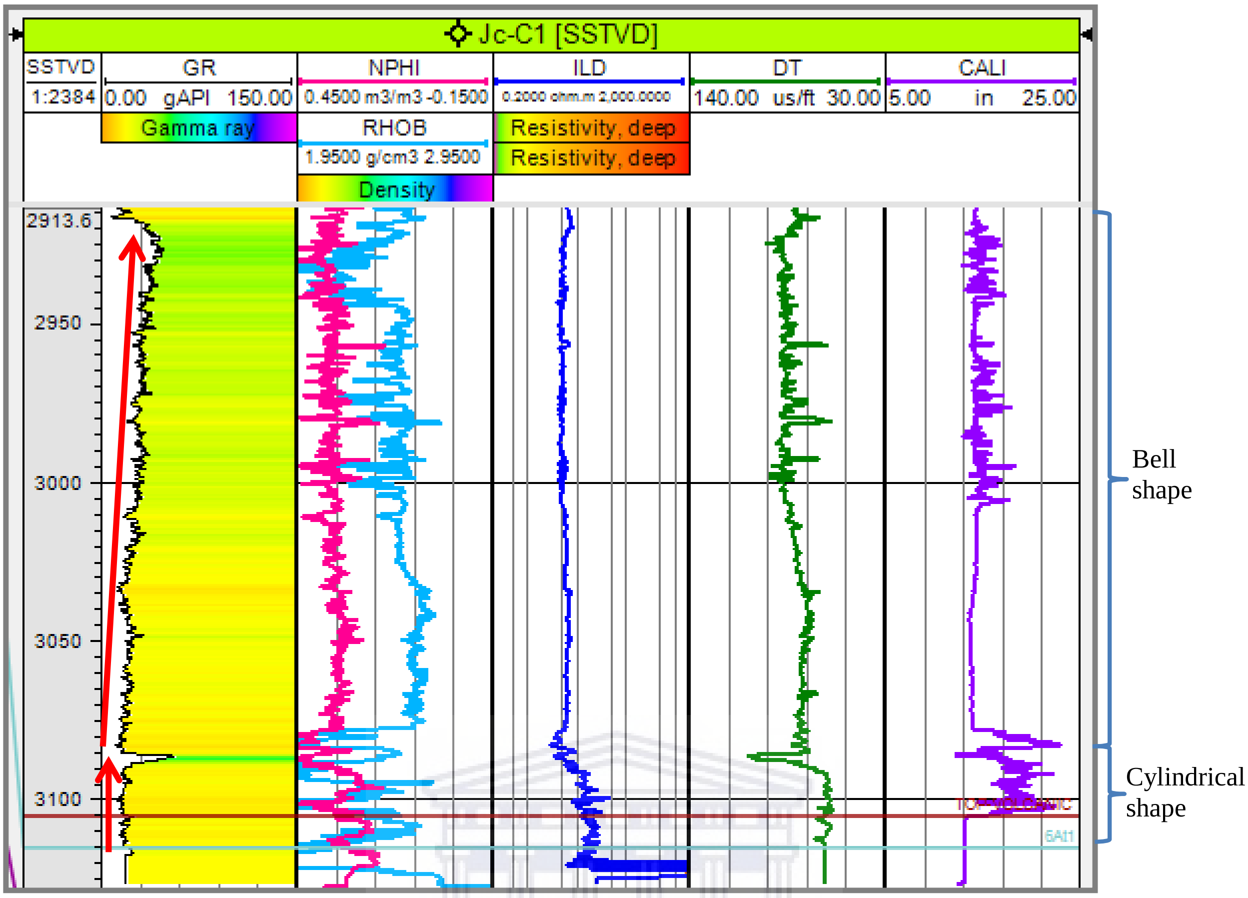


Figure 4.8 Depositional environment interpretation of well Jc-C1 early Cretaceous: GR log motif shows cylindrical and bell motifs with NPHI, RHOB, ILD and DT logs.

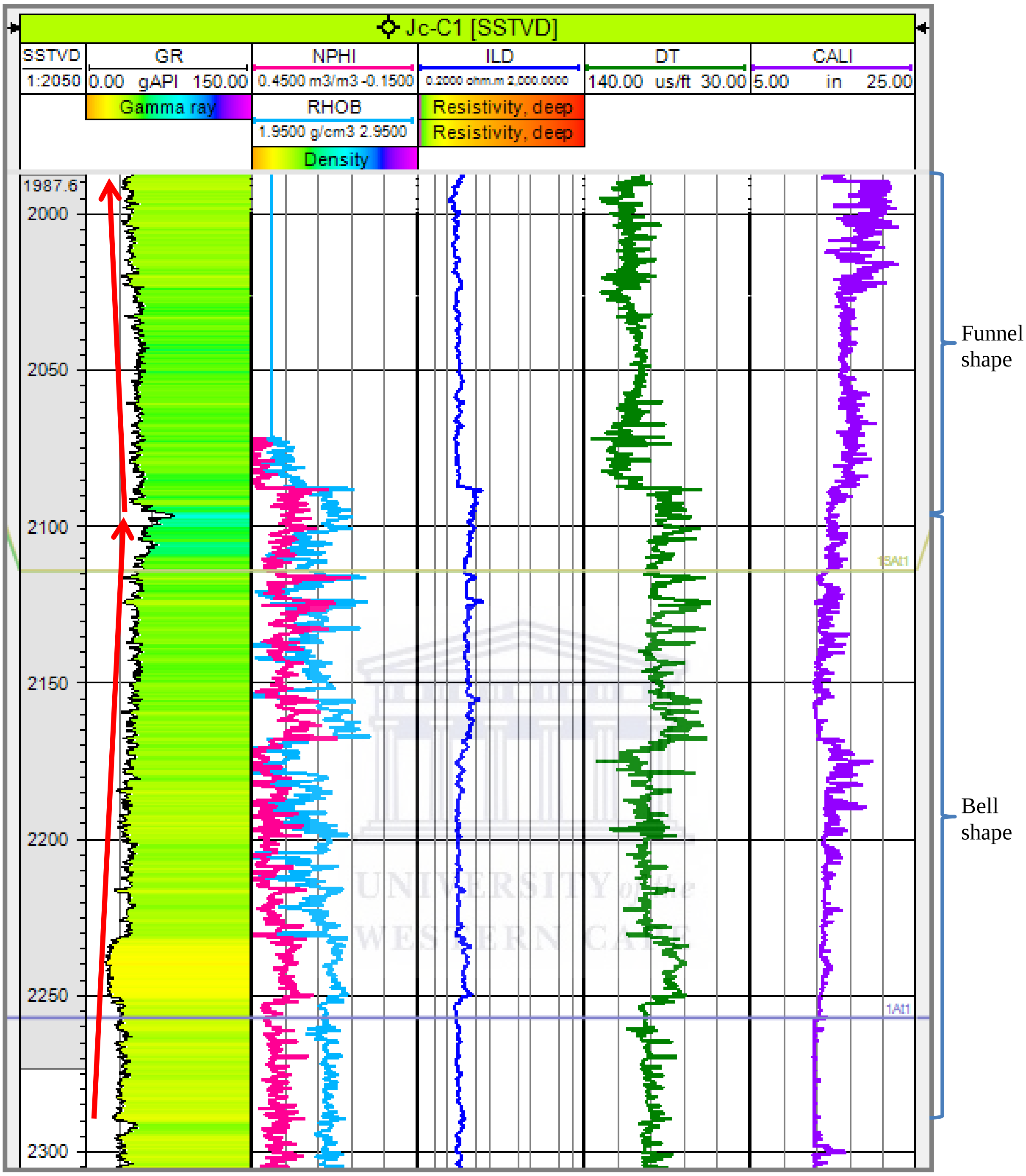


Figure 4.9. Depositional environment interpretation of well Jc-C1 early Cretaceous: GR log motif shows bell and funnel motifs with NPHI, RHOB, ILD and DT logs.

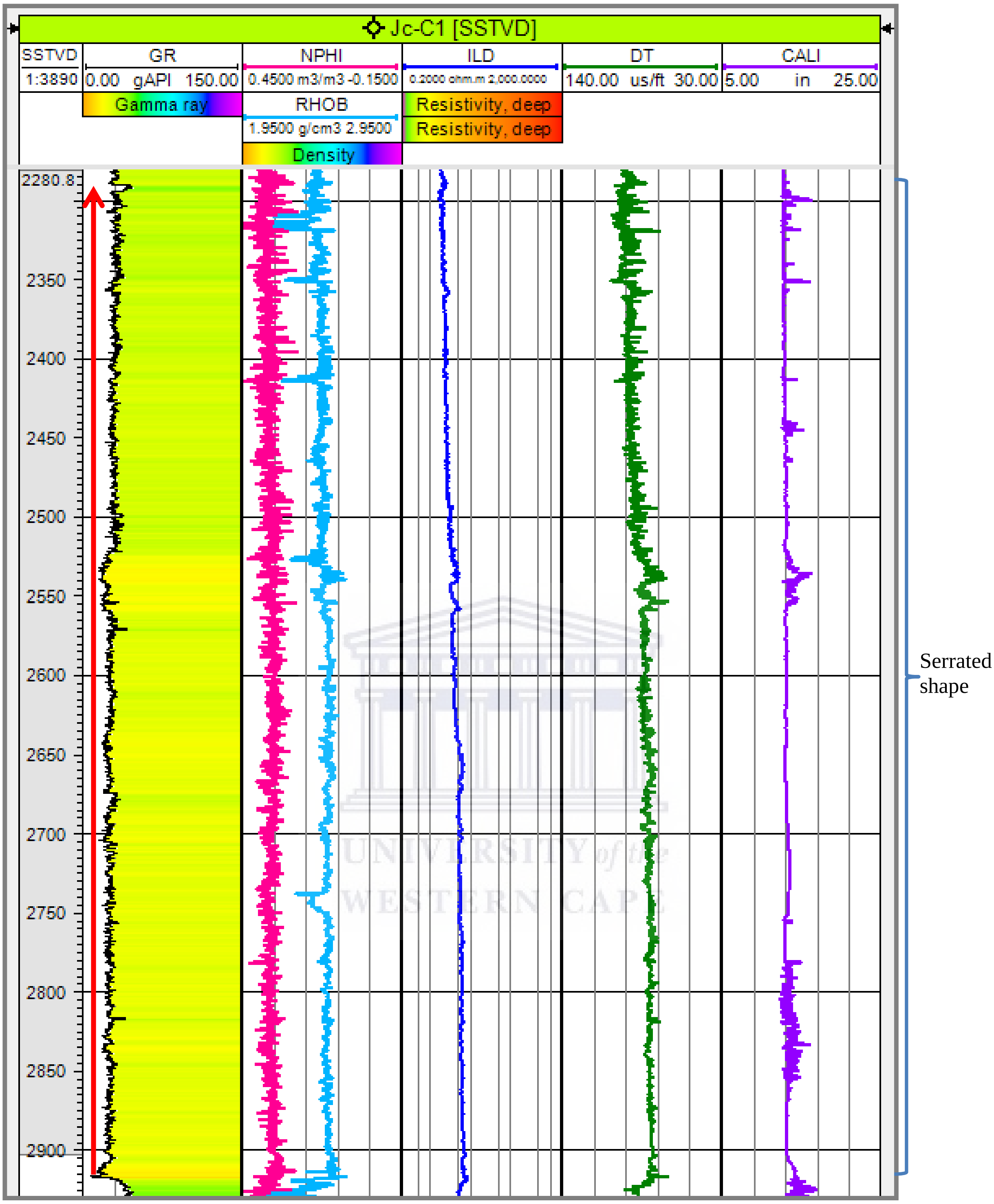


Figure 4.10. Depositional environment interpretation of well Jc-C1 early Cretaceous: GR log motif shows serrated motif with NPHI, RHOB, ILD and DT logs.

Well Jc-D1

In this well, the intervals between 2620m and 2846m was studied for analysis for well log characters, lithology and biostratigraphy (Fig. 4.11). Based on well log motif the entire 226m interval can be subdivided into three sub intervals. The depositional environment prediction based on integrated lithological studies and well log motif analysis can be summarized as follows:

Interval 1: 2807-2846m

Funnel shape log motif is observed within this 26m thin interval. This interval is a conglomeratic interval with volcanic rock fragments and fine silty intervals. The lithology is similar to graben fill sediments. Amygdaloidal white colored fillings are very common in the volcanic fragments. Thin siltstone beds are common and are commonly pyritic. The log motif suggests a prograding deltaic environment within an unstable shelf.

Interval 2: 2698-2846m

Funnel log motif is also characteristics of this interval. The bottom part of this interval is similar conglomeratic type of lithology with present of siltstone and finer sands are more frequent compared to the lower interval. Between 2898m and 2720m in the upper part is claystone with frequent presence of fine limestone beds. This suggests a fining upward trend in the upper 20m+ interval. The prograding delta environment continues from below interval but progressively indicating a deeper marine environment (possible submarine fan).

Interval 3: 2698-2620m

Serrated log motif is typical characteristics for this interval. It is a very thick section comprises mainly of claystone with several limestone bands at certain intervals. Fine siltstone and fine sandstone units are rare within this interval. The integrated result indicates a possible distal marine slope environment with frequent shallowness.

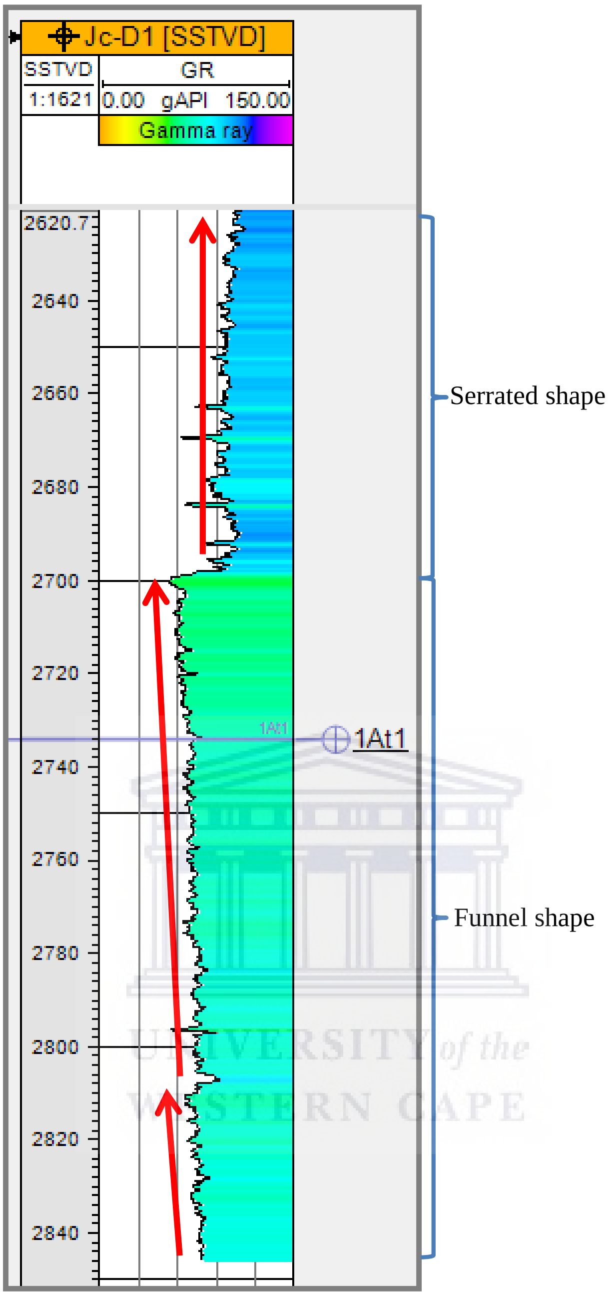


Figure 4.11 GR log motif shows two of funnel motifs overlaid by the serrated/irregular motif in well Jc-D1

4.3 Petrographic studies from the solitary Conventional Core CC#1, Well Jc-B1

As already mentioned in the previous chapters that only one Conventional core (CC#1) was available from the Well Jc-B1 (Fig. 8.1 & 8.2, in Appendix). Petrographic analysis from a few selected samples were carried out to identify the mineralogical composition. This conventional core comprises of less than a meter (0.84m) clastic lithology followed by an igneous intrusion. The clastic component constitutes mainly sandstone and siltstone with minor clayey lamination. An attempt has been made to know the effect of the intrusion on the clastic lithology. The cored interval in CC#1 have clastic component between 3428.00-3428.84m and

the rest between 3428.88-3439.45m is the intrusive. A total 12 thin sections from 12 selected samples (5 clastic and 7 igneous materials) were studied under Petrological microscopes to know the lithology details (mineral compositions, textural properties etc.).
The important observations from the petrographic studies is summarized below:

4.3.1 Sandstones

The clastic components in the sandstones are medium- to fine-grained, poorly-sorted and are immature. Quartz is the dominant mineral. Alternation of medium to fine grained layers are observed. The grains are aligned and forming layers. The alignment is most likely due to compaction at the lithification diagenetic stage (Plate 1-3). The grains are mostly angular to sub-rounded having point, long, tangential, concavo-convex and sutured grain contact types in places. The matrix part comprises of clayey particles, quartz overgrowths and calcite particles and the cement material are calcareous in nature. The framework grains comprise mostly of quartz, K-feldspar, plagioclase with accessory opaque minerals, chlorite, aragonite, ferric oxide (rust brownish stain in some places) and clay particles. Quartz grains are of various sizes (between 0.129-2.193mm along the length axis) indicating poor nature of shorting. Plagioclase is common with its crystals are smaller in size (between 90-232µm along the length axis). K-feldspar is altered and sericitized in some places. The thick medium-grained bed is K-feldspar-rich and was affected by late-stage intrusive activities with abundant calcite veins branching subparallel to the bedding plane (Plate 3).

Description

Thin section abbreviations:	
Qtz: Quartz Plg: Plagioclase Ser: Sericite Oxy: Ferric oxyhydroxide Op: Opaque minerals	Kfs: Potassium feldspar Calc vein: Calcite vein Calc Cement: Calcite cement PPL: Plain polarized light XPL: Cross polarized light
Plate 1: Depth: 3428.10m The immature medium- to fine-grained sandstone shows diagenetic foliation formed due to overlying pressure resulting in grain alignments. Sandstone grains are poorly sorted (Plate 1a-d, PPL). The rock is composed of quartz, K-feldspar (sericitized), small crystals of plagioclase, chlorite, ferric oxyhydroxide and opaque minerals (Plate 1a-d, PPL). Plagioclase is common with its fairly small crystals (between 90-232µm along the length axis) (Plate 1a-d, PPL). Central band of the sandstone is K-feldspar-rich, filled with silty particles and finer grains of sands; the band is sericitized having a brownish colour from K-feldspar alteration (Plate 1b-d, PPL). The rock is matrix-supported. The	

matrix is made up of abundant microcrystalline quartz, sericite, chlorite and rare ferric oxyhydroxide (brown stain). The presence of quartz gives the greyish appearance to the rock. Quartz grains are mostly angular, of variable sizes and have concavo-convex, tangential and long contact types.

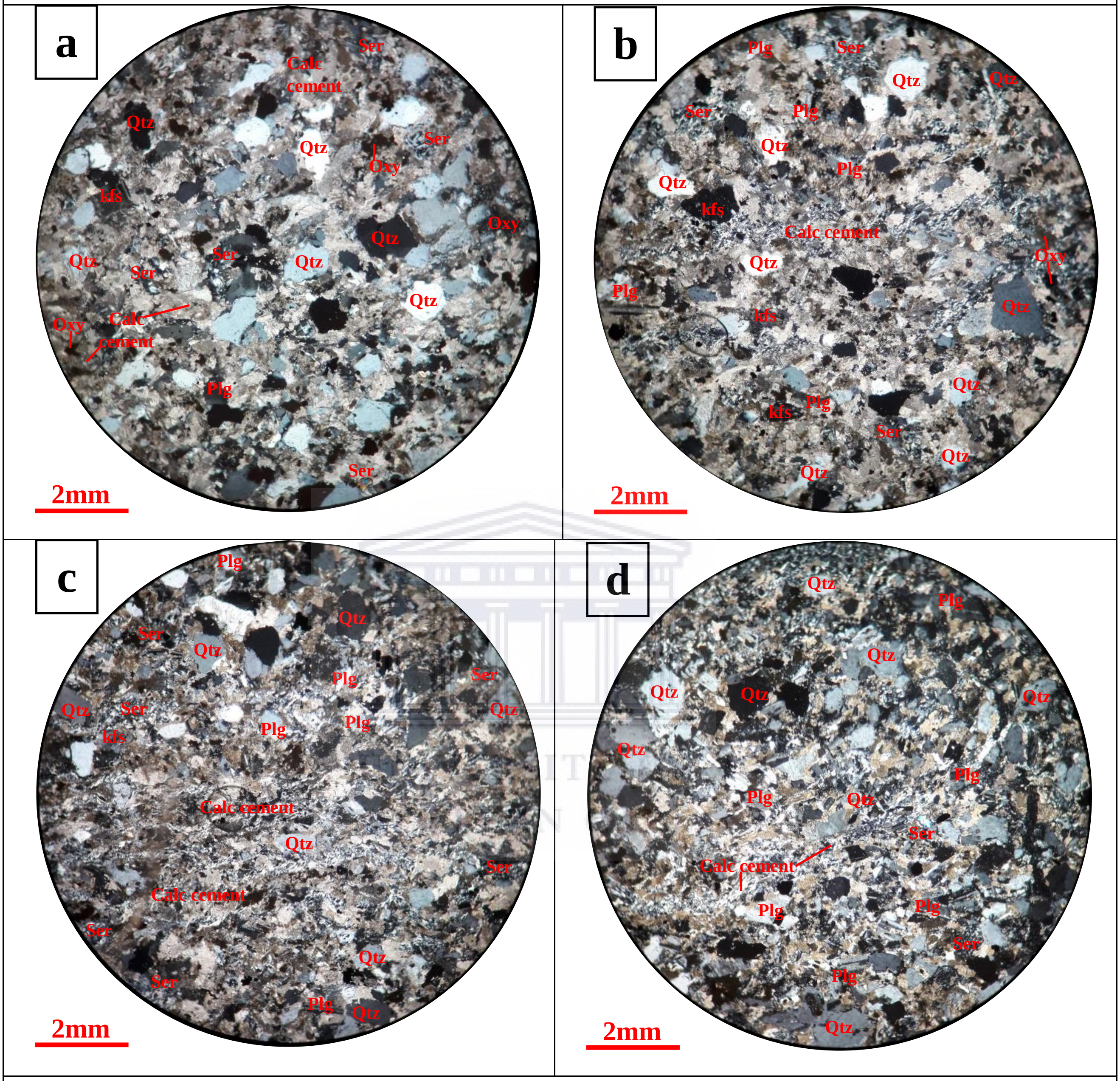
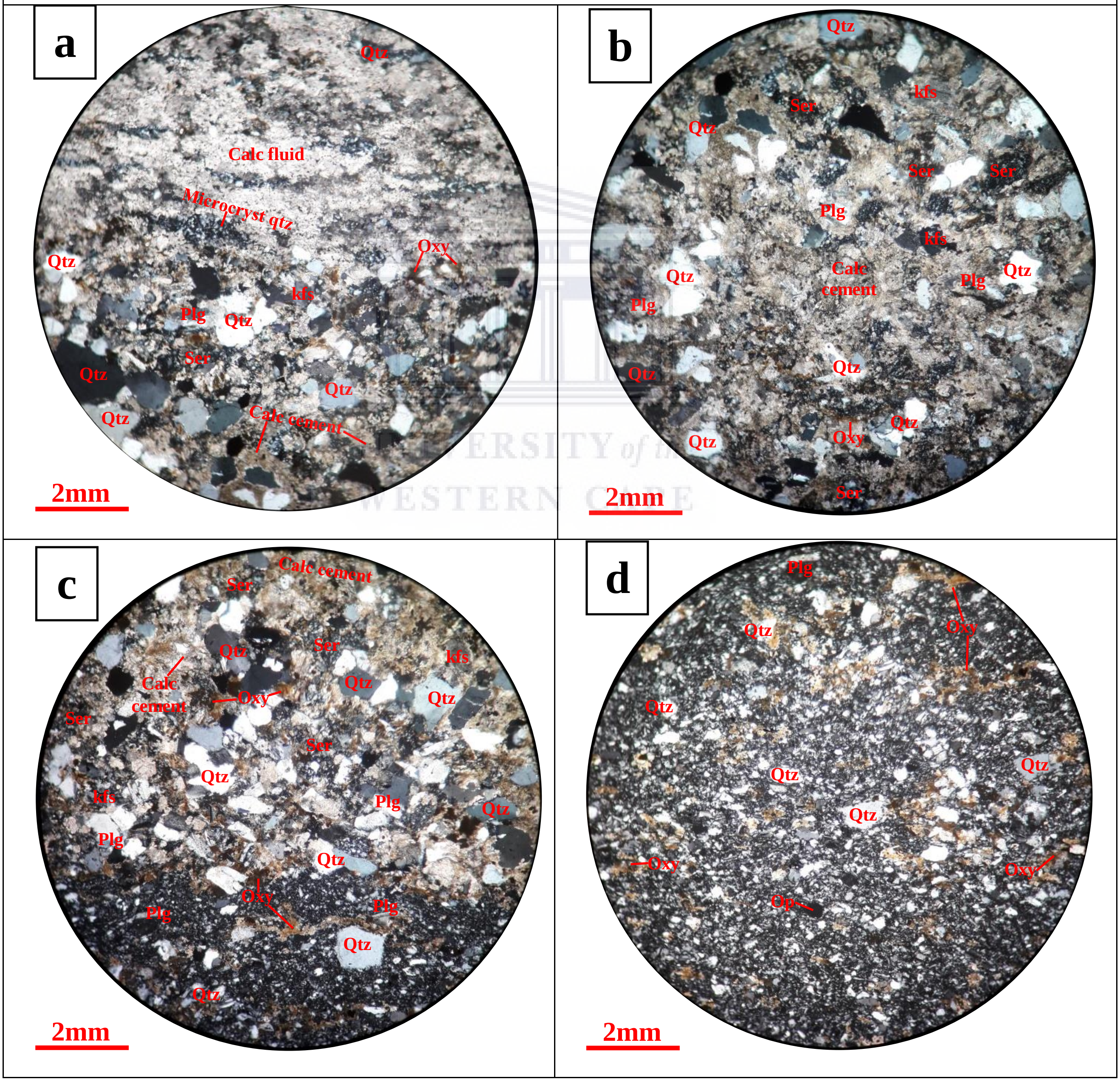


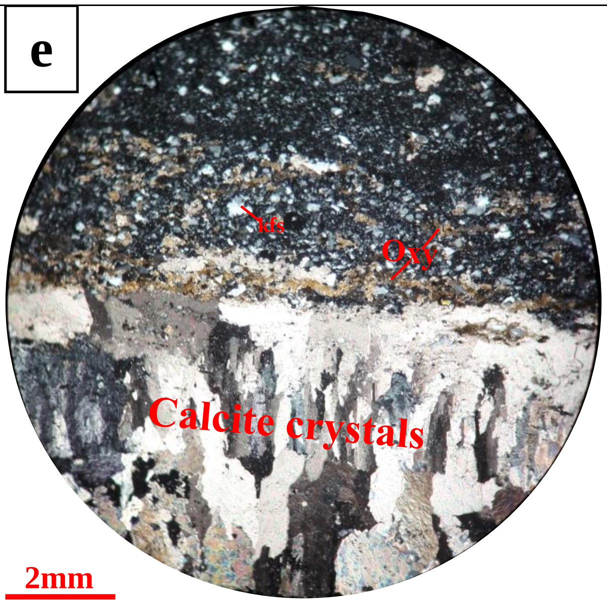
Plate 2:

Depth: 3428.42m

Interbedded sandstone showing two distinctly different grain size (Plate 2a-f, PPL). The interbedded rock is composed predominantly of quartz, K-feldspar (sericitized), plagioclase, chlorite, clay minerals, sericite, opaque minerals and aragonite. The central bed is poorly sorted and made of medium- to fine-grained quartz clasts of variable sizes (Plate 2a-c, PPL). The quartz clasts are angular to sub-rounded having long, tangential and rare concavo-convex grain contact types in places. The bed nature of matrix varies from matrix- to clast supported. Abundant microcrystals of quartz, sericite, chlorite and random ferric oxyhydroxide (brown stain) make up the matrix. The quartz grains are altered and K-feldspar sericitized. Clay minerals, grains of zircon, chlorite and chloritized minerals are also present in this band.

The upper fine-grained bed is filled with calcite-rich minerals, and has similar texture with the lower bed (Plate 2a, PPL). The lower fine-grained bed is dark in colour filled with sparsely distributed medium-grained quartz clasts showing interpenetrating boundaries with the surrounding matrix particles (Plate 2c-f, PPL). In addition, the quartz overgrowths represent quartz cements. The bed is densely compacted and composed of moderately sorted, sub-angular to sub-rounded quartz grains. The ferric oxyhydroxide and opaque minerals are common. Calcite vein edges the lower bed with carbonate minerals intruding the country rock (Plate 2e, PPL and f, XPL). Smaller crystals close to the fracture wall show the early growth of calcite crystals. The elongate-shaped calcite crystals developed from the wall toward the centre of the vein. The vein shows an anastomosing pattern with high order interference colour.





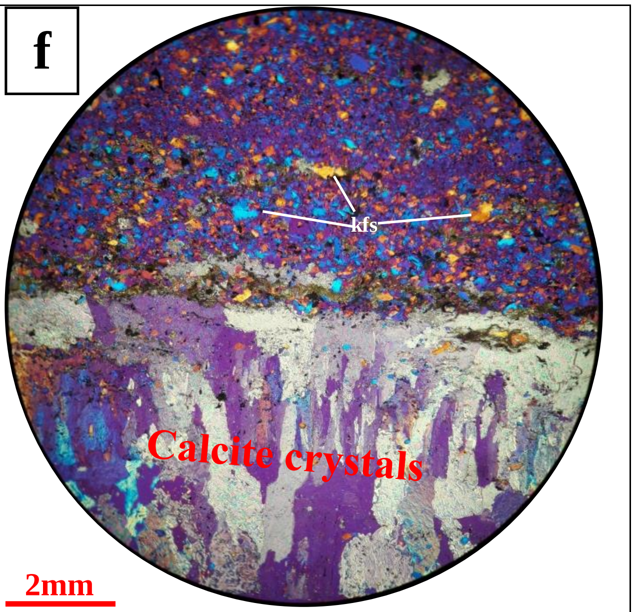
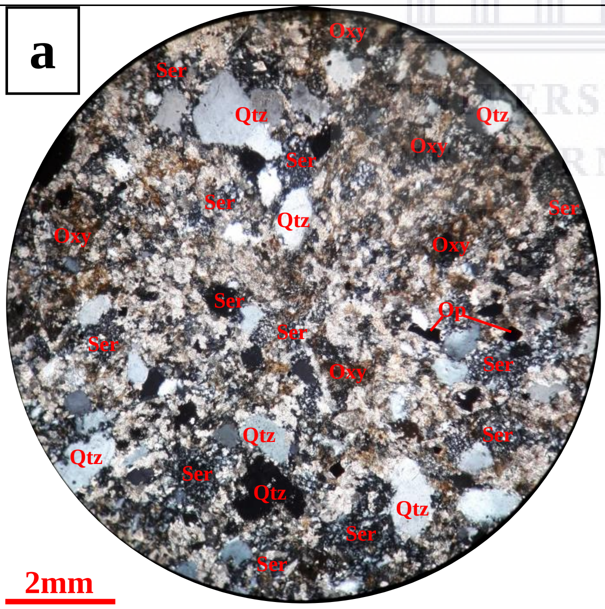
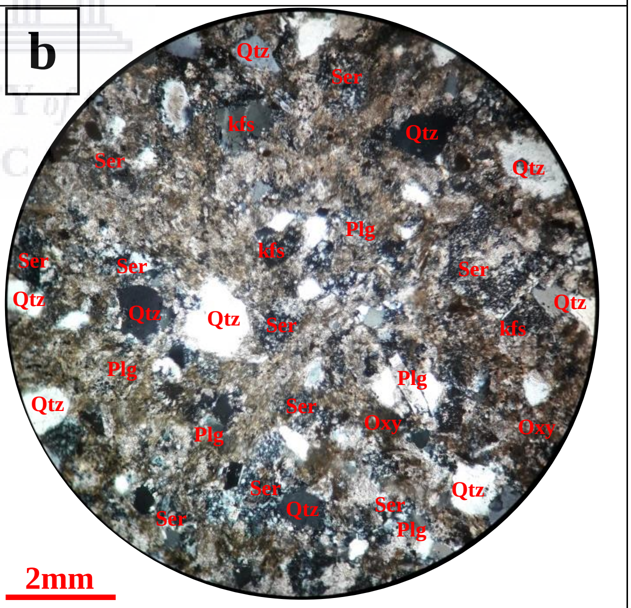


Plate 3:

Depth: 3428.73m

The immature, poorly sorted medium- to fine-grained sandstone share similar characteristics of the interbedded sandstone central bed (Plate 2). The rock has altered K-feldspar, small crystals of plagioclase, chlorite with extensive sericitization of K-feldspar (sericite - high order interference colour). Ferric oxyhydroxide is widely distributed. The quartz grains are sutured (Plate 3a-b, PPL).



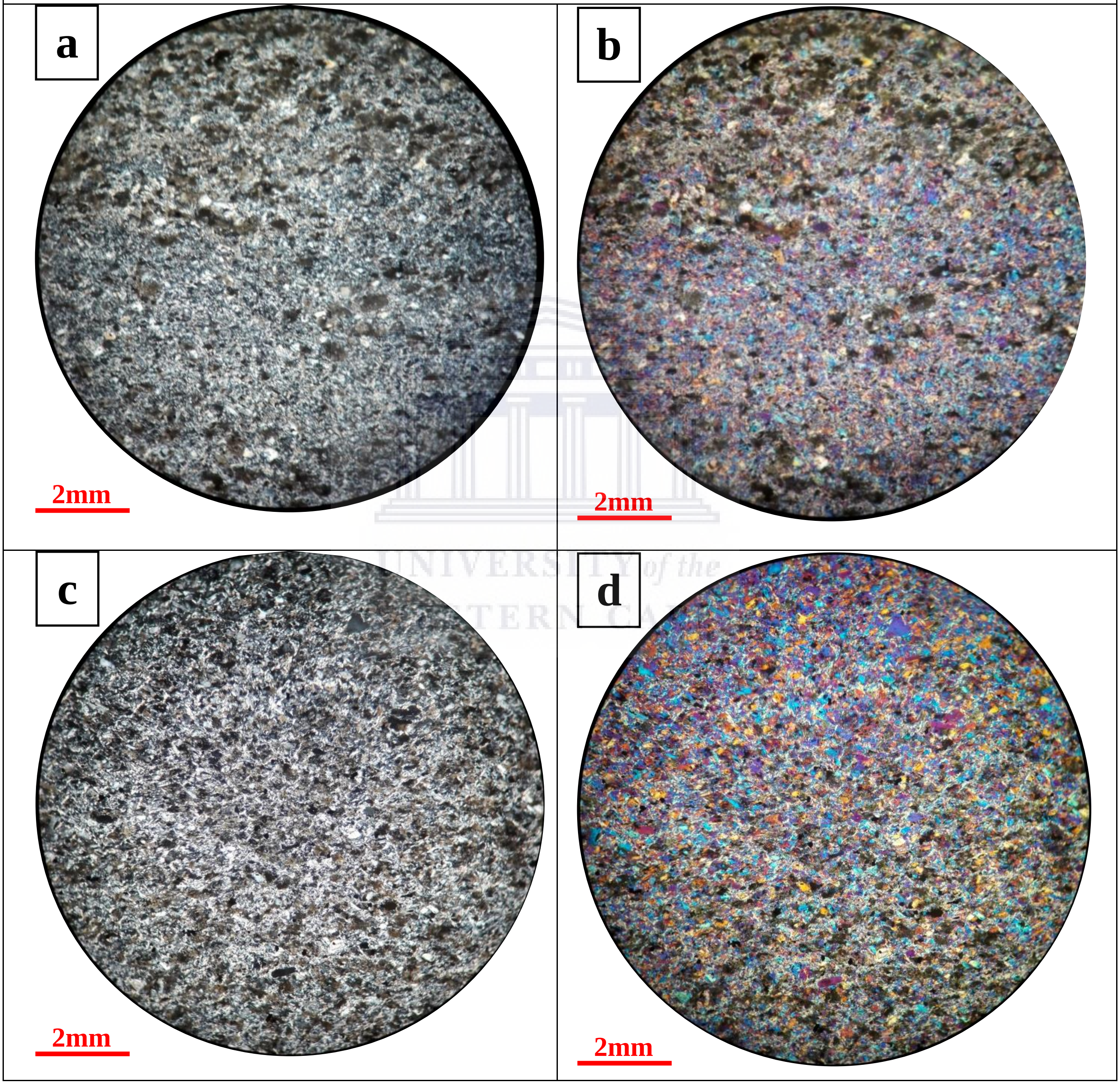


4.3.2 Siltstone

Plate 4:

Depth: 3428.31m

The siltstone is composed of very fine silt-sized microcrystalline quartz grains, clay minerals, ferric oxy-hydroxide (rusty-brown) and opaque mineral particles (Plate 4a-d). Monocrystalline quartz shows undulose extinction (Plate 4c-PPL & d-XPL). The rock shows microscale grading accompanied with faint lamination. Among the cements, quartz overgrowths are present (Plate 4a-PPL & b-XPL).



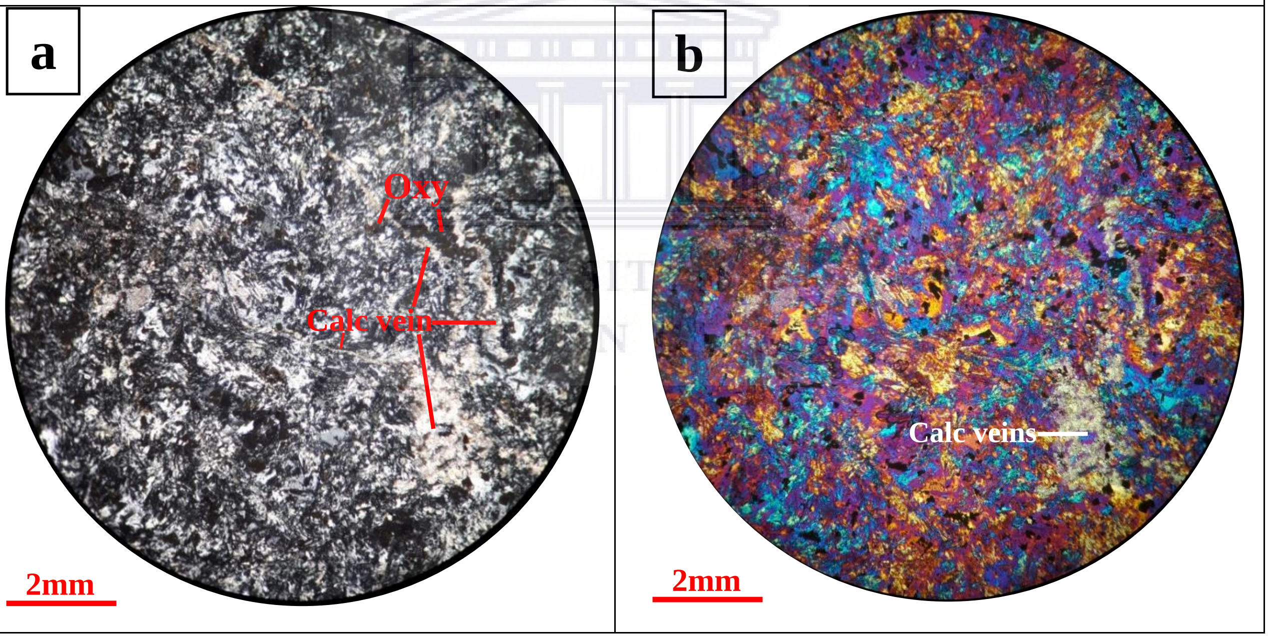
4.3.3 Mudstone

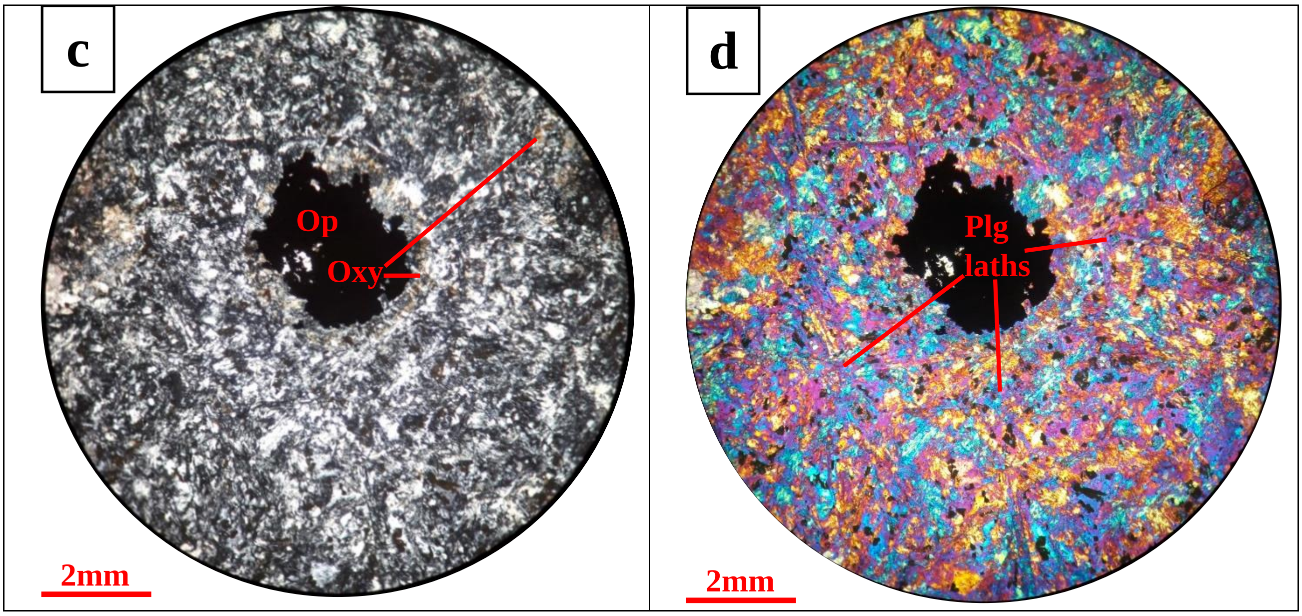
A dark grey, immature, very fine-grained mudstone sample penetrated by calcite veinlets of light brown colour which indicate the fluid pathway following magmatic intrusion into the country rock (Plate 5). The fluid followed the foliating layers. The mineralogical composition include quartz, plagioclase, good amount of K-feldspar, traces of carbonate materials (e.g. aragonite), chlorite, and clay minerals. K-feldspar is sericitized, the presence of carbonate materials in the rock is an indication of metasomatized fluid of dolerite which released calcite into the country rock. In addition, opaque mineral and dark red-brown ferric hydroxide are also present (Plate 5c-d).

Plate 5:

Depth: 3429.18m

Immature very fine-grained mudstone made up of quartz, very small crystals of plagioclase (laths), chlorite, K-feldspar (sericitized), carbonate (e.g. aragonite), clay minerals, and opaque minerals with microcrystalline quartz (Plate 5a-d). Plagioclase laths are randomly oriented (Plate 5d). The rock has penetrating calcite veins formed during magmatic intrusion (dolerite) into the country rock (Plate 5a-PPL & b-XPL). In addition, ferric oxyhydroxide is dark red-brown coloured (Plate 5a & c).





4.3.4 Igneous Intrusive

The major part of the Conventional Core CC#1, in well Jc-B1 comprises of basic intrusive (possibly sill) in represented by dolerite (Fig. 8.3, in Appendix). The immediate contact with the clastic segment it is extremely fine-grained resembling basaltic character. The igneous part within the core covers the depth interval 3428.88-3439.45m. The rock is mafic in composition and the texture ranges between ophitic to intersertal. Mineralogically the main components are plagioclase and pyroxene. Plagioclase is commonly zoned forming elongated laths (0.1-2mm long, may reach >3mm) of random orientations. Others minerals include chlorite, epidote, carbonates (e.g. calcite), ferric oxyhydroxide and opaque minerals (e.g. pyrite, magnetite, etc.). Three main alteration processes, namely sericitization, chloritization and epidotization affected the rock main minerals (plagioclase and pyroxene) and produced sericite, chlorite and epidote. Intensive calcite veins, products of late-stage intrusion, cut across the rock. Glassy materials products of rapid cooling of magma when coming into contact with cooler country rock are present.

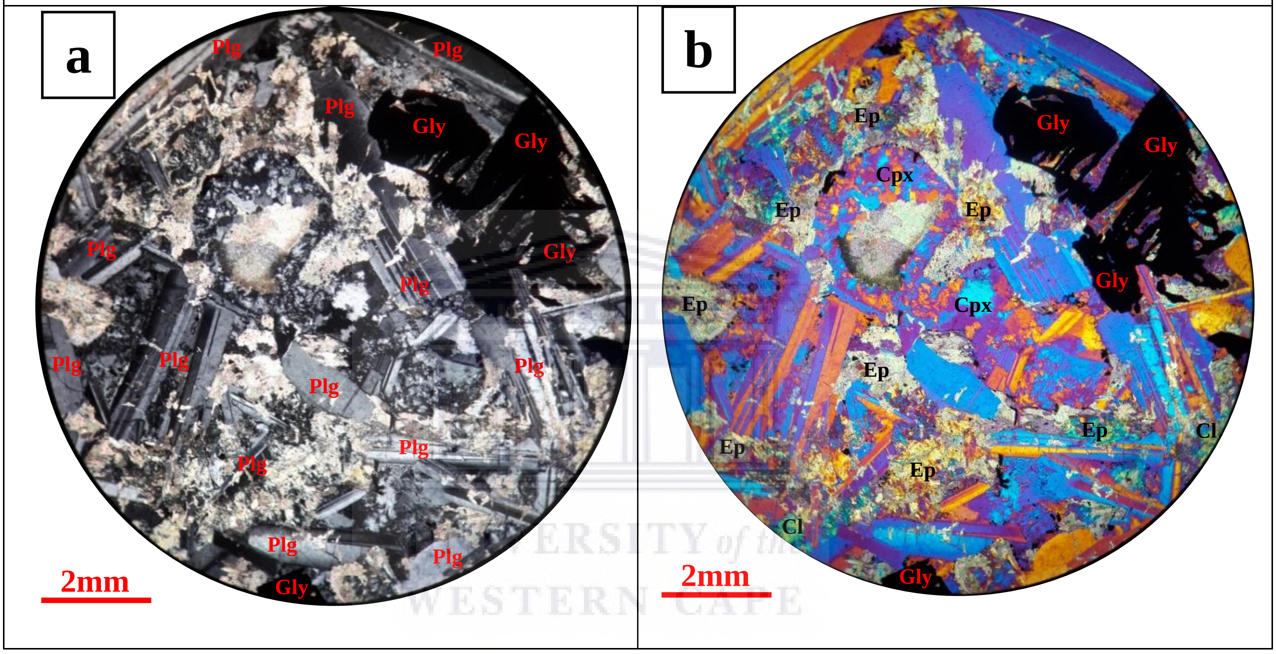
Description

Thin sections abbreviations:	
Plg: Plagioclase	Gly: Glassy materials
Cpx: clinopyroxene	Cal: Calcite
Ep: Epidote	Mg: Magnetite
Cl: Chlorite	PPL: Plain polarized light
Alt Plg: Altered plagioclase	XPL: Cross polarized light

Plate 6:

Depth: 3429.98m

Moderately altered coarse-grained basalt composed of well-preserved plagioclase laths, pyroxene, volcanic glass, chlorite, epidote and opaque minerals (Plate 6a-PPL, b-XPL). The sample exhibits sub-ophitic and intersertal textures. The plagioclase minerals are elongated and partly altered. They are the main constituents. Pyroxenes are of small crystals and they radiate. They are chloritized and epidotized (partly replaced by chlorite and epidote). The glassy materials (magma) are of a dark-brown colour (Plate 6a-PPL). The presence of epidote in this sample could indicate a low-grade metamorphism and hydrothermal activity (Plate 6b-XPL). The granular and fibrous epidote replaces primary minerals (plagioclase and pyroxene) and forms mineral association with chlorite (Plate 6a PPL –b XPL).



4.3.5 Discussion and conclusion

None of the four exploratory wells drilled in Durban Basin are hydrocarbon producer. Out of the four wells the very first well Jc-A1 did not encounter any early Cretaceous sediments. In this well unfossiliferous sandstone and diamictite unit at the bottom is directly overlain by late Cretaceous sediments belonging to late Cenomanian–Turonian age. This has been confirmed from the presence of late Cretaceous planktonic foraminifera. Therefore, this well was not considered for the present study.

All three wells viz. Jc-B1, Jc-C1 and Jc-D1 have penetrated the early Cretaceous succession with varying thickness. Evidence of earliest part of early Cretaceous series (Berriasian to Hauterivian stages) were not found in any of these wells. Graben filled sediments (in Well Jc-D1) and presence of dolerite intrusive was recorded in the bottom part of the drilled section in the two wells (Jc-B1 and Jc-C1). Nature of well log motifs for the early Cretaceous section in combination with the lithological characters available in the three wells (megascopic examination and description available from the Well Completion Reports) and limited petrographic thin section studies provide a broad understanding of depositional condition of the area.

In the northern well Jc-D1 the lower part of the studies section shows graben filled sediments with intervening silty layer deposited under a prograding deltaic environment. This also indicates an unstable environment. Presence of dolerite fragments in the conglomeratic interval and presence of igneous intrusive in the bottom part of the other two wells indicates a highly unstable tectonic phase. In the central area (Jc-B1 locality) the Cylindrical log motif and lithological information (cutting sample analysis and petrographic studies from the conventional core) suggests a delta distributary channel or lower deltaic environment. Due to the presence of thick dolerite intrusion in the equivalent section in southernmost well Jc-C1, makes the interpretation unreliable. However, the presence of only claystone and absence of any coarse clastics (siltstone or sandstone) suggests a definite deeper environment of deposition.

In the northern area the section above the conglomeratic interval (Jc-D1) locality, the graben fill sediments continued further followed by a deeper incursion of sea level as indicated by the fining upward log motif. A submarine fan is interpreted based on the log characters and lithology. This typical character was not found in the central and southern part.

The younger interval in all the three wells shows serrated log signature. The lithological association is somewhat common recorded in all the three wells represented mainly by claystone with frequent shallow condition as revealed by presence of siltstone or sandstone. This cyclic pattern is indicative of distal marine slope with frequent shallowness.

Chapter V

5. Early Cretaceous foraminiferal biostratigraphy

The prime objective of this research is to study the marine microfossil group 'foraminifera' for dating the early Cretaceous drilled section and also to interpret the depositional environment. In this basin so far four exploratory wells have been drilled viz. Jc-A1, Jc-B1, Jc-C1 and Jc-D1. To understand the depositional environment information derived from lithological characters as revealed by Well logs motifs, limited seismic and sedimentological studies (mainly megascopic and microscopic petrographic studies). The use of planktonic foraminifera is well known for dating or assigning the stage boundaries. Benthic foraminifera are useful for understanding the depth of deposition (Paleobathymetry) and understanding sea level fluctuation.

The present research is based on the study of well samples (10-20m) intervals and integration of the foraminiferal biostratigraphic data. A broad overview of the age on the basis of foraminifera of the Cretaceous drift succession (early Barremian to late Maastrichtian) on the seven basins of Southern Africa is available (McMillan, 2003). However, the present work is restricted to the early Cretaceous succession (considered to be important for petroleum exploration for the seven South African sedimentary basin) only.

All age assignment carried out in this work is based on the classical work and zonation of planktonic foraminifera (Bolli et al., 1989). For generic level identification of benthic foraminifera, the standard taxonomic reference text and plates (Loeblich and Tappan, 1988) as well as various other publications were used in the present work. For Cretaceous benthic foraminifera morph grouping, the classical work of Murray et al. (2011) and Haggart et al. (2013) and for paleobathymetric interpretation methods adopted in Nagy (1992) was followed.

As already mentioned, the Durban Basin located on the eastern coast of South Africa and its early history of development is very erratic (McMillan, 2003). The distribution pattern of sediments after the basin came into existence as revealed from seismic data indicates that in the initial stage localized graben filled sediments derived from the older Gondwana groups (Hauterivian or older), these localized basins were flanked by Karoo/Cape series basement highs. The early Cretaceous drift succession is much localized in some places it is quite thick and, in some areas, due to absence of datable microfauna it is extremely difficult to assign proper stage name. Around the later part of late Cretaceous (Campanian stage), the basin came to being as one depocenter. Localized minor subsidence occurred in the distal part of the basin in the early Cretaceous period particularly in the Aptian- middle Albian -early Cenomanian to early Santonian time. The present work also indicates that the first well Jc-A1 did not encounter any early Cretaceous sediments. The earliest basin datable sediments within the late Cretaceous is possibly of Late Cenomanian age. Therefore, in this locality almost the entire early Cretaceous is represented by a hiatus overlying the Gondwana group of sediments. A detail discussion on the foraminiferal assemblages, demarcation of age and interpretation of the depositional environment is presented in the following section.

5.1 Methodology

The processing method for isolation of foraminifera from well cuttings adopted in this work has already discussed under Chapter Three. The following methodology was followed in this work.

The identification of foraminifera microfossils was carried out using various standard reference books. Planktonic foraminifera are considered to be the most useful too; for dating marine sedimentary succession. Although, they appeared in late Jurassic due to poor variation and diversity they are not important during this geological period. They gained importance in the early Cretaceous (Hauterivian stage) and later diversified in Aptian and younger stages. The Generic and Species level identification and age assignment the work of (Bolli, 1989) was adopted in this work. The important planktonic foraminifera reported in the present work and ranges in stratigraphy is given in Figure 5.1.

For both planktonic and benthic foraminifera, the actual frequency for each sample interval was recorded and arranged. For paleoenvironmental interpretation and paleodepth determination the use of benthic foraminifera morpho-groupings is well known and has been discussed by various workers (Nagy, 1992; Murray et.al, 2011).

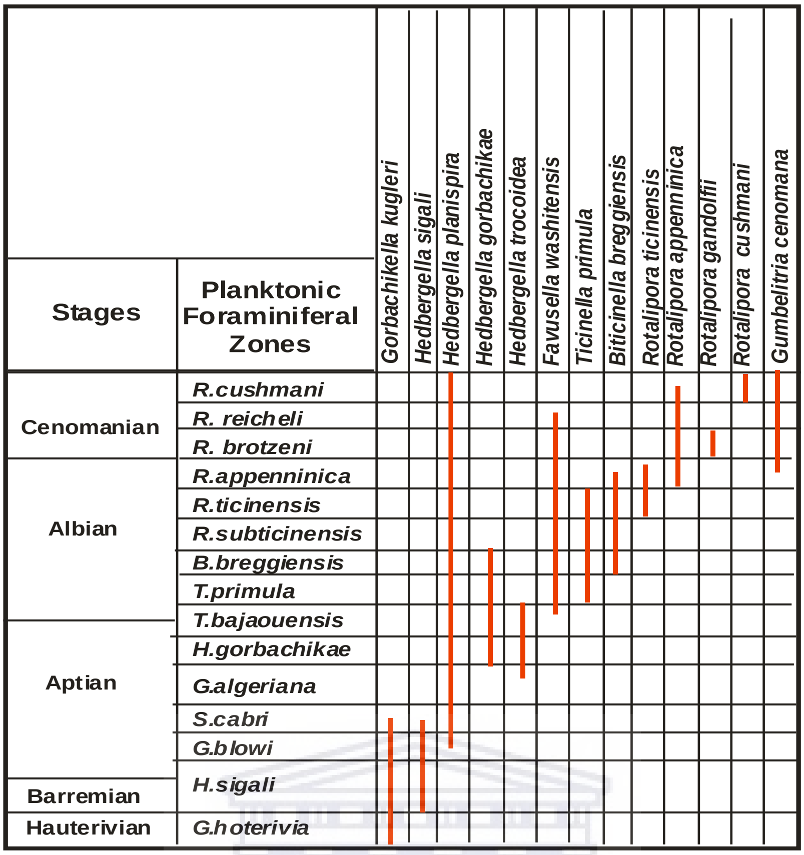


Figure 5.1 Planktonic species recorded in the present work, the Planktonic foraminiferal zones and stage boundaries adopted from Bolli et.al. (1989).

The following section deals with the early Cretaceous foraminiferal biostratigraphy of the drilled well sections of the Durban Basin.

5.2 Early Cretaceous foraminiferal biostratigraphy

5.2.1 Well Jc-A1

The well Jc-A1 is the first exploratory well drilled in the year 1971 on the continental shelf east of the Natal coast. The prime objective of the well was to explore hydrocarbons within a large fault bound trap as defined by seismic reflection profiling. The drilling was terminated at a depth of 2400m in hard quarzitic sandstone and no hydrocarbon accumulation was found (Well Completion Report Jc-A1, Soekor, 1971). The bottommost datable sediments in this well Turonian-Cenomanian? foraminifera at 2140m depth. Below this there is quarzitic sediments possibly belongs to late Carboniferous age (Paleozoic, Gondwana series). Therefore, the entire early Cretaceous is absent in this well and is represented as a hiatus. In this present early Cretaceous biostratigraphic research therefore this well was not studied.

5.2.2 Early Cretaceous foraminiferal biostratigraphy of Well Jc-B1

The Well Jc-B1 was drilled in 1983 to explore development of reservoir facies (sandstone) below horizon 13At1 and between 13At1 and 15At1 (Cenomanian and older). The well JC-B1 was drilled to a depth of 3943m to explore any trap (combination fault and unconformity). As per information derived from the Well Completion Report (Unpublished Well Completion Report, Jc-B1,1983), very poor reservoir facies encountered in the drilled section and the well was terminated under a status of poor gas shows. Out of the four wells drilled in Durban Basin, the only conventional core CC#1 (3428-3440m, recovery 95%) was cut from this well. However, except for the topmost one-meter metasedimentary rock, the remaining core was in the dolerite intrusion.

In the present foraminiferal biostratigraphic studies available well cuttings between the intervals 3100m - 3500m was processed after careful selection of lithology from well-logs, Geological Composite logs and megascopic observation of the cutting samples in the department laboratory. All efforts were made to sect the samples from regular intervals and preferably from the argillaceous intervals. Presence of any caved particles were manually removed. For some specific intervals either samples were not available in Petroleum Agency of South Africa (PASA), Core laboratory, Cape Town or were of very small amount. Due to this precise demarcation of age boundaries could not be made in most places. Total 21 well cuttings samples were processed for this well. The detail observations made from the temporal distribution of foraminifera, age assignments and inferred paleodepth and environment is discussed in the following paragraphs. Sample wise distribution and integrated results are presented in Table 5.1 and Figure 5.2 respectively.

Interval 3359-3491m: The lithology within this interval comprises of finer mainly clastics (claystone/shale) with occasional siltstone and fine sand. Within this interval two dolerite intrusive were also encountered. The sediments comprise mainly of dark grey claystone with fine disseminated pyrite grains. The fine sandstones and siltstones are light yellow to brownish in color. A core CC#1 in the interval 3428-3440m contains a one-meter thick metamorphosed siltstone (?). Due to the igneous nature, no detail core analysis was performed.

The bottommost sample at 3488m-3491m yielded foraminifera with low frequency. Presence of *Hedbergella sigali* (the earliest Cretaceous plankton) along with *Bathysiphon* sp. *Ammobaculites* sp., *Haplophragmoides* sp. and the calcareous benthics *Lenticulina nodosa* were recorded. The next three samples from the overlying interval shows an increase in frequency and diversity in foraminifera. The lithology is essentially an intercalation of claystone with fine sandstone or siltstone. Presence of ferruginous rock particles and red coloration in benthics at 3447m suggests temporary shallow condition and possible diastem/unconformity surface. Apart from *Hedbergella sigali* no other planktonic forms were recorded. However, there is an increase in frequency and diversity in agglutinated foraminifera. *Bathysiphon* sp., *Ammobaculites* sp., *Haplophragmoides* sp. and *Glomospira* sp. are common in all the three samples and calcareous benthics like *Nodosaria* sp. and *Lenticulina nodosa* is also present. Presence of the typical calcareous benthics *Conorboides oronata* (Barremian - early Aptian) is recoded in the uppermost sample. On the last occurrence of *Hedbergella sigali* at 3447m and typical calcareous benthic association of *Conorboides oronata* and *Lenticulina nodosa* the entire interval is placed under Barremian- early Aptian age. The typical benthic agglutinated assemblage of *Bathysiphon* sp., *Haplophragmoides* sp. and *Glomospira* sp.in good frequency suggests deposition around 500m water depth marine slope environment (upper to middle bathyal condition).

The lithology of the overlying succession interval 3347m to 3380m shows increased influx of coarse clastics (fine grained sandstone and siltstone) and also an overall decrease in microfauna frequency. Although agglutinated foraminifera viz. *Bathysiphon* sp. *Reophax* sp., *Ammobaculites* sp. are present but their frequency has decreased considerably compared to the underlying section. Moreover, relatively shallow water forms like *Ammodiscus* sp. along with calcareous benthics *Gavelinell*a sp. is common in this interval. The benthic foraminifera assemblage suggests shallow outer shelf condition. The section is devoid of any planktonic foraminifera. In absence any age diagnostic planktonic foraminifera and the next presence of *Rotalipora ticinensis* at sample interval 3359-3362 m (first appearance only in late Albian) this interval is tentatively placed under later part of Aptian or younger.

The overlying section is almost 200m thick (3359-3167m). This thick section although lithologically dominated by dark grey claystone with minor shale bands but frequent presence of light yellowish white siltstone layers with considerable thickness has been encountered at several intervals like 3300-3340m and 3210-3240m. Foraminiferal frequency is generally poor in the siltstone intervals. Radiolaria is common in some of the samples within the interval. The planktonic foraminifera assemblages present within this interval are mainly *Rotalipora ticinensis, R. appenninica, Hedbergella gorbachikae* and *H. planispira.* On the last appearance of *Rotalipora ticinensis* at 3167m, the entire section is placed under late Albian age. The frequency of benthic foraminifera varies from low to moderate in the arenaceous intervals but increases to good frequency in the claystone sections. Agglutinated benthics like *Bathysiphon* sp., *Reophax* sp., *Glomospira* sp., *Saccammina* sp., and *Dorothia* sp. are commonly present throughout claystone dominated intervals with very good frequency. These agglutinated benthics indicates a rise in sea level of more than 500m (uppermost upper bathyal to middle bathyal). Presence of agglutinated benthics like *Saccammina* sp. and *Flabellammina* sp. are recorded in the silty intervals indicating deposition on upper part of outer shelf. In general, the depth of deposition within the 200m late Albian section between 3359m to 3167m fluctuates from inner-shelf to middle bathyal environment. The calcareous benthics present within this interval are *Lenticulina angulosa*, *Nodosaria* sp. and *Osangularia* sp.

The overlying interval between 3100 m and 3167m is characterized by typical planktonic suite of *Rotalipora gandolfii*, *R. cushmani* and *Hedbergella planispira*. The two *Rotalipora* species confirms the age of this interval as Cenomanian. The calcareous claystone rich interval at sample position 3149-3152m indicates a drop in bathymetry to outer shelf otherwise presence of *Glomospira* sp., *Bathysiphon* sp., *Dorothia* sp. and *Lenticulina* sp., suggests deposition under upper to middle bathyal environment.

Table 5.1 Temporal distribution of microfauna in well Jc-B1 (interval 3107-3491m)

	PLANKTONIC							BENTHIC																						
								AGGLUTINATED															CALCAREOUS								
Sample Interval	*Hedbergella sigali*	*Rotalipora ticinensis*	*Rotalipora appenninica*	*Hedbergella gorbachike*	*Hedbergella planispira*	*Rotalipora grandolfii*	*Rotalipora cushmani*	*Bathysiphon* sp.	*Ammobaculites* sp.	*Haplophragmoides*	*Reophax* sp.	*Glomospira* sp.	*Spiroplectammina* sp.	*Trochammina depressa*	*Bathysiphon alexandari*	*Saccammina* sp.	*Verneulina* sp.	*Gaudryina* sp.	*Ammodiscus* sp.	*Dorothia* sp.	*Textularia* sp.	*Flabellammina* sp.	*Nodosaria* sp.	*Lenticulina nodosa*	*Conorboides oronata*	*Marginulopsis* sp.	*Gavelinella* sp.	*Lenticulina* sp.	*Lenticulina angulosa*	*Osangularia* sp.	RADIOLARIA SP
3107-3110					●	●	●	X		X		●								●								●			
3123-3126					●	●	●			X																		●			
3149-3152						●			●	X											●										
3167-3170		X	●		●			X		X										●											
3197-3200		X	●	X				∇		X	X	●								●											●
3218-3221									X	X	●					X															X
3239-3242								X															●								
3257-3260		X	X					X		X	X	●				X				●			X								
3278-3281		●	X					X		X	X	X				●						●	X						●		
3299-3302												●				●				●											
3317-3320		X	●	X	●			X		●	X	●				X			●	●			X						X	X	
3329-3332		●	●					X															X								
3338-3341								X			●								X									●			
3359-3362		●						X	X	X	X						●	●									X				●
3377-3380								●	●		●																				
3407-3410								●	X		●						X										X	X			
3422-3425								X	X		∇	X			X	X	X							X			X				X
3447-3450	X							∇		X	X	∇	X	X										X	X	●					
3458-3461								∇	X	□	X	X											X								
3467-3470								X	X	X	●																				
3488-3491	●							X	X	●														●							

● solitary X 2 to 5 ∇ 5 to 10 □ > 10

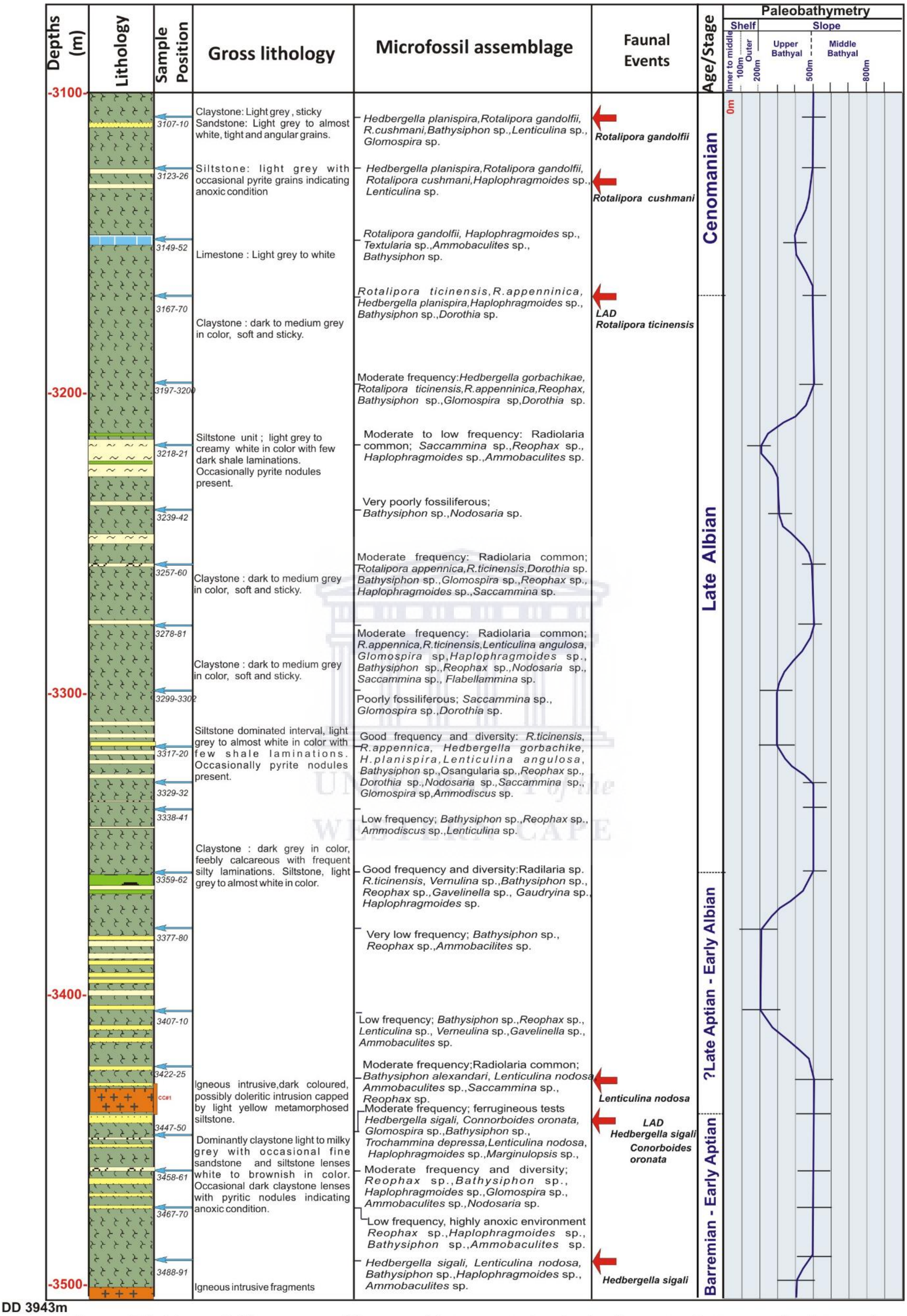


Figure 5.2 Foraminifera assemblage and interpreted paleobathymetry between the interval 3100-3500m in well Jc-B1, Durban Basin, Offshore South Africa.

5.2.3 Early Cretaceous foraminiferal biostratigraphy of Well Jc-C1

The well Jc-C1 located about 24km east at Stanger, Natal as a New field exploratory well. The well was drilled to a depth 3943m and was terminated as a dry well (PASA well Completion report, 1983). No conventional core was cut in this well and the biostratigraphic work was carried out is based on well cuttings.

A total 32 well cuttings were selected from the argillaceous interval 2000m to 3200m. The samples were processed using conventional methods adopted and discussed under sample preparation section. In the following section detail account of temporal distribution of foraminifera along the well is discussed along with interpreted stage boundaries and paleo depositional environment. The temporal distribution is presented in Table 5.2, and integrated biostratigraphy in Figures 5.3 and 5.4 respectively.

Interval 2857-3200m: the lower 343m interval of the studied section is a dominantly argillaceous section with a few thin limestone/calcareous beds in the middle and upper part. This section also shows presence of three dolerite intrusions. The intrusive igneous fragments are dark greenish grey to brownish black in color with hard crystalline fragments. The claystone is mostly dark grey, soft and sticky. The fine limestone beds present mostly in the upper half of the interval are limestone, pale yellowish to brownish in appearance and are argillaceous in nature. Foraminiferal frequency throughout this interval is low to moderate. Presence of the early Cretaceous planktonic foraminifera *Hedbergella sigali*, *Hedbergella aptiana*, *Globugerina hoterivica* and *Gorbachikae kugleri* (rare) indicates that this section belongs to Barremian to early Aptian age. Top of this interval is marked at 2737m on the last appearance of *Hedbergella sigali.* The interval also shows presence of agglutinated benthics in variable frequency in different intervals. This indicates fluctuating bathymetry from middle-outer shelf to uppermost bathyal during this period. Important agglutinated deep water foraminifera like *Hyperammina elongata*, *Hyperammina* sp. at certain interval indicates deep water middle bathyal environment at certain level. The other agglutinated forms present within this interval are *Bathysiphon alexandari*, *Bathysiphon* sp., *Saccammina* sp. *Trochammina* sp., *Textularia* sp., *Haplophragmoides* sp., *Ammobaculites* sp., *Nodosaria* sp., *Gavelinella* sp., *Gaudryrina* sp. in various frequency throughout the section. The calcareous benthic includes *Conorboides oronata*, *Lenticulina nodosa*, *Epistommina oronata*, *Involutina* sp., *Biloculina* sp. etc.

Interval 2665m- 2857m: This section although dominated by argillaceous units many thin units of fine sandstone and siltstone appear frequently. The siltstones are light grey to white in color with mostly angular quartz grains. Pyrite nodules are common in some of these siltstone units. The overall section shows a drop in foraminiferal frequency compare to the underlying section already discussed. Presence of *Inoceramus* prisms common in the bottom most samples also indicates a drop in bathymetry to inner-shelf to middle shelf (100-150m). The important planktonic foraminifera present in this interval includes *Hedbergella trochoidea and Globigerinelloides* cf. a*ptiensis*. On the last appearance of the important planktonic species *Hedbergella trochoidea* at 2665m this interval is placed under Late Aptian age. As already mentioned, this interval shows presence of *Inoceramus* prisms (fragments of bivalves) along with *Ammodisus* sp. indicating middle shelf condition.

Interval 2305-2665m: This thick interval of argillaceous unit has several interesting characters. In the lower part frequent presence of calcareous siltstone units with disseminated pyrite grains, then around 2500m till 2400m it is totally devoid of any micro fauna. Then above this barren interval very low yield of planktonic foraminifera and around 2305m first benthics are recorded. In the bottom part presence of *Hedbergella gorbachikae* is present in two consecutive samples along with benthics like *Epistomella caracolla* and *Pleurostomella obtusa.* The planktonic foraminifera *Hedbergella gorbachikae* is known to occur only in the early Albian (Bolli, 1989: page 36) and above this interval there is a very thick (2420–2581m) section completely devoid of any fauna. Above this unit only the presence of planktonic species *Favusella washitensis* is recorded. *F. washitensis* is a relatively long ranging from appear in the early Albian and ranges up to early Cenomanian. However, the age diagnostic planktonic foraminifera *Rotalipora ticinensis* (a typical early Albian species) appears at 2305m. On basis of this the entire interval from 2305m and below 2665m is placed under early Albian, this includes the unfossiliferous interval also.

Interval 2185-2305m: This interval is a dominantly argillaceous interval however, there are a few sandstone and siltstone interval in the lower part. There is an intrusive (dolerite?) body in the lower part. The section is poor in faunal frequency however, presence of both planktonic and benthics are recorded in some of the samples. The planktonic foraminifera *Rotalipora ticinensis* is present in a few samples along with *Favusella washitensis*. The planktonic species *Rotalipora ticinensis* ranges within late Albian only (Bolli, 1989). Also, presence of *Sachakonia cabri* within this interval confirms the late Albian age. The other species *Favusella washitensis* is a long ranging form. On the basis of total ranges of the planktonic species *Rotalipora ticinensis* this interval is placed under late Albian. The top of late Albian is marked tentatively at 2185m (LAD of *Rotalipora ticinensis*) in this well. The early Albian section also contains a few benthic foraminifera represented by *Trochammin*a sp., *Gavelinella* sp., in the lower part. This indicates a shallow bathymetry of around 100-200m shelf environment. The bathymetry gradually increases towards the top of the section as indicated by the presence of deep water agglutinated foraminifera *Hyperammina* sp.

Interval 2000-2185m: This section comprises of shale with frequent presence of siltstones with a few limestone layers. The interval is fairly fossiliferous with a new planktonic suite belongs to Cenomanian age. The notable species includes *Gumbeletria cenomana, Rotalipora gandolfi, Praeglobotruncana pseudoalgeriana, Dicarinella imbricata, Clavihedbergella simplex* and *Rotalipora appenninica*. The overall assemblage indicates late Cretaceous, Cenomanian stage. Presence of agglutinated benthics like *Bathysiphon alexandari, Glomospira* sp., *Reophax* sp., *Trochammina* sp. indicates that the deposition took place in uppermost bathyal to upper bathyal (slope) environment.

Table 5.2 Temporal distribution of microfauna in well Jc-C1 (interval 2015-3166m)

Sample Interval	PLANKTONIC																			BENTHIC FORAMINIFERA																																					
																				AGGLUTINATED																	CALCAREOUS																				
	Hedbergella sigali	*Gorbachikella kugleri*	*Hedbergella aptiana*	*Globugerina hoterivica*	*Hedbergella gorbachike*	*Hedbergella trochoidea*	*Globigerinilloides cf.aptinenses*	*Favusella washitensis*	*Schakonia sp.*	*Protoheterohelix sp.*	*Gumbeletria cenomana*	*Clavihedbergella simplex*	*Heterohelix moremanii*	*Rotalipora ticinensis*	*Rotalipora grandolfii*	*Rotalipora appenninica*	*Hedbergella sp.*	*Hedbergella cf.infracretacea*	*Praeglobotruncana pseudoalgeriana*	*Hyperammina sp.*	*Hyperammina elongata*	*Trochammina sp.*	*Trochammina globigeriniformis*	*Gaudryina sp.*	*Ammobaculites sp.*	*Bathysiphon alexandari*	*Kalamopsis sp.*	*Ammodiscus sp.*	*Haplophragmoides sp.*	*Reophax sp.*	*Glomospira sp.*	*Textularia sp.*	*Saccammina sp.*	*Recurvoides sp.*	*Psammosphaera fusca*	*Dorothia sp.*	*Conorboides oronata*	*Biloculina sp.*	*Gavelinella sp.*	*Quilqueloculina sp.*	*Lagena sp.*	*Lenticulina nodosa*	*Nodosaria sp.*	*Involutina sp.*	*Epistomina oronata*	*Dentalina sp.*	*Osangularia sp.*	*Reinholdella sp.*	*Eponoides sp.*	*Oolina sp.*	*Pleurostomella obtusa*	*Epistommina caracolla*	*Lagenammina pyriformis*	*Pyrulina sp.*	*Rotalina sp.*	*Bimonilina sp.*	*Gyroinoides sp*
2015-2020												•			X				•						X	X				X	X											X															
2050-2055													X		X	•	•	•				X				X			X	•	X					X			X			•				•											
2090-2095										•	•	•										X				•			X	•	X		X																								•
2130-2135																									X														•				•														
2165-2170																						X				X			X										X					•			X									X	
2185-2190								•						•						X											•				•									•										•	X		
2225-2230								•	X																										X																						
2265-2270								D	E	V	O	I	D					O	F						M			I			C			R			O			F			A			U			N			A					
2305-2310								•						•								X																	•																		
2340-2345								X																																													X				
2380-2385								X						•																																							•				
2420-2425								D	E	V	O	I	D					O	F						M			I			C			R			O			F			A			U			N			A					
2440-2445								D	E	V	O	I	D					O	F						M			I			C			R			O			F			A			U			N			A					
2460-2465								D	E	V	O	I	D					O	F						M			I			C			R			O			F			A			U			N			A					
2500-2505								D	E	V	O	I	D					O	F						M			I			C			R			O			F			A			U			N			A					
2542-2545								D	E	V	O	I	D					O	F						M			I			C			R			O			F			A			U			N			A					
2581-2584					•																																															•					
2623-2626					•	•																																													•						
2665-2668					X	•	•													•		•						•																													
2695-2698					•		•																					•																		•											
2737-2740	X																			•		•																												•							
2773-2776																						X	•			X			X	•				X																							
2815-2818	•																									X			X	•											•					•	•	X	•								
2857-2860				X																													X																								
2896-2899	•			X																	X								X			•							X					X	•												
2935-2938	X			•																						•													•																		
2974-2977	•																									•														•																	
3013-3016				•																						•													•																		
3052-3055			X	•																					X	•	•	•	•											•	•	•															
3091-3094	X	•																						•															•																		
3133-3136																																•						•					X	•													
3163-3166	•																			X		X		•													•	X																			

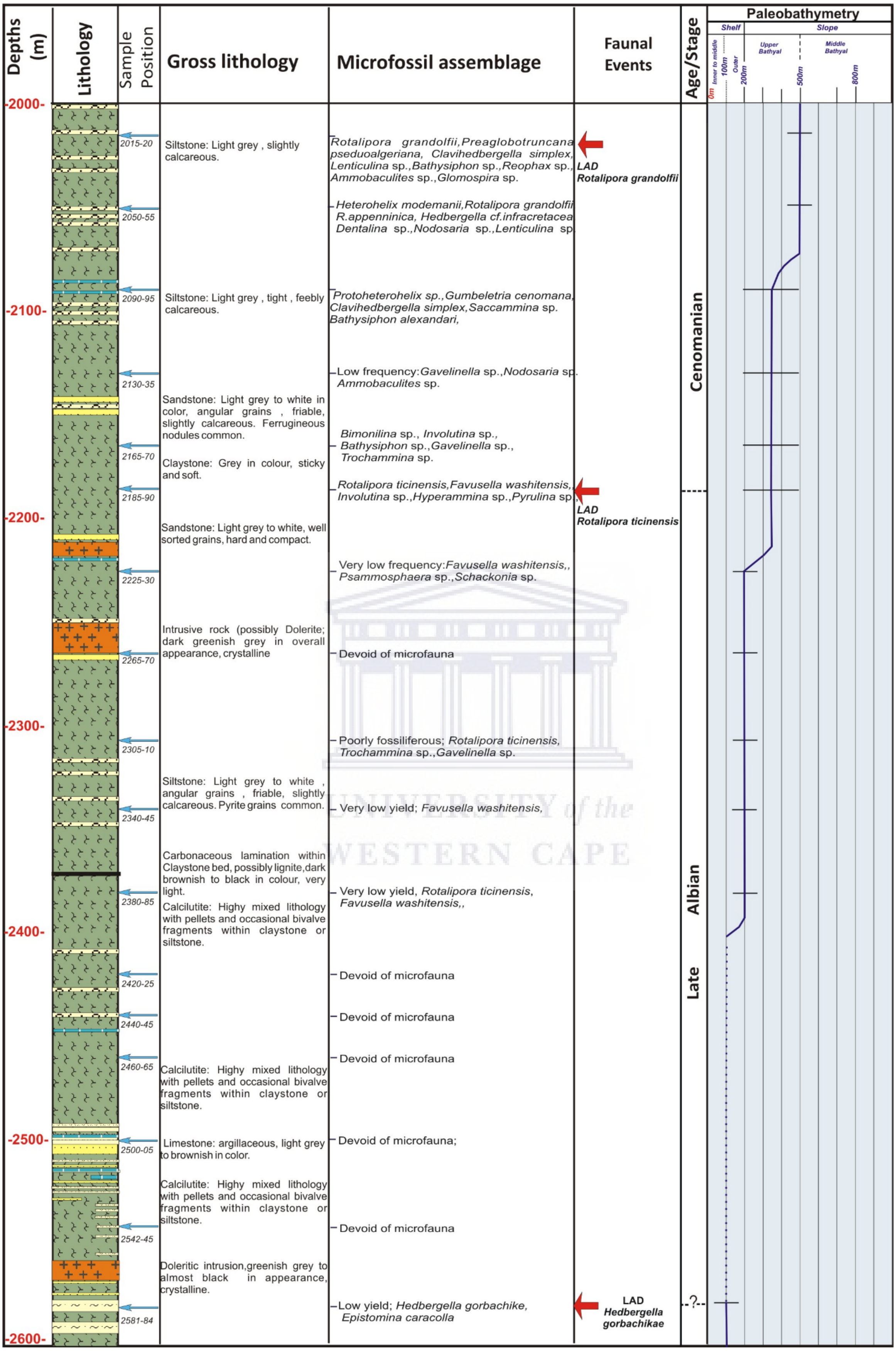


Figure 5.3 Foraminifera assemblage and interpreted paleobathymetry between the interval 2000-2600m in well Jc-C1, Durban Basin, Offshore South Africa

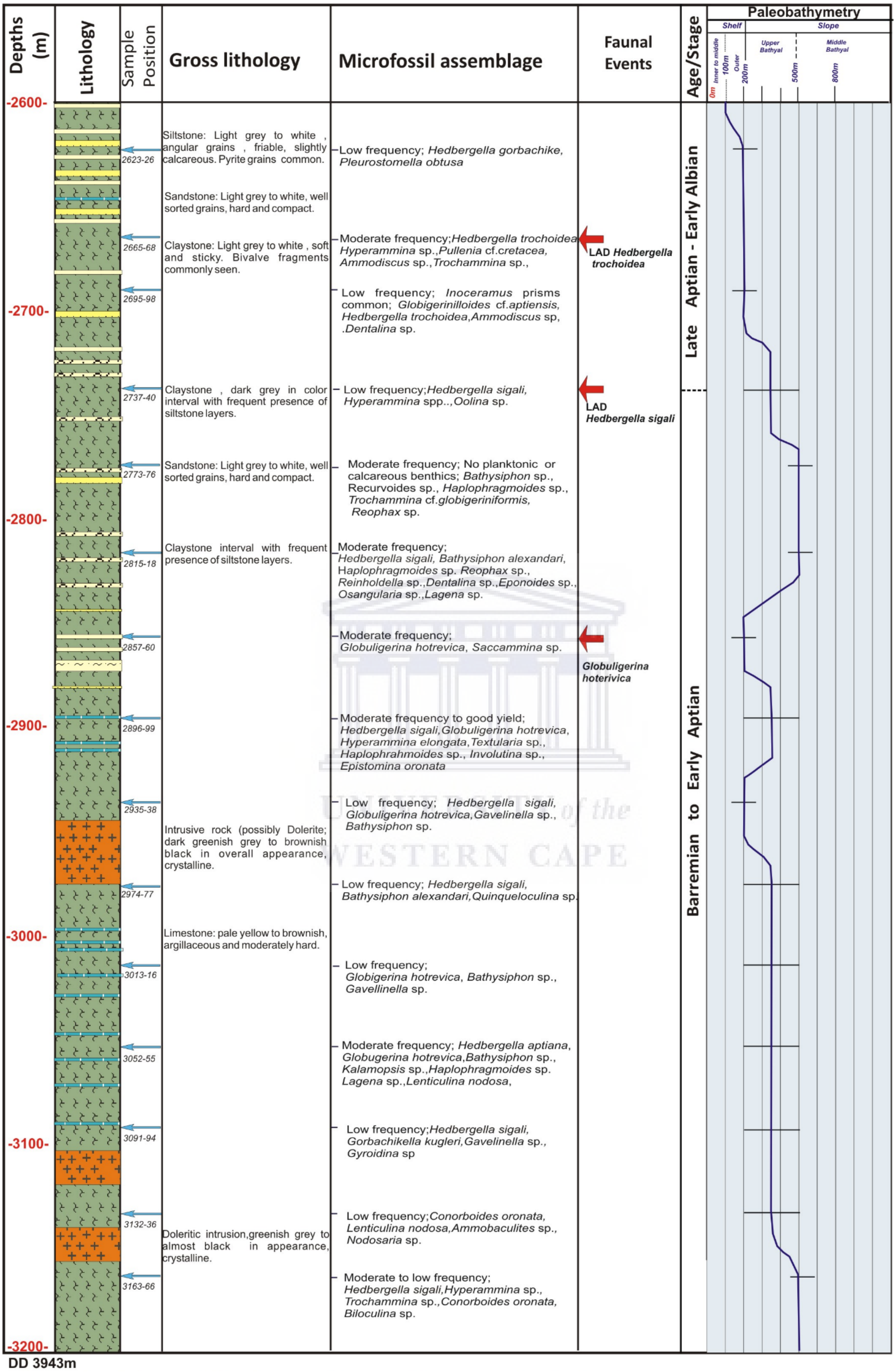


Figure 5.4. Foraminifera assemblage and interpreted paleobathymetry between the interval 2600-3200m in well Jc-C1, Durban Basin, Offshore South Africa.

5.2.4 Early Cretaceous foraminiferal biostratigraphy of Well Jc-D1

The well Jc-D1 is the fourth and last exploratory well drilled almost two decades back in offshore Durban Basin. The well was drilled as an exploratory test well to evaluate the hydrocarbon potential of late Jurassic- early Cretaceous reservoirs on a seismically defined structural and stratigraphic trap (Well report Jc-D1, 2000). The well was drilled to a depth of 2900m and was terminated at early Cretaceous conglomerate (graben fill) sediments, abandoned as a dry well. No conventional core was cut in this well and the biostratigraphic study carried out from the available well cuttings selected from physical verification of samples and composite well logs. A total 15 cutting samples (20gm.) was processed in the laboratory for biostratigraphic analysis. The samples were selected from the interval 2620m to 2820m. The depth wise temporal distribution of foraminifera is presented in Table 5.3 and the integrated biostratigraphic work is presented in Figure 5.5 the detail of the results is presented in the following paragraphs.

Interval 2748–2820m: This section comprises of graben fill sediments mainly conglomeratic type of lithology with thin beds of silty-claystone. The framework grains in the conglomerate comprises of chart fragments, volcanic rock fragments mixed with clay. The overall lithology suggests a graben fill section with periodic incursion of sea depositing the fine silty claystones. A total of six samples processed from these intervals are lithologically clay rich siltstones, greenish grey to light grey in color, with frequent presence of disseminated pyrite nodules. The microfaunal frequency is mostly very low with the slight increase in the uppermost sample at 2748-2751m. However, three samples within the interval has yielded age diagnostic planktonic foraminifera *Gorbachikella kugleri* and *Hedbergella sigali*. On the basis of the occurrence of the two diagnostic planktonic foraminifera the interval 2748-2820 m is placed under Barremian- early Aptian age. Apart from these planktons both agglutinated and calcareous benthics are present in most of the samples but with low frequency. The agglutinated benthic like *Bathysiphon* sp., *Reophax* sp., and *Ammobaculites* sp. and calcareous benthics viz. *Lenticulina gaultina*, *Involutina* sp., *Globulina* sp. in low frequency suggests deposition in middle shelf condition to outer shelf environment (~ 100-200m water depth) with anoxic condition during the deposition. There was an increase in water depth above 2763m as revealed by the higher frequency of benthic foraminifera particularly of *Bathysiphon* sp. and presence of *Lenticulina gaultina* from Outer shelf to upper bathyal. On the last occurrence of (LAD) of *Hedbergella sigali* the top of early Aptian is marked at 2748m in this well.

In the immediate overlying succession, the conglomerate lithology continues till 2720m. However, the foraminiferal frequency continues to increase in the silty intervals indicating a gradual increase in sea level. Although, no planktons were recorded an increase in frequency of *Bathysiphon* sp., *Haplophragmoides* sp., *Reophax* sp., *Glomospira* sp. and *Lagena* sp. all indicates upper bathyal depositional set up. Due to absence of any age diagnostic planktonic foraminifera within this section and unit overlie the early Aptian age group of sediments, this unit is tentatively placed under late Aptian.

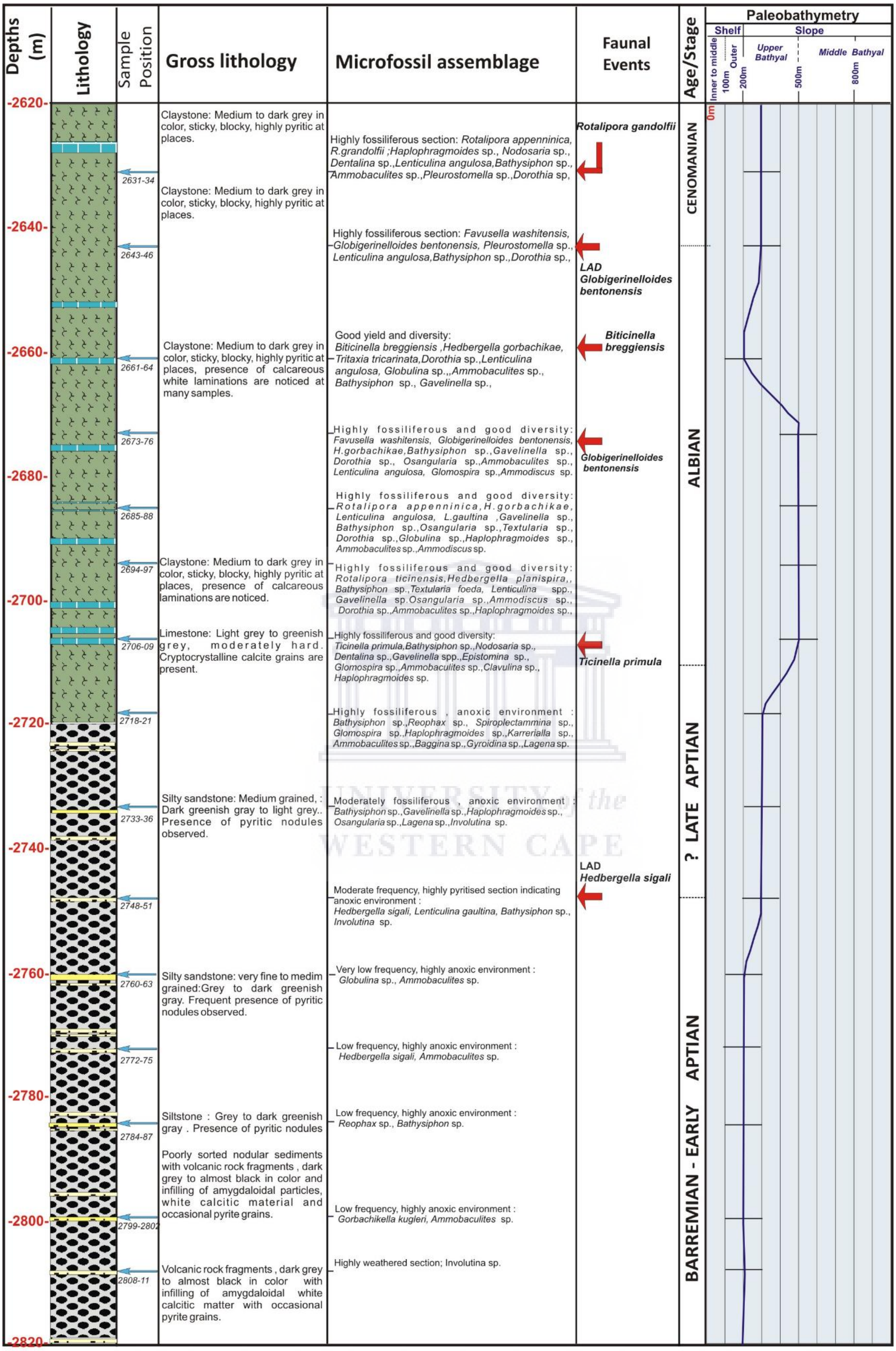
Above the graben fill lithology an abrupt in sedimentary rock composition was recorded. The coarse lithology overlies a very thick succession of grey claystone succession with intermittent calcareous thin beds in the rest of the studied interval. The first appearance of planktonic foraminifera *Ticinella primula* at 2709m confirms the early Albian age. All sample above this depth up to 2643m a continuous higher frequency and diversity was recorded. The notable planktonic foraminifera include *Rotalipora ticinensis, R. appenninica, Hedbergella gorbachikae, H. planispira, Favusella washitensis* and *Globigerinelloides bentonensis*. The common occurrence of all these planktonic foraminifera suggests Albian age for this interval. Although some of these planktonic like *Hedbergella planispira, Rotalipora appenninica* and *Favusella washitensis* are long ranging continues till Cenomanian or younger age the presence of *Rotalipora ticininsis* and Hedbergella *gorbachikae and Bicitinella breggienensis* are restricted within Albian stage. On the last occurrence of Globigerinelloides *bentonensis* the Albian boundary is marked at 2463m in this well. Benthic foraminifera association within the Albian stage in well Jc-D1 shows very good frequency and diversity. A rapid increase of agglutinated foraminifera like *Haplophragmoides* sp., *Bathysiphon* sp., *Dorothia* sp., *Textularia* sp. and *Ammodiscus* sp. along with calcareous benthics like *Gavelinella* sp., *Osangularia* sp. and *Lenticulina angulosa* indicates an uppermost bathyal to middle bathyal environment for the major part of the Albian stage in this location.

The remaining studied interval between 2620m and 2643m is lithologically similar to the underlying Albian succession. There was no significant change in bathymetry as the benthic characters are almost same. Presence of index planktonic foraminifera *Rotalipora gandolfii* at sample interval 2631-2634m confirms Cenomanian age for this section.

Table 5.3 Temporal distribution of microfauna in well Jc-D1 (interval 2631-2811m)

	PLANKTONIC															BENTHIC																									
																AGGLUTINATED												CALCAREOUS													
Sample Interval	*Gorbachikella kugleri*	*Hedbergella sigali*	*Hedbergella aptiana*	*Ticinella primulla*	*Rotalipora ticinensis*	*Hedbergella gorbachike*	*Hedbergella trochoidea*	*Globigerinilloides* cf. *aptinenses*	*Hedbergella planispira*	*Hedbergella gorbachikae*	*Favusella washitensis*	*Globigerinelloides bentonensis*	*Biticenella breggiensis*	*Rotalipora appenninica*	*Rotalipora grndolfii*	*Ammobaculites* sp.	*Bathysiphon* sp.	*Reophax* sp.	*Haplophragmoides* sp.	*Glomospira* sp.	*Karreriella* sp.	*Spiroplectammina* sp.	*Clavulina* sp.	*Textularia foeda*	*Ammodiscus* sp.	*Dorothia* sp.	*Tritaxia tricarinata*	*Involutina* sp.	*Globulina* sp.	*Gavelinella* sp.	*Osangularia* sp.	*Lagena* sp.	*Baggina* sp.	*Gyroidina* sp.	*Nodosaria* sp.	*Dentalina* sp.	*Epistomina* sp.	*Lenticulina gaultina*	*Lenticulina angulosa*	*Lenticulina* spp.	*Pleurostomella* sp.
2631-2634														•	X	X	□		∇	X						X									∇	X			X		X
2643-2646											X	•					∇		□	•						•													X		X
2661-2664										X			•			X	X		∇	•						X	X		X	X	X								X		X
2673-2676										•	X	•				X	X		∇	•					•	X				•	X							X			
2685-2688										X				•		X	∇		∇					•	•	•			X	X	X							X	X		
2694-2697					•				•								∇		□					X	•	•					X									X	
2706-2709				•												X	X		X	X			•							X					X	•	X				
2718-2721																∇	□	X	X		•	•										X	X	X							
2733-2736																	X		X	•								•		X	X	X									
2748-2751		•															X											•													
2760-2763																X													X												
2772-2775		•														X																									
2784-2787																	X	•																							
2799-2802	•															•																									
2808-2811																												•													

• solitary X 2 to 5 ∇ 5 to 10 □ > 10



Claystone: Medium to dark grey in color, sticky, blocky, highly pyritic at places.

Claystone: Medium to dark grey in color, sticky, blocky, highly pyritic at places.

Claystone: Medium to dark grey in color, sticky, blocky, highly pyritic at places, presence of calcareous white laminations are noticed at many samples.

Claystone: Medium to dark grey in color, sticky, blocky, highly pyritic at places, presence of calcareous laminations are noticed.

Limestone: Light grey to greenish grey, moderately hard. Cryptocrystalline calcite grains are present.

Silty sandstone: Medium grained, : Dark greenish gray to light grey.. Presence of pyritic nodules observed.

Silty sandstone: very fine to medim grained:Grey to dark greenish gray. Frequent presence of pyritic nodules observed.

Siltstone : Grey to dark greenish gray . Presence of pyritic nodules

Poorly sorted nodular sediments with volcanic rock fragments , dark grey to almost black in color and infilling of amygdaloidal particles, white calcitic material and occasional pyrite grains.

Volcanic rock fragments , dark grey to almost black in color with infilling of amygdaloidal white calcitic matter with occasional pyrite grains.

Highly fossiliferous section: *Rotalipora appenninica, R.grandolfii ;Haplophragmoides* sp., *Nodosaria* sp., *Dentalina* sp.,*Lenticulina angulosa,Bathysiphon* sp., *Ammobaculites* sp.,*Pleurostomella* sp.,*Dorothia* sp,

Highly fossiliferous section: *Favusella washitensis, Globigerinelloides bentonensis, Pleurostomella* sp., *Lenticulina angulosa,Bathysiphon* sp.,*Dorothia* sp.,

Good yield and diversity: *Biticinella breggiensis ,Hedbergella gorbachikae, Tritaxia tricarinata,Dorothia* sp.,*Lenticulina angulosa, Globulina* sp.,,*Ammobaculites* sp., *Bathysiphon* sp., *Gavelinella* sp.,

Highly fossiliferous and good diversity: *Favusella washitensis, Globigerinelloides bentonensis, H.gorbachikae,Bathysiphon* sp.,*Gavelinella* sp., *Dorothia* sp., *Osangularia* sp.,*Ammobaculites* sp., *Lenticulina angulosa, Glomospira* sp.,*Ammodiscus* sp.

Highly fossiliferous and good diversity: *Rotalipora appenninica,H.gorbachikae, Lenticulina angulosa, L.gaultina ,Gavelinella* sp., *Bathysiphon* sp.,*Osangularia* sp.,*Textularia* sp., *Dorothia* sp.,*Globulina* sp.,*Haplophragmoides* sp., *Ammobaculites* sp.,*Ammodiscus* sp.

Highly fossiliferous and good diversity: *Rotalipora ticinensis,Hedbergella planispira,, Bathysiphon* sp.,*Textularia foeda, Lenticulina* spp., *Gavelinella* sp.*Osangularia* sp.,*Ammodiscus* sp., *Dorothia* sp.,*Ammobaculites* sp.,*Haplophragmoides* sp.,

Highly fossiliferous and good diversity: *Ticinella primula,Bathysiphon* sp.,*Nodosaria* sp., *Dentalina* sp.,*Gavelinella* spp.,*Epistomina* sp., *Glomospira* sp.,*Ammobaculites* sp.,*Clavulina* sp., *Haplophragmoides* sp.

Highly fossiliferous , anoxic environment : *Bathysiphon* sp.,*Reophax* sp., *Spiroplectammina* sp., *Glomospira* sp.,*Haplophragmoides* sp.,*Karrerialla* sp., *Ammobaculites* sp.,*Baggina* sp.,*Gyroidina* sp.,*Lagena* sp.

Moderately fossiliferous , anoxic environment : *Bathysiphon* sp.,*Gavelinella* sp.,*Haplophragmoides* sp., *Osangularia* sp.,*Lagena* sp.,*Involutina* sp.

Moderate frequency, highly pyritised section indicating anoxic environment : *Hedbergella sigali, Lenticulina gaultina, Bathysiphon* sp., *Involutina* sp.

Very low frequency, highly anoxic environment : *Globulina* sp., *Ammobaculites* sp.

Low frequency, highly anoxic environment : *Hedbergella sigali, Ammobaculites* sp.

Low frequency, highly anoxic environment : *Reophax* sp., *Bathysiphon* sp.

Low frequency, highly anoxic environment : *Gorbachikella kugleri, Ammobaculites* sp.

Highly weathered section; Involutina sp.

Figure 5.5 Foraminifera assemblage and interpreted paleobathymetry between the interval 2620-2820m in well Jc-D1, Durban Basin, Offshore South Africa.

5.3 Discussion on the age

Although in the offshore parts of South Africa a number of wells has been drilled below lower Cretaceous level it is very difficult to date the older succession on basis of foraminifera. Diagnostic planktonic foraminifera are absent below Hauterivian level. Many of the wells penetrated unfossiliferous graben filled sediments. Presence of late Jurassic (Kimmeridgian–Tithonian) and earliest Cretaceous (Berriasian -Valanginian- Hauterivian) is present on the surface section in the onshore areas in the Eastern Cape of South Africa. In the present work the three studied well sections have penetrated maximum up to the Barremian stage sediments. In absence of age diagnostic planktonic foraminifera in some intervals and non-availability of continuous well cuttings in some of the wells makes it difficult to mark the stage boundaries precisely in this work. However, important planktonic foraminiferal groups are present in all the three wells which helps to assign age for different intervals.

Overall the South African Cretaceous drift succession has been divided into 22 units which are seismically defined unconformity boundaries (McMillan, 2003). However, not all these boundaries can be recognized in each basin. Some of these units can be subdivided further on the basis of foraminifera. In absence of planktonic foraminifera some local marker benthics are also helpful to assign the age and also for subsurface correlation. A discussion on the different early Cretaceous stages recognized in this present work and their foraminiferal composition is discussed in the following paragraphs.

Barremian to early Aptian:

This interval is quite thick (430m+) in well Jc-C1, but much thinner in the other two wells Jc-D1 (60m+) and JC-B1 (50m+). Although many of the bottom samples were not available for analysis, these variations in thickness can be attributed to the basinal topography. Lithologically, sediments under this age group varies widely from one well to the other. In well Jc-C1 where the thick interval has been encountered, the lithology comprises of mainly claystones with minor siltstone beds or fine sandstone. There are a few layers of intrusions within this section. Similar lithology has been encountered in well Jc-B1. The lithology in the well Jc-D1 is very interesting. The entire succession is represented by graben filled sediments comprises of pebbles of older volcanic rocks, charts with interbedded clayey siltstone. Presence of foraminifera in most of the studied samples within this interval (siltstones) indicates that the deposition took place with frequent marine incursion. However, the bathymetry in the equivalent section was relatively shallow in the other two wells (Jc-C1 and Jc-B1). Presence of disseminated pyrite grains, pyrite coated nodules and microfauna tests are common in all the three wells. Presence of these pyritic grains indicates anoxic condition prevailed in the depositional area during this time interval Durban Basin.

The overall frequency and diversity of foraminifera in all the three wells are moderate to low in the three wells for the Barremian -Early Aptian interval. Only few planktonic forms recorded in the three wells. *Hedbergella sigali* is the common planktonic species present in all the three well sections. The other planktonic foraminifera present are *Gorbachikella kugleri* (in Jc-C1 and Jc-D1), *Hedbergella aptiana* and *Globugerina hoterivica* (in Jc-C1 only). The co-occurrence of all these forms extending from in *Hedbergella sigali* zone (Barremian- earliest Aptian) and *Globigerinelloides blowi* zone and up to the lower most part of *Schakonia cabri* zone (Bolli, 1989, p.32) confirms Barremian to early Aptian age for this interval.

The overall frequency and diversity of benthic foraminifera is variable in the wells. Several agglutinated foraminifera particularly *Bathysiphon* sp., *Haplophragmoides* sp. along with calcareous benthics (low frequency) *Conorboides oronata*, *Lenticulina nodosa* are present in these intervals. The overall frequency and diversity of agglutinated foraminifera diversity in the three wells vary, it indicates relatively shallow middle to outer shelf in the conglomeratic graben filled section in the northern well Jc-D1, it is much deeper (upper to middle bathyal) in southern wells Jc-B1 and Jc-C1. Presence of local occurrence of calcareous benthics *Lenticulina nodosa* is known from almost all other basins in South Africa (McMillan, 2003, p.556) in the clay rich intervals.

Late Aptian (?) - Early Albian:

Sediments deposited during late Aptian and (?) the early part of Albian stage in this basin as indicated from the data available from the three wells shows marked difference in lithological characters and depth of deposition. While in northern well Jc-D1, the interval 2706-2748m is represented by the continuation of graben fill lithology and followed by thick claystone interval. The faunal frequency and diversity are good in this interval. However, in absence of age diagnostic planktonic foraminifera and because this interval overlies the early Aptian it could be placed tentatively under late Aptian. The benthic foraminifera composition, frequency and diversity shows a progressive increase in depth of deposition from the middle-outer shelf (neritic) in the lower part to upper bathyal to middle bathyal (lower-middle slope) in the claystone rich upper part.

In well Jc-B1, the equivalent section is having similarity in thickness but here the lithology comprises of claystone interval with very closely spaced beds of fine-grained sandstones and siltstone. This interval above 3447-3359m in well Jc-B1 is devoid of any age diagnostic planktonic foraminifera but the assemblage of agglutinated benthics are indicative of an upper bathyal environment. The presence of index planktonic species *Rotalipora ticinensis* in uppermost sample interval (3359-3362m) at indicates late Albian age.

In well Jc-C1 located in the southern part of the basin the equivalent interval is represented by around 56m (+) thick argillaceous section with interbedded thin siltstone or minor fine sandstone. Although, the microfossil frequency is generally low in the bottom part and gradually increases towards the upper part, presence of definite late Aptian to early Albian planktonic foraminifera *Hedbergella trochoidea* and *H. gorbachikae* justifies the geological age. The planktonic species *Hedbergella trochoidea* appears for the first time in the *Globigerinelloides algeriana* zone of late Aptian and ranges till the top of *Ticinella bejaouensis* zone at the base of early Albian (Bolli, 1989, p.36). The other notable planktonic foraminifera *Hedbergella gorbachikae* also make their first appearance in late Aptian and ranges up to the top of early Albian (base at *Rotalipora ticinensis* zone). The co-occurrence of both the planktonic foraminifera justifies the age for this section. Overall benthic foraminifera composition and frequent presence of sandstone/siltstone beds in the lower part of this section shows a rapid drop in sea level from upper bathyal to middle shelf. Presence of planktons helps to assign age for this section but presence of middle-outer shelf benthics like *Ammodiscus* sp., *Epistomina* spp. and common occurrence of *Inoceramus* sp. fragments confirms the drop in sea level in the southern area of this basin.

Late Albian:

In well Jc-D1 immediately after the doubtful late Aptian top is marked by the presence of the typical Albian planktonic species *Ticinella primula*. As this planktonic species appears in the lower Albian and continues till late Albian *Rotalipora ticinensis* zone, it is difficult to subdivide the Albian into early and late in this well. The Albian section in well is about 68m thick (2661-2709m) and comprises of dark grey claystone with interbedded thin limestone bands at regular intervals. This entire interval is highly fossiliferous with both planktonic and benthics groups are equally dominant. The overall composition indicates open marine condition.

Planktonic species frequency dominates towards the upper part. *Ticinella primula, Rotalipora ticinensis, Hedbergella planispira* are present in the lower part followed by *Hedbergella gorbachikae, Rotalipora appenninica* and *Biticenella breggiensis* in the upper samples. Some long ranging planktonic foraminifera (Albian-Cenomanian or younger) viz. *Favusella washitensis and Globigerinelloides bentonensis* are also present. The common occurrence of all these planktonic foraminifera indicates definite Albian age but it is difficult to mark any further subdivisions within Albian stage in this well. The overall foraminiferal composition also suggests possible slow but uninterrupted sedimentation. Presence of agglutinated benthics *Bathysiphon* sp., *Haplophragmoides* sp., *Glomospira* sp., *Textularia foeda*, *Ammobaculites* sp. and *Dorothia* sp. etc. throughout the section in good numbers suggests deposition in upper to middle bathyal slope environment. The deep-water environment is also supported by the presence of calcareous benthics viz. *Lenticulina gaultina*, *L. angulosa*, *Osangularia* sp. Overall the foraminiferal composition as encountered in the northern area of Durban Basin (in vicinity of well Jc-D1) suggest an uninterrupted bathyal depositional environment during Albian.

In the central part of the study are in well Jc-B1, the interval 3347m to 3362m is placed under late Aptian to early Albian. This interpretation is purely based on stratigraphic superposition as it overlies the Barremian-early Aptian sediments and no definite late Aptian or early Albian foraminifera was recorded. Immediately above this the approximately 200m succession (3167-3362m) is dated as late Albian here. The foraminiferal yield in this section is characterized by variable frequency with poor foraminifera presence in usually in the arenaceous patches. The section is however dominated by fine argillaceous lithology. parts. Presence of the planktonic foraminifera assemblages comprises of *Rotalipora ticinensis*, *R. appenninica*, *Hedbergella gorbachikae* and occasional *H. planispira*. Although some of these planktons are long ranging presence of late Albian index planktonic species *Rotalipora ticinensis* from the lowest sample to the uppermost sample is justifies the late Albian age for this interval. The variable frequency of benthic foraminifera indicates periodic fluctuation of sea level possibly three stages of sea level rise to upper bathyal (500m and more) within this period. In the northern locality Jc-D1 these fluctuations are less prominent.

In the southern area where the well Jc-C1 is located the early Albian interval is possibly thicker than encountered in well Jc-B1. In well Jc-C1, the underlying interval (2581-2185m) is dated as late Aptian- early Albian on the occurrence of *Hedbergella trochoidea* and *H. gorbachikae*. The top of this interval is marked by the last appearance of *H. gorbachikae (*uppermost known occurrence in the base of planktonic zone *Rotalipora subticinensis*) of early Albian stage (Bolli, 1989, p.36). Above this, the interval above 2581m till 2185m the lithology is dominated by claystone/shale with carbonaceous patches and red coloration in some places. Although, this interval does not differ much in lithological composition, the red coloration in the lithology in a few samples shows periodic shallow water condition close to exposure or diastem. The bottom 150m interval is totally devoid any microfossil and therefore it is difficult to assign a geological age for this interval. Since the interval overlies late Albian (marked on the last appearance of *Hedbergella gorbachikae* at 2581m) it is tentatively placed under late Albian. Above this unfossiliferous succession the first planktonic foraminifera assemblage at 2380-2385m interval recorded includes *Rotalipora ticinensis* and *Favusella washitensis* confirm late Albian age. The top of late Albian in this well is marked at 2185m on the last appearance of *Rotalipora ticinensis*. The entire late Albian interval is poorly fossiliferous, with few occurrences of planktonic foraminifera and very few shallow water benthics like *Trochammina* sp., *Gavelinella* sp., in faunal frequency throughout the late Albian in Jc-C1 suggests shelf sedimentation.

The late Albian in the Durban Basin in general shows initial rise in sea level and then gradual drop in sea level in the northern part (well Jc-D1), fluctuation of sea level is also could be seen in the JC-B1 site and in general it is shallow in the southern area (Jc-C1). Overall, the deposition of argillaceous lithology (claystone/shale) with frequent presence of fine sand, siltstone and limestone under fluctuating and shallow middle to outer shelf environment.

Early Cretaceous/Late Cretaceous boundary

The Cenomanian

As already observed in the three well sections in late Albian stage sediments were deposited mostly in middle to outer shelf environment. However, towards the end of Albian there is a general trend in rise of sea level in all the three sites. Sedimentation at the early Cretaceous top in Durban Basin took place in upper bathyal set up.

In the Northern well Jc-D1, the lithology in studied Cenomanian is dominantly dark grey claystone with frequent presence of pyrite in the lower part. The Cenomanian age for this interval is confirmed by the presence of Cenomanian index planktonic foraminifera *Rotalipora gandolfii*. Presence of agglutinated benthics like *Bathysiphon* sp., *Haplophragmoides* sp., *Dorothia* sp. along with calcareous foraminifera *Lenticulina angulosa* confirms deep water deposition at upper to middle bathyal environment. In well Jc-B1, the Cenomanian age for the studied interval above 3167m is based on *Rotalipora gandolfii* (present in all three samples) and *R. cushmani*. The claystone dominated lithology in the studied interval and its deep water benthics *Haplophragmoides* sp., *Glomospira* sp., *Bathysiphon* sp., *Textularia* sp. and *Lenticulina* sp. suggests slope environment (upper to middle bathyal condition).

In the southern area the Cenomanian sedimentation took place in uppermost bathyal around 300m and more water depth. The agglutinated benthic indicates a gradual rise to more than 500m in the upper part. Presence of a number of planktonic species viz. *Rotalipora gandolfii*, *Gumbeletria cenomana*, *Clavihedbergella simplex* confirms Cenomanian stage for this interval.

5.4 Summary of the foraminiferal biostratigraphy

Drilled cutting samples from the three well sections were studied in this work to demarcate the stages within the early Cretaceous sections of the Durban Basin. None of the three wells has encountered earliest Cretaceous sediments in this area. In the very first well Jc-A1, the late Cretaceous section is underlain by highly quarzitic unfossiliferous sediments belonging to (?) Gondwana or older age group of rocks. The following conclusions were drawn on the basis foraminiferal data from the three drilled well sections of the Durban Basin:

1. The oldest datable sediments encountered in all the three wells belongs to Barremian-early Aptian age. Planktonic foraminifera like *Hedbergella sigali*, *Hedbergella aptiana* and *Globuligerina hoterivica*. These planktonic foraminiferal assemblages and associated benthic indicates deposition in slope (upper to middle bathyal) in the south and central part of the studied area (Jc-B1 and Jc-C1). In the northern part of the studied area the deposition took place is relatively shallow condition and represented by conglomeratic and mixed lithology with occasional fine siltstone. The silty intervals have also yielded planktonic foraminifera *Hedbergella sigali* and *Gorbachikella kugleri*.

2. Frequent presence of dolerite intrusions was recorded in the lower part of the drilled intervals in Jc-B1 and Jc-C1 areas. However, presence of sediments unaffected by the igneous intrusive shows presence of both planktonic and benthic foraminifera. This indicates that the deposition took place under marine environment. Presence of pyrites sediments and pyritised foraminifera test indicates anoxic condition developed at certain stages of deposition.
3. In absence of continuous samples, or smaller quantity of samples the stage boundaries could not be marked precisely in these wells but the overall faunal composition remains almost similar with Aptian and Albian stages.
4. Various diagnostic foraminifera considered as zonal marker within the Aptian –Albian and late Cretaceous Cenomanian sections were recorded in all the three wells.
5. Above the Barremian- early Aptian tentative boundary the deposition took place in later part of Aptian and in entire Albian in upper slope (upper bathyal) to middle slope. This is supported by the presence of claystone in the studied sections.
6. Periodic fluctuation of sea and drop in bathymetry resulted in deposition of clastic sediments (siltstone and sometimes fine-grained sands), showing low frequency of foraminifera (benthic) and absence of deep water benthic in the sandstone-siltstone rich samples.
7. In general, the depth of deposition in the northern area (in Well Jc-D1) took place in relatively shallow depth. Only during Albian stage in this area deposition took place in relatively deeper water.

Chapter VI

6. Summary and Conclusions

The studied area is located on the eastern offshore of South Africa is a part of Durban Basin. All the four exploratory wells viz. Jc-A1, Jc-B1, Jc-C1 and Jc-D1 were considered for detail integrated studies involving the early Cretaceous sediments.

None of the exploratory wells are found to be hydrocarbon bearing. The very first well Jc-A1 (drilled in 1971) did not encountered any early Cretaceous sediments. The lowermost lithology shows sediments of Gondwana or older (Devonian?) clastics unconformably overlain by late Cretaceous sediments (Turonian and younger stage). It seems during the time of early Cretaceous sedimentation the location Jc-A1 was a positive (horst) area.

During the time of initial break up of Gondwana land followed by drifting stage the area might have received sediments of late Jurassic or earliest Cretaceous (recorded in the surface sections located along the eastern coast of South Africa). However, these sediments were not encountered in any of the remaining three wells.

In the Northern part of the studied area the exploratory well Jc-D1 encountered a graben fill lithology mainly conglomeratic in nature. The well log motif, detail lithology from well cuttings indicates graben fill sediments with shallow marine benthic suggests deposition in outer shelf environment during Barremian–early Aptian. The log motif above this interval indicates a fining upward trend suggesting a submarine fan environment. In the later part till upper part Albian there was a progressive rise in sea level with occasional clastics and limestone beds in a thick clay dominant interval.

In the central part of the area where the exploratory well Jc-B1 is located and in the Southern area (location Jc- C1) shows a remarkable similarity in depositional pattern. In the Barremian-early Aptian interval they have almost similar lithological association with claystone dominant lithology and occasional sandstone and siltstone layers. This interval in both the wells has yielded diagnostic planktonic foraminifera. The recorded benthic foraminifera indicate upper bathyal environment of deposition. Many samples within this section could not be studied due to the presence of igneous intrusive. In the younger section (Late Aptian and Albian), there were periodic fluctuation in the central and southern part. This is indicated by the frequent presence of thin sandstone and siltstone units with variable frequency of benthic foraminifera present in them.

Benthic foraminiferal data indicates a general increase of bathymetry (300-500m) in all the three depositional sites during the latter part of Albian and in the Cenomanian (late Cretaceous) stage. Presence of major unconformities (1At1, 6At1, 13At1) has been reported by several authors (McMillan, 2003). However, sample examination at much closer interval is needed to demarcate these unconformable horizons in subsurface sections. Integrated study from the early Cretaceous exposures and their correlation with drilled well samples can help to identify the unconformity surfaces and to measure the duration of hiatus in this basin.

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8. Appendix

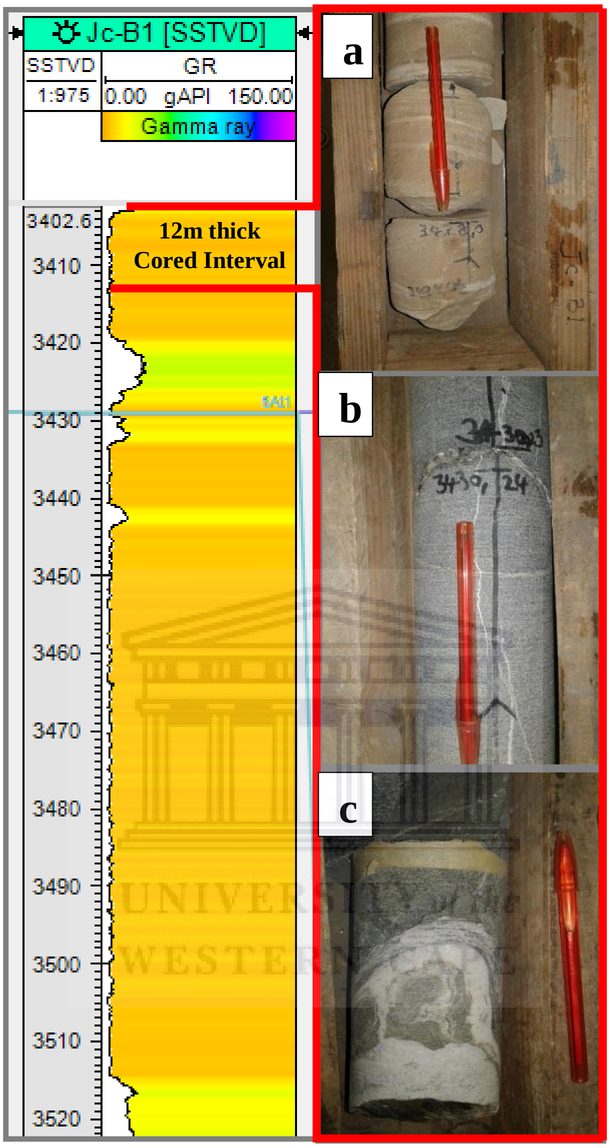

Figure 8.1 Red arrow from figure Kb is the cored samples studied petrographically: (a) clastic, (b) basaltic lithology and (c) dolerite. The clastic sample has a coarsening upward trend on identified from thin sections.

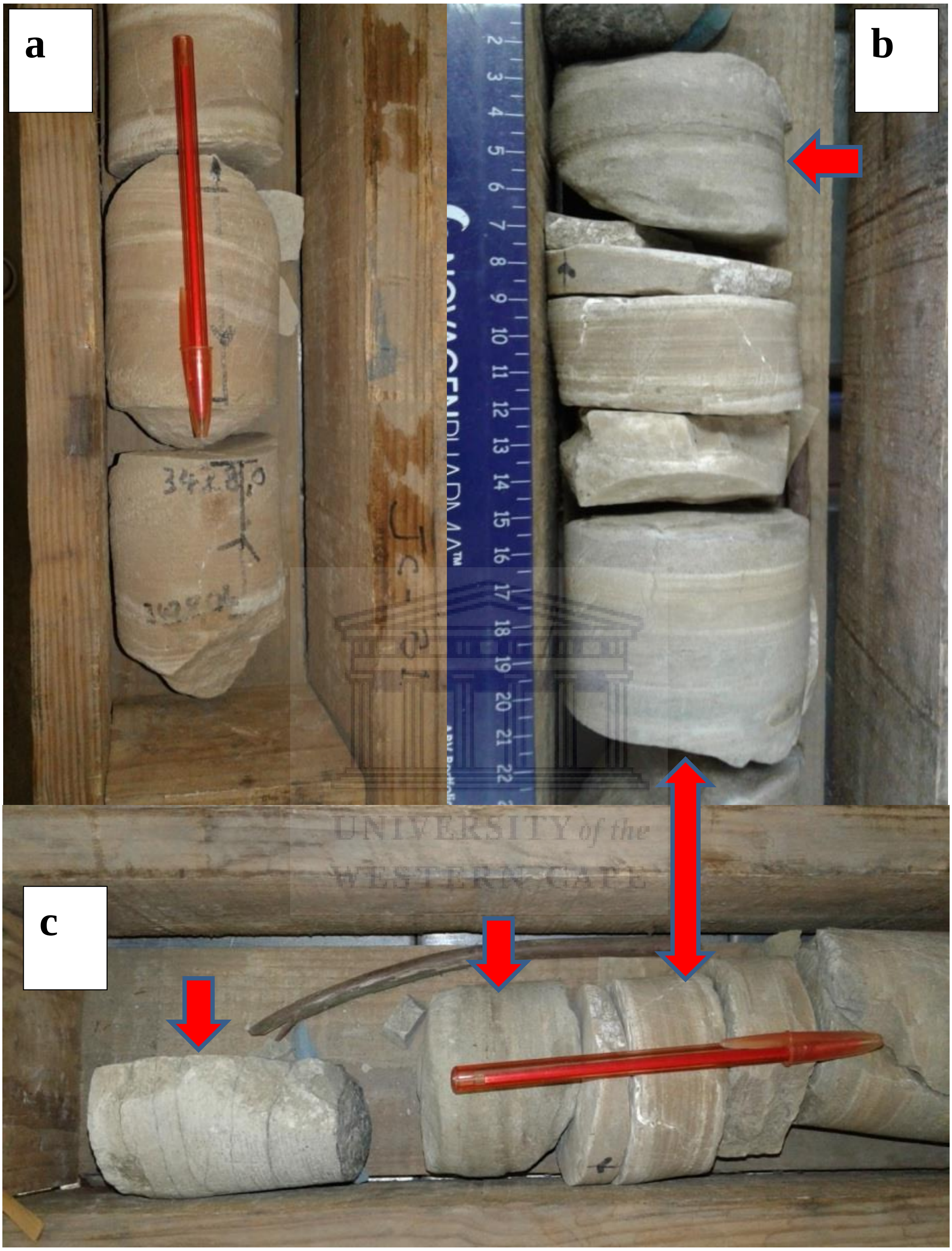

Figure 8.2. Conventional Core (CC#1) segments from Well Jc-B1; Fine-grained sandstone interbedded with siltstone, (b) graded sandstone with arrowed mudstone and (c) sandstone with thin shale intercalations (left arrow), mudstone (centre arrow) and graded sandstone (right arrow).

Figure 8.3. Cored igneous rock samples from Well Jc-B1: (a-b) basaltic part and (c-d) dolerite with calcite vein.