FORAMINIFERAL BIOSTRATIGRAPHIC STUDIES FROM MESOZOIC SUCCESSION OF SELECTED WELLS FROM THE ORANGE BASIN, WESTERN OFFSHORE, SOUTH AFRICA.

By

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RESPICE PROSPICE

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Declaration

I declare that the thesis "Foraminiferal Biostratigraphic Studies from Mesozoic Succession of selected wells from the Orange Basin, Western Offshore, South Africa" is my own work and that the work has not been submitted for any other degree or examination at any other University or institution and that all sources used have been referenced and acknowledged.

GENEVIEVE BEUKES

Signature 27 September 2020

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Abstract

Located on the western offshore on the Atlantic Ocean margin of Southern Africa, the Orange Basin is the youngest and largest of the South Africa's seven sedimentary basins. This passive margin basin in known for its hydrocarbon potential and therefore is the focus of attraction of several oil exploration companies.

The study area lies near the continental margin in which four exploratory wells were drilled. An attempt has been made in this work to understand the depositional settings of these reservoirs and their biostratigraphy.

Distribution of important planktonic index foraminifera helps in dating the reservoir sections. Paleoecological studies of benthic foraminifera were used for understanding the prevailing environment during the Cretaceous period. The study indicates that most of the reservoirs are distributed in the Albian (Early Cretaceous) and a few in the Cenomanian age sediments. Relatively shallow shelf sedimentation prevailed in the Late Aptian to middle part of Albian with deposition of arenaceous units. There were periodic localised deepening as well as very shallow depositional condition leading to exposure (diastem) as indicated by lithology and faunal composition. Gradual rise in sea level started in Late Albian and the entire area was under bathyal environment till the end of Cenomanian stage. This is indicated by deposition of claystone rich units and the associated fossil benthics indicates deposition in slope area. The few relatively minor argillaceous sandstone and siltstone units are with poor reservoir quality.

Keywords: Orange Basin, Cretaceous planktonic foraminifera, stage boundaries, benthic ecology, paleobathymetry, depositional environment.

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1. CHAPTER ONE

1.1 Introduction

In the southern part of the African continent there lies seven important sedimentary basins formed that served as depocenters for sediments of variable thickness, also referred to as the Cretaceous drift succession. These sediments range in age from Early Barremian to Late Maastrichtian (Jungslager,1999; McMillan, 2003) and experienced episodic sedimentary accumulation. The Orange Basin located along the Atlantic margin of the Western Coast of South Africa and Namibia, is the biggest among the seven basins. The paleogeography of the Southern hemisphere during the break-up of Gondwanaland and the emergence of the proto-South Atlantic during the Mesozoic has been a topic of interest to scientists for a long time. The realignment of the landmasses and ultimate formation of the Orange Basin in southern Africa had a profound effect on the environment (Spencer et.al, 2018). The Orange Basin is considered a prospective sedimentary basin for oil and gas exploration. The basin, however, remains largely underexplored and has vast future potential.

1.2 Background

Foraminifera are single celled marine protozoa, widely used in petroleum exploration research. They are considered one of the most reliable tools for dating marine sediments and predicting paleoenvironment of deposition. Apart from dating, the marine succession foraminifera are very useful subsurface correlation, paleoenvironmental analysis and demarcation of hiatus boundaries. Foraminifera are not extensively studied in South African basins aside from notable work done by McLachlan et.al. (1976) and McMillan (2003, 2010). In the present work, foraminiferal biostratigraphic studies of a selected reservoir interval only within the Orange Basin was carried out. The present work was carried out in four exploratory wells where conventional cores and well cuttings were available. The well intervals were selected after careful study of the well completion reports, well logs and examination of cutting samples. In the present work detail account of the foraminiferal studies including the time of deposition (dating), paleobathymetry and paleoecological aspects are discussed.

1.3 Importance of foraminiferal biostratigraphy

The application of biostratigraphy as a tool in hydrocarbon exploration was well known since the 1890’s and it was applied for the first time in Poland (Kaminski et al, 1993). For more than a century biostratigraphy impacted hydrocarbon exploration in various parts of the world, particularly the Gulf of Mexico, Southeast Asia and the Middle East. During most of the period biostratigraphy has been recognized as a vital tool for dating and correlating sediments in the hydrocarbon exploration. Apart from relative age dating, estimates of the depositional environment of sediments can usually be provided. The most important development in the stratigraphic field is the integration of biostratigraphic dating with observable seismic and geomagnetic cycles, presently referred to as sequence stratigraphy. This means that stratigraphers can now provide numeric age estimates for seismic sequences where traditionally only relative ages could be given. This direct link between seismic data and numeric ages can be a powerful aid in regional correlation. Biostratigraphic data is also integrated with other disciplines such as sedimentology. Besides being the basic tool in regional correlation of sedimentological units, biostratigraphy allows the position of a sediment unit in a seismic cycle and also allows more accurate estimates regarding the duration of hiatus. The sedimentological sequences can be placed in a regional and global framework. Other stratigraphic tools, such as chemostratigraphy (stable isotope techniques: Oxygen, Strontium), Graphic Correlation or Cyclicity Analysis (duration estimates from electric logs), are now being integrated with biostratigraphic data. These can provide an additional cross-check besides giving useful paleoenvironmental information.

1.4 The study area

The Orange Basin (Figure 1.1) is a continental passive margin basin located along the western coast of Southern Africa. It is the largest of the seven major sedimentary basins in Southern Africa, considered an area of interest prospect for the past decades. The importance of the Cretaceous succession largely includes the aspect that most of the oil resources are related to this age group of rocks in the southern African sedimentary basins. Majority of the Cretaceous basinal fill of the drift succession in most of the seven basins are comprised of clastic rocks viz. sandstone grading to siltstone and intermittent shale/mudstone.

1.5 Location of the study area

The Orange Basin (Figure 1.1) is a passive margin basin in which the depocenter is located in the passive margin along the western coast of southern Africa in the Atlantic Ocean (Granado et al., 2009; Jungslager, 1999). The four wells K-A2, K-A3, K-E1 and K-H1 are all located in the continental shelf margin, in the northern section of basin, off the coast of southern Africa. The Orange Basin is the largest offshore basin in southern Africa, covering an area of approximately 130000km^2 in relation to the 200m isobath (Gerrard and Smith, 1982). The Orange Basin, located in a volcanic rifted margin (Granado et al., 2009), is subdivided into the northern and southern sections, extending from Namibia northward down to the northern section of South Africa and has been extensively studied in the past few decades.

The Orange Basin forms as part of the Agulhas basins along with the Bredasdorp sub-basin to the east proceeded by the, Pletmos, Gamtoos, Algoa, Durban and Zululand basins following along the east coast of southern Africa. This passive margin deposits in this area consists of mostly sandstone, siltstone and intermittent shale/clay. The studied wells within the northern area of the Orange Basin will be further discussed in the latter part of this study. The basin is largely underexplored with approximately one well drilled for every 400km^2. Despite being underexplored the basin has proven hydrocarbon reserves and potential for further discoveries.

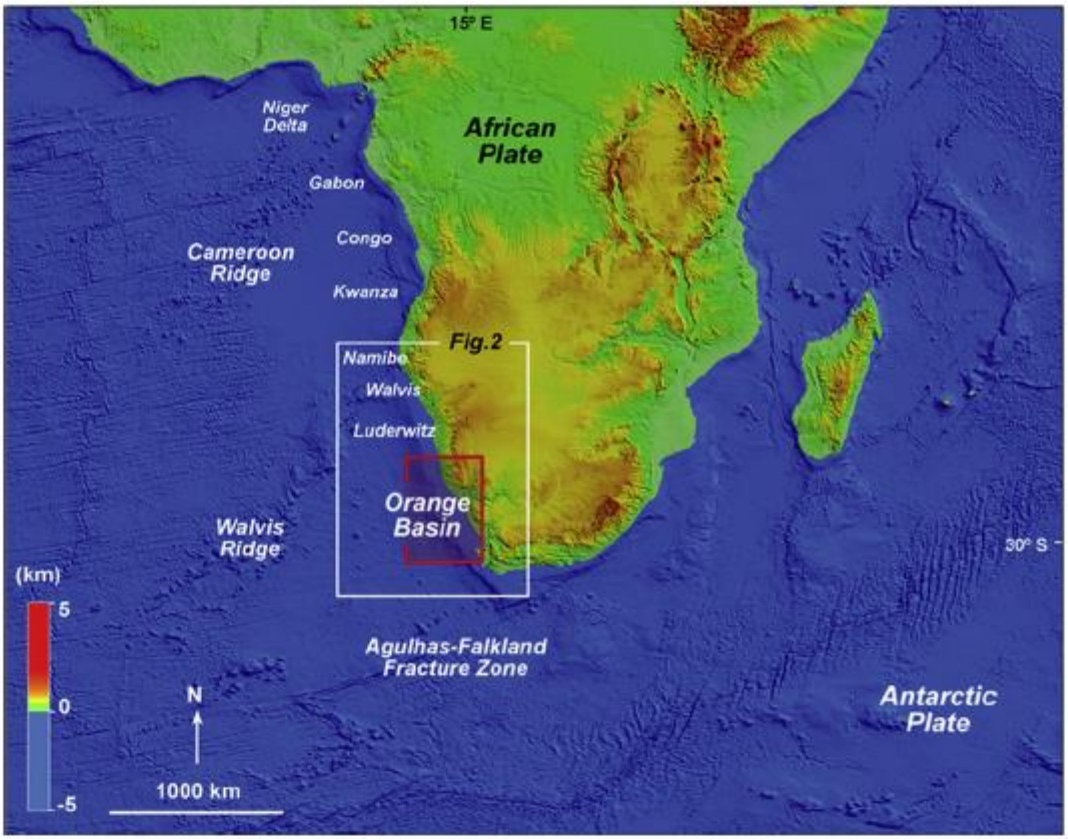


Figure 1.1: Location map of the Orange Basin, West coast of South Africa (after de Vera, et.al. 2010)

1.5.1 Tectonic setting and basin evolution

The Orange Basin was created in response to the fragmentation of Western Gondwanaland and the opening of the South Atlantic. The Orange Basin is a sub-basin of the larger Southwest African Coastal Basin and it covers an area of 160000 km^2 to the 2000m isobath (Jungslager, 1999). There are three depocenters the Walvis, Lüderitz and Orange sub-basins. The evolutionary history of this basin has been defined by its post -rift sediments rather than its structure (Salmo, 2012) (Figure 1.2).

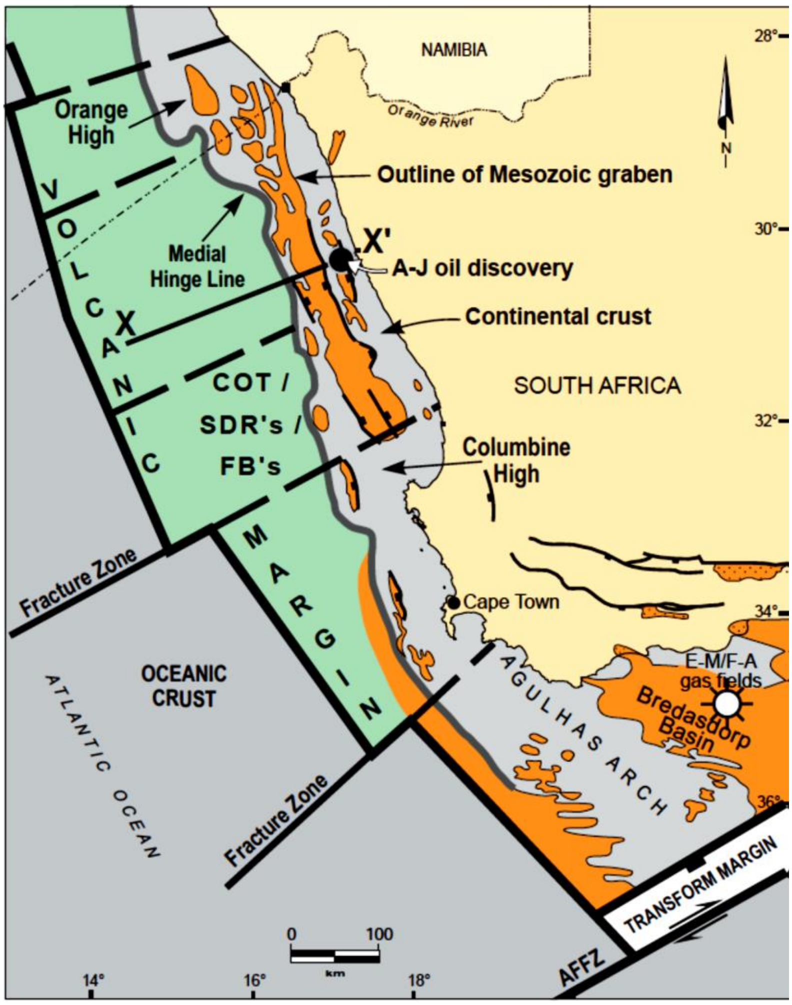


Figure 1.2: Major tectonic elements of Orange Basin (after Jungslager, 1999).

The entire sedimentary succession can be subdivided into two subdivisions namely, the older synrift and its overlain post rift unit. The rifted plate margin is underlain by pre-rift and synrift grabens and is covered by drift sediments. During the synrift phase North-South trending grabens were formed and were filled by Early Cretaceous sediments of shallow water continental fluvio-lacustrine sediments including volcanoclastics. A thick seaward and thin landward cover of sediments overlies the rifted basin thus created. The sedimentary fill was mainly transported by the Orange River and smaller rivulets.

The basin evolution initiated around 117.5 Ma (Salmo, 2012) in Early Cretaceous with definite marine incursion and continued throughout rest of the Cretaceous and Tertiary. A total of five major super-sequences bounded by major sequence boundaries were recognised (Figure 1.3).

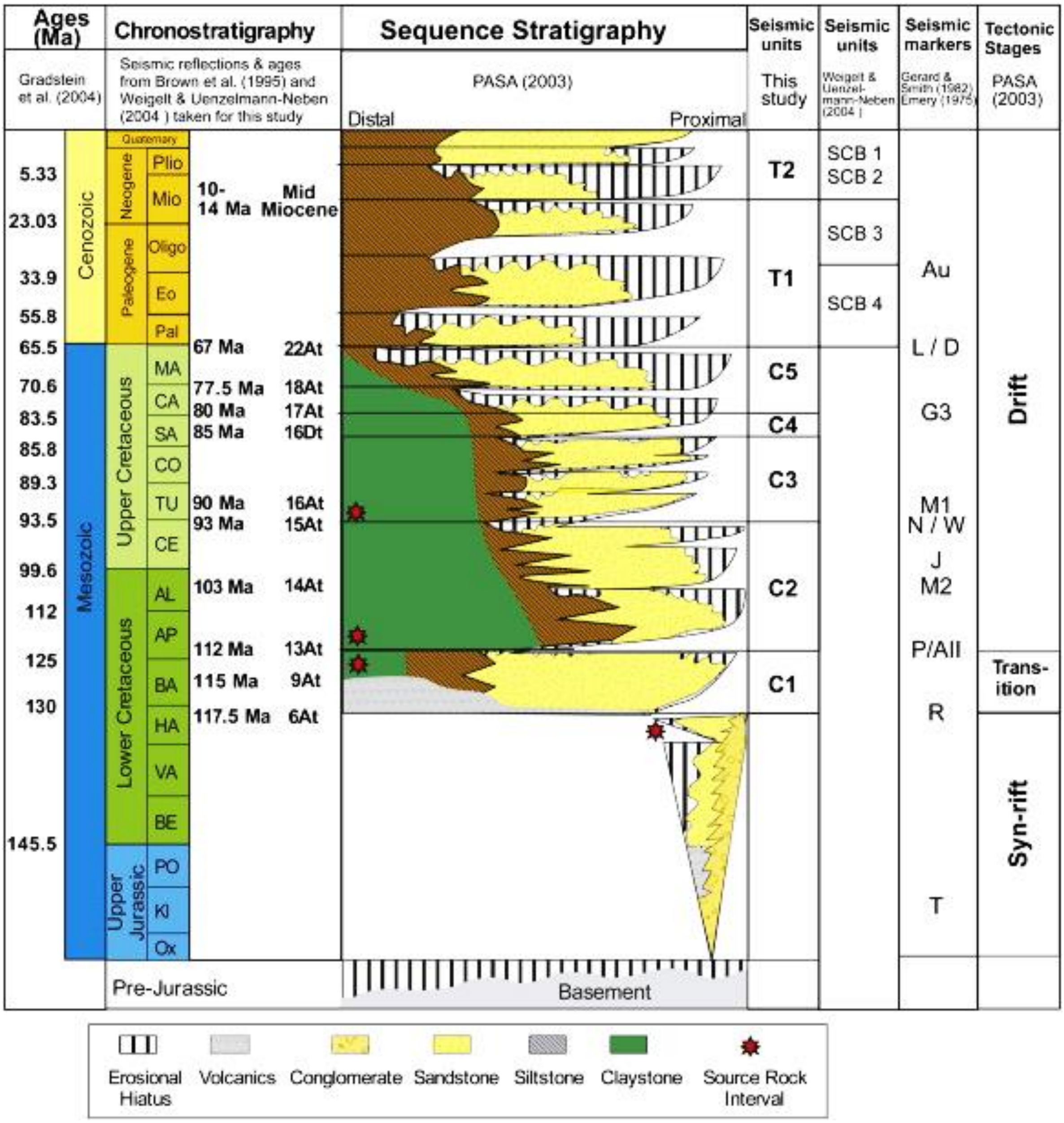


Figure 1.3: **S**ummarized sequence stratigraphy in Orange Basin, Southern Africa.

1.6 Problem statement

The Orange Basin is a well-known passive margin basin that does not, however, have detailed published work using microfossil (foraminifera) to study the Early Cretaceous stages in the area age boundaries. Although McMillan (2003) has outlined the foraminiferal studies in his publication, a detailed well-related biostratigraphic account, faunal distribution and paleoecology of the reservoir sections are not available. The present work includes the temporal distribution of microfauna in the four well sections (K-A2, K-A3, K-E1 and K-H1). Within the identified reservoirs of a sedimentary basin, usefulness of foraminiferal biostratigraphy is well known. The biostratigraphic analysis helps to differentiate sub-environments under varied sea level conditions and helps to locate favorable sites for future exploration. One of the main aims of this study included using foraminifera as a tool for identification of depositional environment in which the reservoirs units were deposited. However, more studies involving more wells should be done to aid further research.

1.7 Rationale for the study

This study is important as the selected wells in the basin have not undergone detailed biostratigraphic analysis, which is imperative for well correlation and more accurate estimation of reservoir potential of the basin. Micropaleontology, focusing on the fauna identified within the provided samples allows for the identification of potential hydrocarbon reservoirs. This field of research should be done because the Orange Basin is an area of interest. Age dating in biostratigraphy allows the evaluation of the extent to which fossils in a well are diachronous and provides indicators for the environmental deposition. This field of study could help map the pattern of deposition in the Cretaceous period.

1.8 Aims and objectives

The aim of this research was to understand the environment of deposition in the subsurface sections of the wells containing the reservoir units within Cretaceous through detail integrated litho-biostratigraphic analysis. Foraminiferal dating helps in the demarcation of various stage boundaries, and record the various major transgressive- regressive events as well as identifies the unconformity surfaces using the marine microfossil group 'foraminifera'.

The objectives of the present research are as follows:

- To identify the Early Cretaceous reservoirs in the four exploratory wells K-A2, K-A3, K-E1 and K-H1 of the Orange Basin using well log information.
- To study the temporal distribution of foraminifera (and associated marine microfossils) to demarcate the stage boundaries and assign geological age using the index planktonic foraminiferal suite.
- To infer the environment of deposition of the sedimentary package within the studied intervals and predict the possible changes in sedimentation pattern and paleobathymetry in the depositional site using depth indictor benthic foraminiferal assemblages.
- To construct transgressive and regressive (T-R) cycle curves in each of the wells to understand extent of sea level fluctuations within the area.
- Integration of the data generated from foraminiferal studies with the lithological observations obtained from megascopic studies of conventional cores, well cuttings and electrical logs.

1.9 Research Questions

- Can the foraminiferal distribution within the studied well sections demarcate the stage/ zonal boundaries and be utilised to understand the depositional environment within the selected intervals?
- Does benthic foraminiferal temporal distribution help in predicting the various depositional environments and sub-environments during the Cretaceous period?
- What evidence does foraminiferal studies provide as support that the studied area within the Orange Basin is suitable for hydrocarbon accumulation/source rock?

1.10 Methodology/ Research approach

The present research integrates the results of foraminiferal biostratigraphic analysis. The available samples from conventional cores and drilled well cuttings were processed in the biostratigraphy laboratory. Foraminifera (and other microfossil groups) were isolated. The foraminifera groups were identified down to the generic/species level using standard international methods using a binocular stereo-zoom high magnification microscope. All samples analysed in this work were available from the Petroleum Agency of South Africa (PASA), Cape Town Core house.

Sample preparation, processing, sorting and identification took place in the Earth Sciences Department laboratories, at the University of the Western Cape. Petrel software was used to load and interpret the well log motif for lithology identification. Apart from well cuttings and conventional core samples, Geological Well Completion Reports (WCR) of the four exploratory wells and well log data (LAS files) were also collected from PASA.

The study started by reviewing previous work done in the Orange Basin. Thereafter, a geological background was completed to understand how the basin formed in relation to sedimentology, structural and tectonic evolution as well as the petroleum system of the offshore basins of southern Africa.

This was followed by the collection of samples, megascopic study of the lithology from actual cutting samples and well logs. Thereafter, laboratory processing of samples, identification, and study of temporal (vertical) distribution of all foraminifera benthic groups (agglutinated and calcareous) and planktonic foraminifera ranges using standard references took place. The data and information were used to determine the depositional environment, stratigraphic boundaries and paleobathymetry.

1.11 Limitation of the study

A few constraints were encountered during this study. The main constraint was the time available for processing, sorting and identification of the foraminifera microfossils from an interval of more than 6000m. Due to the highly arenaceous nature of some of the sections, faunal recovery was extremely poor or the intervals were devoid of microfauna Availability of continuous well cuttings proved to be a challenge. Due to this many of the stage boundaries demarcated in this research are approximate and are represented by dotted lines. Limited literature resources deal with the foraminiferal details of South African sedimentary basins.

1.12 Thesis chapters outline

The six chapters under the present research were outlined/presented as follows:

Chapter One: Introduction, background and importance of foraminiferal biostratigraphic studies; Orange Basin location and brief geological details, problem statements, objective, methodology outlines and limitations.

Chapter two: This chapter provides an overview of the related literature studied and incorporated in this work. The classical concepts of the creation of South African basins with special reference to the present area geology, tectonic setting and stratigraphic framework. Biostratigraphic details in Cretaceous foraminiferal zonation and age boundaries and foraminiferal ecology and paleoenvironmental interpretation carried out by different workers.

Chapter three: This chapter covers the data collection procedure and sample processing techniques followed in this work.

Chapter four: This chapter discusses the detail integrated foraminiferal biostratigraphic analysis followed in the present work; well wise temporal distribution of foraminifera, interpreted stage boundaries and paleobathymetry, presence of anoxic or oxidised intervals.

Chapter five: This chapter deals with paleoecological studies and morpho-grouping of benthic foraminifera, paleoenvironment of deposition from the distribution of microfauna.

Chapter six: Summary of work done, results and conclusions.

2. CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter presents an overview of the important literature and records that were consulted during the course of the present research. It includes the classical concepts of geological evolution of the South African sedimentary basins with special reference to Cretaceous deposits, foraminiferal biostratigraphic aspects including dating methods and ecology that helps in understanding the Cretaceous depositional environment in the studied area.

2.2 Geology of the Orange Basin

The Southern African sedimentary basins were created subsequent to the separation of Gondwana during the late Jurassic period. This passive rift margin formed as a result of the separation of Gondwana, with the opening of the Atlantic Ocean during the Jurassic period. This separation resulted in the subsequent formation of the seven major South African sedimentary basins (Nurnberg and Muller, 1991; Macdonald et al., 2003; Reeves and de Wit, 2000).

South African offshore area can be divided into three distinct tectonostratigraphic zones, namely, the eastern, southern and western offshore zones. The eastern offshore is a narrow passive margin that was formed as a result of the breakup of Africa, Madagascar and the Antarctic in the Jurassic period. Limited deposition occurred in the east with only the Durban and Zululand Basins containing an appreciable sedimentary section. The southern offshore region, known as the Outeniqua Basin, shows a history of strong strike-slip movement during the Late Jurassic-Early Cretaceous breakup and separation of Gondwana. The Outeniqua Basin consists of a series of en-echelon sub-basins (Bredasdrop, Pletmos, Gamtoos and Algoa basins) each of which comprises a complex of rift half-grabens overlain by variable thicknesses of drift sediments. The deep-water extensions of these basins (excluding the Algoa Basin) merge into the Southern Outeniqua Basin (Petroleum Agency SA, 2013).

The western offshore of South Africa comprises a broad passive margin basin related to the opening of the South Atlantic in the Early Cretaceous period, known as the Orange Basin.

This basin is one of the largest offshore basins. During the Middle to Late Jurassic, the extensional stress associated with the breakup, caused the formation of a series of coast-parallel graben systems .These graben systems are separated laterally from an outbound synrift wedge by a flexural high which is known as the Medial Hinge (Gerrard and Smith 1982).

The passive margin Orange Basin came into existence as Africa separated from South America. This major continental breakup resulted in the formation of the Agulhas-Falkland-Fracture Zone (Figure 1.2). Sedimentation in the syn-rift sequence initiated during the early part of Late Mesozoic (Late Jurassic -Early Cretaceous) leading to depositional sequence till Hauterivian (Kuhlmann et al., 2010). Earliest marine incursion in the basin dated from 117.5Ma leading to a transgression and the deposition of the drift sequence which however did not affect the north -eastern part of the basin. The Late Cretaceous succession which was mostly associated with the post-rift phase characterized by thermal subsidence of the basin and open ocean circulation (Dingle et al., 1983).

2.3 Stratigraphy

2.3.1 Late Paleozoic

During the Late Paleozoic the area suffered subduction on the southern margin of Gondwana in the Late Carboniferous-Early Permian period and transformation of an old passive margin into a foreland basin (the Great Karoo Basin) took place. Further convergence in the Permo-Triassic resulted in the development of the Cape Fold Belt which extends from Australia through Antarctica and South Africa to South America (Petroleum Agency SA, 2013).

2.3.2 Mesozoic and Tertiary

Widespread volcanism in the Early to Middle Jurassic followed by erosion in the region covered in areas that include southern Africa, the Falkland Island and Antarctica. This led to the first imminent breakup of Gondwana. At this point in time, the Falkland Islands lay off the south or southeast coast of South Africa. Breakup started on the eastern margin of Africa with Madagascar and Antarctica starting to move away in the Middle Jurassic. This instigated the formation of the Durban and Zululand basins. During the Early to Mid-Cretaceous a complex series of microplates including the Falkland Plateau gradually moved west south-westwards past the southern coast of Africa creating important dextral shearing of the South African margin. This created the Outeniqua sub-basins as a series of oblique rift half-grabens which may be regarded as failed rifts, oldest in the east and youngest in the west. The rift phase on the south coast ended during the lower Valanginian age. This, however, was followed by at least three phases of inversion in relation to the continuous dextral shearing which took place and ended in the mid-Albian age as the final separation of the Falkland Plateau from Africa occurred. The transitional rift-drift phase was followed by development of a true passive margin. The lower Valanginian drift-onset unconformity on the south coast is concurrent with the earliest oceanic crust in the South Atlantic. The Orange Basin was initiated as a series of isolated yet linked north-south trending grabens during the lower Cretaceous period. The drift-onset unconformity has been dated as Hauterivian, and slightly younger than in the Outeniqua Basin. A rift-drift transitional phase in the Orange Basin occurred until the Early Aptian period. Later, Cretaceous and Tertiary sedimentation took place in a marine passive margin setting. All these basins are generally clastic in nature and have been explored for both oil and gas over the last few decades. Gas production has been ongoing since the middle 90's from shallow marine sandstones on the flanks of the Bredasdrop Basin, while oil has been produced from mid-Cretaceous aged basin floor fan deposits in the central basin. Interest in exploration has recently increased dramatically and large areas of the South African offshore, including very deep-water acreage, are currently being explored (Petroleum Agency SA, 2013).

2.4 Sequence stratigraphic framework of the Orange Basin

Sequence stratigraphy is a branch of stratigraphy that subdivides the sedimentary succession into unconformity bound units in terms of variations in sediment supply and variations in the rate of change in accommodation space. The accommodation thus created is due to rise and fall of the eustatic sea level combined with tectonic subsidence. In sequence stratigraphy the hiatus boundary surfaces are identified and are placed in the chronostratigraphic scale. This branch of stratigraphy subdivide the succession into genetically related strata bound by unconformity surfaces.

The term "sequence" in the name refers to cyclic sedimentary deposits. Stratigraphy is the geologic knowledge about the processes by which sedimentary deposits form and how those deposits change through time and space on the Earth's surface.

For South African offshore basins the drift successions are divided into unconformity - bound sedimentary sequences (Fadipe, 2009). According to Van Wagoner et al. (1988) each sequence is considered to be deposited due to worldwide eustatic sea level change and is defined at its base by type 1 unconformity (Figure 2.1). The worldwide eustatic sea level change defines the sequences which comprise of a lowstand sea level followed by a highstand flooding event. The detailed methodology and principles of the sequence stratigraphic process and their application for the South African offshore basins are discussed by Brown et al., (1996).

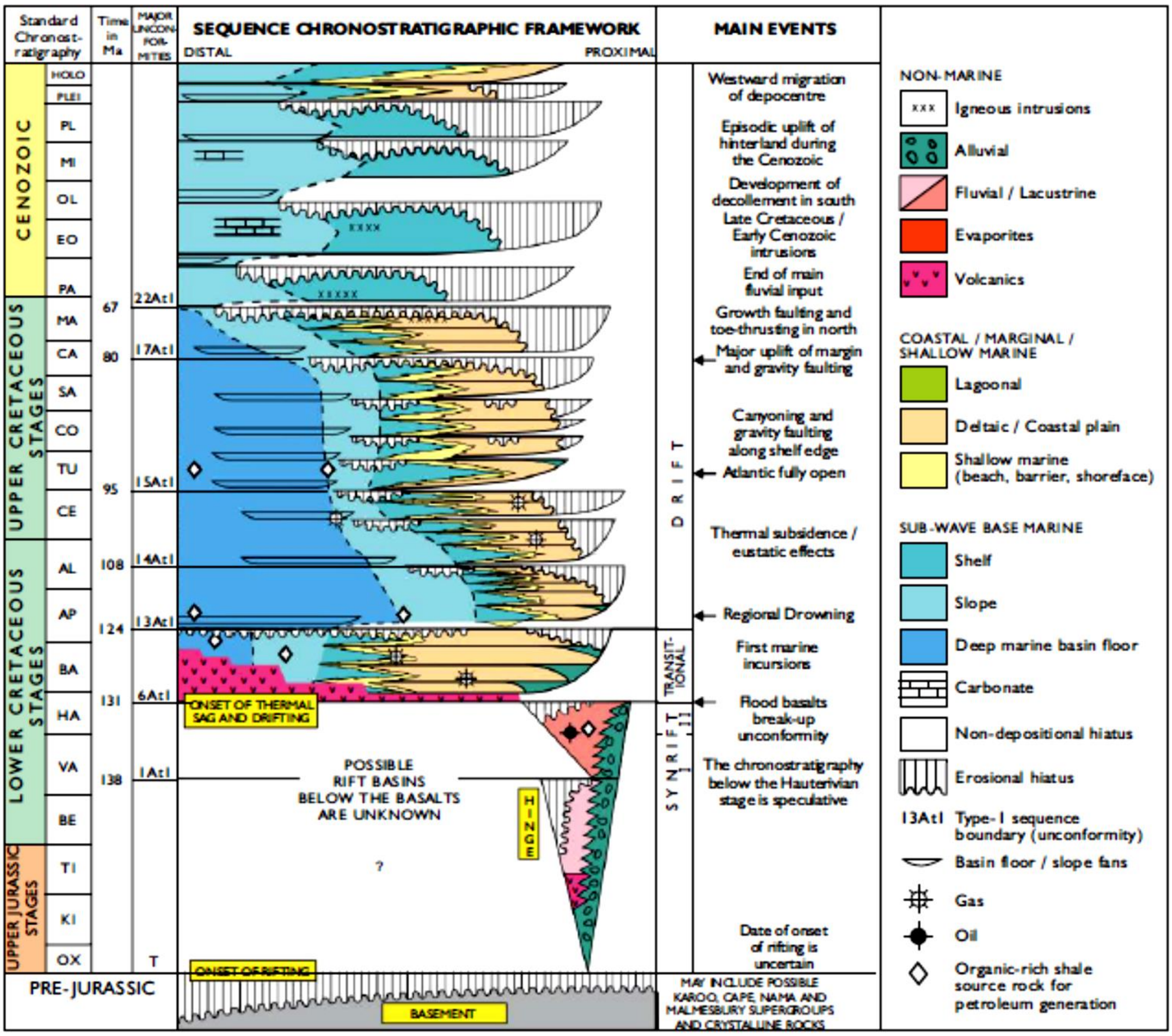


Figure 2.1: Generalised chronostratigraphy of Orange Basin (Geol. Report, PetroSA, 2003)

The detailed tectono-stratigraphic analysis of the Orange Basin revealed (Adekola et al., 2014) that the basin was created within divergent plate boundary setting as a result of lithospheric extension related to the break-up of South America and Africa in the Late Jurassic. This was followed by seafloor spreading and the opening of the South Atlantic Ocean in the Early Cretaceous, around 136 Ma (Brown *et al.*, 1996; Reeves and de Wit, 2000; Macdonald *et al.*, 2003; Adekola et al., 2014). According to Eagles (2007) the updated models of the relative motion between the South American and the African plates propose a diachronous opening of the South Atlantic Ocean, starting in the south and spreading to the north within a period of 40 Ma (Eagles, 2007). The Orange Basin contains the stratigraphic record from lithospheric extension and rift tectonics throughout a fully evolved post-break-up setting, providing an idyllic area to study the evolution of a “passive” continental margin (Hirsch et al., 2009). The stratigraphy consisted of a pre-rift successions (~130 Ma), beneath syn-rift deposits of Late

Jurassic to Hauterivian age (~121 to~117.5 Ma). That, in turn is overlain by sediments of early drift stages to Aptian age (~113 to ~108 Ma). Aptian marine deposits overlie the pre-Aptian successions (Jungslager, 1999). The rift stage basin was characterised by the formation of north to south oriented grabens and half-grabens trending roughly parallel to the rift axis, (neighboring Walvis Bay to south of Cape Town) (Gerrard and Smith, 1982). These graben structures were filled predominantly with siliciclastic continental, lacustrine rocks, and variable thicknesses of volcanic rocks (Brown *et al*., 1996). The Upper Jurassic and Lower Cretaceous in age syn-rift fill sequences rest unconformably on the Precambrian or Paleozoic basement. This basement in turn, was overlain unconformably by Early Cretaceous to present post-rift successions. Lithologically, the early post-rift successions comprised of sandstone and shales, with most of the post-rift successions being claystones. The syn-rift sequences were mostly deposited directly to the east of the marginal ridge and within isolated half grabens on the mid to inner shelf. The post-rift sequence had a ~7 km thick post-rift Barremian/Lower Aptian to present day interval that thinned out to an approximately 3 km thick sequence in the studied area in the south (Gerrard and Smith, 1982). The Barremian/Lower Aptian sequence corresponded to a transitional phase between synrift and drift. The highest quality source rock was deposited at that time and overlain by more than 5500 m of Upper Cretaceous shales and claystones that remained relatively undeformed. The overlying Cenozoic strata was deposited basin-ward of the Cretaceous sequence with a thickness of more than 1500 m towards the outer margin (Gerrard and Smith, 1982). Seven major deposcentres of variable thicknesses are situated on the continental margin of Southern Africa (McMillan, 2003).

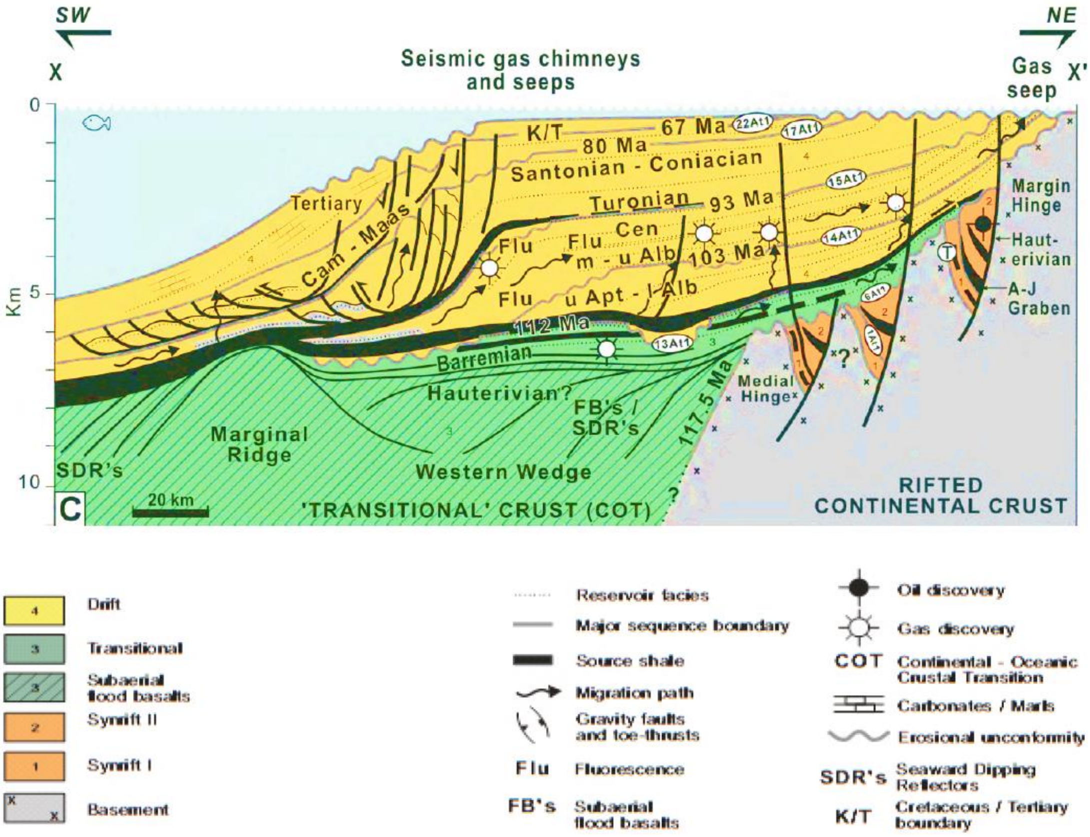


Figure 2.2: Generalised composite stratigraphic cross-section through the Orange Basin (Jungslager, 1999).

2.5 Microfossil biostratigraphy and paleoenvironmental studies

Biostratigraphy is the study of rock strata using fossils. For more than a century there has been a close association between micropaleontology and petroleum exploration. This dates back to 1890's when Josef Grzybowsky described Cretaceous and Paleogene benthic foraminifera of the oil fields of the Polish Carpathians and pioneered their use in Stratigraphic studies (Kaminski et al., 1993). This led to systematic documentation of stratigraphically significant species and establishment of local foraminiferal zonation schemes for areas as diverse as California, Gulf coast (US), Iran, Nigeria, Papua New Guinea and Malaysia. In the subsequent years application of microfossil biostratigraphy integrated with other geoscientific sub disciplines leading to geological modelling, technical risk reduction and coast saving of oil exploration (and production). There are many advantages of using microfossils in biostratigraphic analysis. Because of their small sizes they can easily avoid crushing under the drilling bit in oil wells and can be collected from well cuttings and conventional /side wall cores. A large number of microfossil specimens can be collected from a relatively small amount of rock samples thus giving a much wider spectrum of data. These microfossils are identified in the laboratory under a high magnification microscope.

Foraminifera are marine protozoa and are the most important microfauna for classification and correlation of marine sediments especially of Cretaceous to Late Tertiary age. Apart from relative dating of the sedimentary strata to reconstruct stratigraphy and correlation they are very useful in predicting the depositional environment, demarcating the unconformity surfaces and predicting the duration of a hiatus, identifying short duration exposure (diastem), identification of Maximum Flooding Surface (MFS) and condensed sections, predicting anoxic environment and recognise paleobathymetry changes etc. Such studies are important in understanding the depositional conditions and are extremely useful to prepare depositional models with reasonable predictiveness. Conventionally micropaleontological studies have remained largely a tool in the exploration arena.

2.6 Relative dating by foraminifera

For age dating of marine sediments planktonic foraminifera are considered to be one of the best tool in oil exploration. This group are floating protozoa lives on the water surface or near the water surface, therefore dispersed over a much broader part of the world oceans and often are found in large numbers. They are most useful for dating marine successions. This group appeared first in the Middle-Late Jurassic and become abundant in the Cretaceous and Tertiary. However, this group provide little information concerning the environment of deposition, since they lived floating in the water column. In dating subsurface well sections and correlation of the last appearance data (LAD) or extinction is considered very important). The first appearance is not of much importance while working with well cuttings due to caving problem from younger horizons.

In the present work the application of Last Appearance Datum for planktonic species were widely used (chapter four). Index planktonic foraminifera with short vertical range and wide geographic distribution are important to identify correctly and to place a particular stratigraphic section under a planktonic foraminiferal zone. In the present work the classical Cretaceous planktonic foraminiferal zone (Caron, 1985) was followed. Existence of several planktonic species and genus are known from Cretaceous time. A total of 28 planktonic zones were recognized e.g. 12 zones between Hauterivian to Albian (Early Cretaceous) and 16 between Cenomanian to Maastrichtian (Late Cretaceous). Important planktonic genera like *Hedbergella, Favusella, Ticinella* and *Rotalipora* are important genera under Cretaceous in South African basins. For morphological identification of planktonic foraminifera the work of Caron (1985) was found to be very useful in the present research.

The benthic foraminifera on the other hand are bottom dwellers characterised by high diversity and abundance. In benthic foraminifera, the cytoplasmic body is encased in an organic or mineralized test that provides a fossil record. They first appeared in Cambrian (Early Paleozoic) and continues to the modern time. Benthic foraminifers are the chief indicators of temperature, salinity and bottom conditions and useful for paleoenvironmental interpretation. Most of the benthic foraminifera are long ranging and are therefore not very useful for age determination (dating) except for a few genera viz. *Nummulites, Assilina, Miogypsina* etc. common in shallow marine Tertiary (Paleocene-Miocene) carbonate succession. The abundance of certain genera in some sedimentary units (abundance peak) is sometimes useful for local correlation. These groups are ecologically sensitive and facies dependent. In the present research they are abundant in all the four wells in Orange Basin. Identification of this group was made primarily consulting the morphological characters provided in the classical reference by Loeblich and Tappan (2013). A comprehensive discussion and description of Cretaceous benthic foraminifera is also available in Frizzell (1954) which helps in identification of benthics in the present work. The paleoecological studies by morphological grouping the benthic foraminifera is a relatively new development in biostratigraphic studies. This procedure was applied in the present research, it helps identify various sub-environments and assign paleodepth values in the studied well intervals and aid in construction of a sea level fluctuation curve (transgressive-regressive events).

Paleoecological studies and usual depth ranges of foraminifera have been discussed in detail by Murray (1989, 2006). The basic concept in benthic morphogrouping is based on the observation that different test shapes in foraminifera are due to their preferred habit (e.g. feeding strategies) hence different underwater environment. It was also observed that an abundant group of similar morphology indicates a change in environment (Corliss, 1985; Jones and Charnock, 1985; Kaminski et.al., 1995, Murray et.al., 2011 and Setoyama et.al., 2017). The original morphogroups scheme for agglutinated foraminifera were subsequently modified by some workers (Murray et.al. 2011). For morphogroups of calcareous benthics the scheme adopted by Frenzel (2000) is adopted here.

3. CHAPTER THREE: WORK METHODOLOGY AND SAMPLE PREPARATION

3.1 Introduction

This chapter highlights the different materials and methods used to achieve the objectives of the present research. One of the main objectives of the study was to understand the temporal distribution of foraminifera microfossils and to subdivide the penetrated succession into various age groups. The entire research under this project was carried out with the help of well samples (well cuttings and conventional cores) of Orange Basin available from the four exploratory deep wells available from the Petroleum Agency of South Africa (PASA), Cape Town. The following section deals with the work methodology adopted in the present investigation.

3.2 Data Collection

Apart from well samples, important records like geological well completion reports of the four wells and the electrical logs for the wells were collected. Well completion reports are always prepared by Petroleum exploration agencies after a well is drilled. The geological well completion report provided valuable information about the subsurface section penetrated by the drilling bit. The recorded lithology prepared at the drill sites and corresponding geophysical logs (well-logs viz.GR, bulk density, formation resistivity helpful to demarcate lithology) were helpful in selecting the correct sample intervals for biostratigraphic sample analysis. The summarised stratigraphic intervals before and after drilling helps to identify overall intervals of each wells to be studied. As most of the wells are quite old (more than three decades old) cutting samples for some of intervals in well K-H1 were not available for analysis. The four wells were drilled with an aim to explore Cretaceous reservoirs in this area for hydrocarbon. Due to the huge sample interval for each well, samples were collected from specific depth intervals within Cretaceous where chances of faunal recovery is maximum but sample gaps were maintained in regular intervals except in the sandstone interval of each wells where chances are faunal recovery is very low.

3.2.1 Sample selection procedure:

Argillaceous intervals are always considered to be the best for optimum faunal recovery. Apart from the well logs and lithology details of composite logs available from the well completion reports the cutting samples were physically examined before final collection from the PASA core laboratory. All the samples collected were processed and frequency of each foraminiferal species were recorded and then presented in the frequency charts and then plotted against the lithology as given in the integrated biostratigraphy diagrams (provided in chapter four).

Similarly, the core samples were studied in detail and samples were collected from the argillaceous intervals from the six conventional cores cut in the four wells. Summarised information about samples processed and analyzed for biostratigraphic studies in the present work is shown in Table 3.1:

Table 3.1: Summarised information about the sample intervals studied

Well Name	K-A2	K-A3	K-H1	K-E1
Selected Interval	3479m-5790m (2311m)	2310m – 3900m (1590m)	2717m-3923m (1206m)	2900m-4130m (1230m)
No of cutting samples studied	87	74	85	53
Sample gap	Nil	Nil	(3058m-3188m) and 3685m-3785m	Nil
Core number and samples	CC#1 and CC#2 (5 +6 =11 samples)	CC#1 and CC#2 (4+1 =5 samples)	CC#1 (7 samples)	CC#1 (4 samples)
Total samples processed and analyzed	Total 98 samples	Total 79 samples	Total 92 samples	Total 57 samples

A total of 326 well samples (including 27 from the 6 conventional cores) from the 6337m total interval were processed and examined for biostratigraphic analysis from the four exploratory wells K-A2, K-A3, K-H1 and K-E1 respectively. Samples from about 230m from well K-H1 only was not available for processing.

3.2.2 Megascopic examination of well samples

The majority of the samples were well cuttings and a few were conventional core samples. Once they were subject to laboratory disintegration for faunal recovery, they were likely to change their character. Therefore, in biostratigraphic analysis the overall lithological characters of each samples were recorded before processing using laboratory methods that involves chemicals and heating. The lithological properties that were recorded included general textural elements (colour of the grains and overall appearance , angularity, grain size, nature of cement etc.), percentage wise lithology (sand, siltstone, shale, claystone, limestone fragments, presence of fossil and algal remains), presence of accessory materials like carbonaceous matter, oxidised ferruginous grains and anoxic (pyritised) materials, these were important for the interpretation of the paleo-depositional environment. Before recording the information all of the samples were washed with water to remove drill mud contamination.

3.2.3 Laboratory processing

Sample processing techniques usually adopted from drilled cuttings and conventional core samples depends on the nature of the core samples. This has been discussed by Kummel and Raup (1965), Chapman et.al. (1989), Harris et.al. (1989), Green (2001) and others in detail. The main purpose of sample processing is to disintegrate the well cuttings and core fragments into individual grains as much as possible to remove the binding cement material, this facilitates the separation of the microfossils (foraminifera, ostracods, micro invertebrates and radiolarian tests).

The washed samples free from drilling mud were dried and only 20 grams of each samples were considered for processing. This helped in quantitative analysis necessary for biostratigraphic studies. The washed samples were kept in separate enamel bowls with water. Approximate 15ml of Hydrogen Peroxide (30%) was added to the content in the enamel bowls and soaked for 48 hours in standard room temperature conditions. The Hydrogen Peroxide (H_2O_2) helped disintegrate the sedimentary particles by breaking the sediment lattice and removing the cemented material. A small amount of caustic soda / laboratory detergent agent also added with the solution which assist to separate the clay matrix in the sample.

While processing the conventional core samples, 20g of core fragments were washed in water and their geological characteristics (texture, mineral or lithological composition) were recorded. Most of the core fragments were relatively large in size. They were therefore, broken down into smaller fragments by using a wooden hammer before soaking the sample in water

prior to processing. The core pieces were not to be powdered as this could potentially have destroyed the foraminifera tests.
After 48 hours of soaking, the samples were rapidly boiled for about 45 minutes on an electric stove in the laboratory and allowed to cool. The boiling of samples also intensified the disintegration. After cooling, the entire content of the boiled samples were kept in a fine 300 mesh sieve under running water in a sink to remove the clay materials that were separated out of the chemically treated and boiled well cuttings. The sieve would retain the disintegrated sediment fragments along with the microfossils. The washed content in the sieve was transferred to the enamel bowl once again, dried in the oven and then allowed to cool.

The content of each of the bowls were kept in transparent sample tubes with proper identification labels attached displaying the well details and depth interval. Extreme caution was taken while processing the large number of samples as sieve contamination and mixing of identification labels has been known to be a common problem in laboratory samples. Each of the samples were identified by well number, depth interval or core segment number/ depth. The processed samples were then ready for microscopic examination for biostratigraphic studies.

3.2.4 Isolation of microfossils

Isolation of microfauna from the processed well cuttings was a vital manual procedure and was an essential part of the research involving microfossils. It was a time consuming and tedious part of the research. This step involved manually separating microfossils using sable hair sorting brushes of various sizes, made especially for this purpose (00,000,0000 brush sizes). These sorting brush are common standard accessory used in oil companies and research institutes dealing with foraminiferal research.

The sorting procedure involved using a series of sieve sets (meant for foraminiferal studies and are smaller in diameter compared to sieve sets used in grain size analysis). In the present work sieve sets 30, 60, 80, 100 microns were used along with the collecting pan. The oven dried processed samples were placed in the top sieve and the different size fractions were sorted separately. The sample from each sieve fraction was spread as a fine layer in a rectangular brass tray (also known as microfossil sorting tray) and using the tip of wet brush the attached fossils are transferred into the slides. The slides could be a single, double or multichambered and were meant to be kept in the repository. The sides were numbered according to sample depth and well number. Extreme caution had to be taken when picking all fossil fragments as well as any biological material like algae, micro-invertebrates, shell fragments etc. Apart from this, records of pyrite grains, oxidised material, asphalt etc. were also recorded and kept in the slides. The number of slides that could be used in each sample depended upon the frequency. In highly fossiliferous samples, more than one slides with the same sample numbers were to be used. The slides were kept in metallic trays in serial order from bottom depth to higher depth as per convention. In the present research foraminifera and other microfossils from all the wells were sorted from the processed samples and identified using standard procedures. All the slide trays were kept in repository in the Biostratigraphy Laboratory in the Earth Science Department as per international repository protocol for future reference and comparison. Sorting and identification of processed samples were carried out under powerful Stereo-Zoom binocular microscope under reflected light.

3.3 Identification and morpho -grouping

3.3.1 Identification of foraminifera

It was of utmost importance that the identification of foraminifera was done accurately. Accurate identification of the microfauna was necessary for dating and paleoenvironment interpretation. For correct identification standard international reference books, catalogues and several important publications are consulted. Details of these references have already been mentioned in Chapter II -Literature review. Foraminifera are classified into two major groups on the basis of their living condition viz. planktonic and benthic. On the external morphological characters and test composition foraminifera are placed under different Superfamily, Family, Order, Sub-order, Genus and Species level. For Cretaceous planktonic foraminifera the classical work of Caron (1985) was strictly adhered to in the present work and placed under respective planktonic zones. The last appearance datum -LAD (i.e. the first down whole occurrence in case of well cuttings) was important to be able to mark the zonal boundary for which index planktonic foraminifera were very much useful. In absence of index species, co-occurrence of more than one planktonic foraminifera was considered for dating. In biostratigraphic work related to marine successions, the dominance of planktonic forms found in open marine conditions were important and helped in determination of age, stage and zonal boundaries.

The benthic foraminifera are bottom dwelling microorganisms, they are mostly long ranging and are not of much help in age determination except in a few cases found in larger foraminifera found in carbonate sediments of Tertiary age. In Mesozoic marine sediments they are most helpful for paleoenvironment reconstruction due to their unique habitat. In Cretaceous sediments they are widely used to assign paleodepth as morphological parameters are related to water depth. Usually shallow water benthics are not found in a sample with deep water forms. The determination of paleodepth on the basis of morpho grouping is discussed in Chapter Five of this thesis. Benthic foraminifera are broadly classified on two types namely, agglutinated (the external shell, also called 'test' of a foraminifera) made up of siliceous material, minute mineral grains etc. and calcareous foraminifera that are made up of calcium carbonate or sometimes phosphatic material. With the help of a binocular stereo zoom microscope they could be identified easily under reflected light. The two groups were further subdivided under various subdivisions on the basis of their morphological similarity. For generic level identification of benthic foraminifera the well-known reference of Loeblich and Tappan (1988) was used in this work. In addition, several reference books were consulted.

3.3.2 Morpho-grouping of foraminifera

The benthic foraminifera are grouped under different morphological classes based on their external test shape. In this, work this was done for both the agglutinated and calcareous benthics separately. In practice, the microfossils after sorting from samples were identified following standard references as discussed and their frequency per samples were recorded. Usually the fauna under the microscopes were grouped under different morphological classes on the basis of their test shape. For identification, morphology as well as the composition of wall-structures of individual specimens are important. The individual forms are compared with the reference photographs and taxonomic descriptions to place under different genera or species. The individual frequency of all the foraminifera genera identified were recorded for statistical work and bathymetry interpretation.

3.3.3 Record of other microfossil groups

Apart from foraminifera grouping record of other microfossil groups are also recorded (viz. radiolarians, ostracods, pteropods and micro invertebrates if present in the samples). However, presence of algal, carbonaceous, oxidized (ferruginous) or anoxic indicators (e.g. pyrite) particles were not counted but were recorded against the interpreted lithology column in the integrated biostratigraphy charts.

Sample wise temporal distribution of foraminifera and any other microfossils is provided in frequency charts (Figures:4.5,4.7,4.9 and 4.11) and the well wise results including the interpreted bathymetry distribution with respect to every samples (transgressive- regressive) curve is shown in Figures 4.4, 4.6, 4.8 and 4.10). The presence of oxidized and anoxic materials in samples as well in foraminifera indicative of post depositional changes are shown symbolically in the integrated charts.

4. CHAPTER FOUR: FORAMINERERAL BIOSTRATIGRAPHY IN STUDIED WELL SECTIONS

4.1 Introduction

The Orange Basin (Figure 4.1) located on the western continental margin of South Africa and southern Namibia is a late Mesozoic (Cretaceous) drift filled basin (McMillan, 2003). The basin is one of the seven major sedimentary basin containing varied thickness of Cretaceous drift succession ranging in age from Early Barremian to Late Maastrichtian (127 Ma to 65.5 Ma). The Orange Basin is the southernmost West African basin and the largest as well as youngest South African Offshore basin (Campher et. al, 2009). The basin covers an area of about 130000 km^2 (up to 200 m isobath and has roughly one well in every 4000 km^2. The Orange Basin has proven hydrocarbon reserves.

The basin was created in the rift phase that occurred along the west coast during the late Jurassic (Munting, 1993). During the rift stage grabens and half grabens were created. The rifting continued until the Hauterivian stage marked by 6At1 unconformity. Early drifting took place between Hauterivian (132.9 Ma) and middle Aptian (120 Ma). The reservoir sediments deposited during this time lies between unconformities 6At1 and 13At1 and are classified under 'Intermediate sediments'. Barremian to early Aptian argillaceous clastics are considered as the source rock (Munting, 1993). After the 13At1 unconformity full scale drifting took place and a thick sedimentary wedge was created with large scale growth and slump structures and associated thrusts along the shelf edge.

A broad biostratigraphic account using microfossil 'Foraminifera' covering the drift succession of all the seven major basins of South Africa was attempted by McMillan (2003). According to this work:

- The correlation of the seismic horizons between different basins are reliable only for large scale unconformity surfaces such as 5At1, 13At 1 and 15At1.
- The Orange Basin received majority of the sediment input from the interior of the South African landmass starting from Late Barremian (Early Cretaceous) to Early Campanian (Late Cretaceous) time.

- Both the rate of subsidence as well as the rate of sedimentary input in Orange Basin were significantly higher than in the remaining South African basins.
- However, tectonic control in sedimentation existed in the Orange Basin and the adjoining smaller basins. Therefore, the major unconformity surfaces (caused by basin stand still condition and upliftment) as well as the periods of sedimentation (caused by basin subsidence) are almost similar to the adjacent basins.

Figure 4.1: Orange Basin showing well locations K-A2, K-A3. K-E1 and K-H1

4.2 Cretaceous Biostratigraphy

As discussed in the previous chapters, the Orange Basin is considered to be one of the most prospective basin for oil exploration in South Africa. However, very limited information regarding the distribution of foraminifera along the drilled subsurface sections are available. The importance of microfossil for demarcation of the various stage boundaries in marine sediment is well known. Other than dating the sediments, the microfossil group foraminifera helps in identification of hiatus (unconformities) and short duration exposures known as diastem. The quality of the data depends on the lithology of the subsurface as well as reliability of the drilled cutting and conventional cores. Age control in Cretaceous and Tertiary marine sediments mainly depends on the presence of planktonic foraminifera. Unfortunately, due to high sedimentation rate and presence of coarse grained clastics (reservoir sediments) the presence of planktonic foraminifera are found less abundant. Some of the benthics are useful for local zonation but they are more important for ecological

A total of four exploratory deep wells were studied for the biostratigraphic analysis. The wells are K-A2, K-A3, K-E1 and K-H1. Sample intervals were selected after consulting the available well completion reports, well logs and physical megascopic examination of the cutting samples. All efforts were made to select the samples from regular intervals. In many cases continuous samples were not available for processing. For a standard biostratigraphic work usually 20 grams of samples are taken from argillaceous lithology and after careful megascopic observation (colour, mineralogical composition, presence of carbonaceous particles, anoxic minerals e.g. pyrite and oxidised particles) they are processed in the laboratory. Sample processing techniques adopted in the present work is discussed in detail under chapter three.

4.3 Integrated Cretaceous Stratigraphy

The summarised chronostratigraphic and biostratigraphic work of McMillan (2003) as shown in Figure 4.2 shows that the bottommost sediments above the drift onset unconformity 5At1 encountered in the Orange Basin comprises volcanic rock fragments and volcanoclastic shelly sandstones. This is overlain by a thin claystone interval considered as a local source rock unit (between 6At1 and 8At1 unconformities) deposited in the upper slope environment and are encountered only in Kudu area located more than 350km NNW of the studied area. The entire interval is placed in the Barremian stage. This is followed by the Aptian age sediments of about 150m thickness in Kudu area and only 40m thick sediments in O-A1 well around 300km south of the studied area. This is followed by a prolonged hiatus represented by seismic marker 13At1 within the Early Aptian stage.

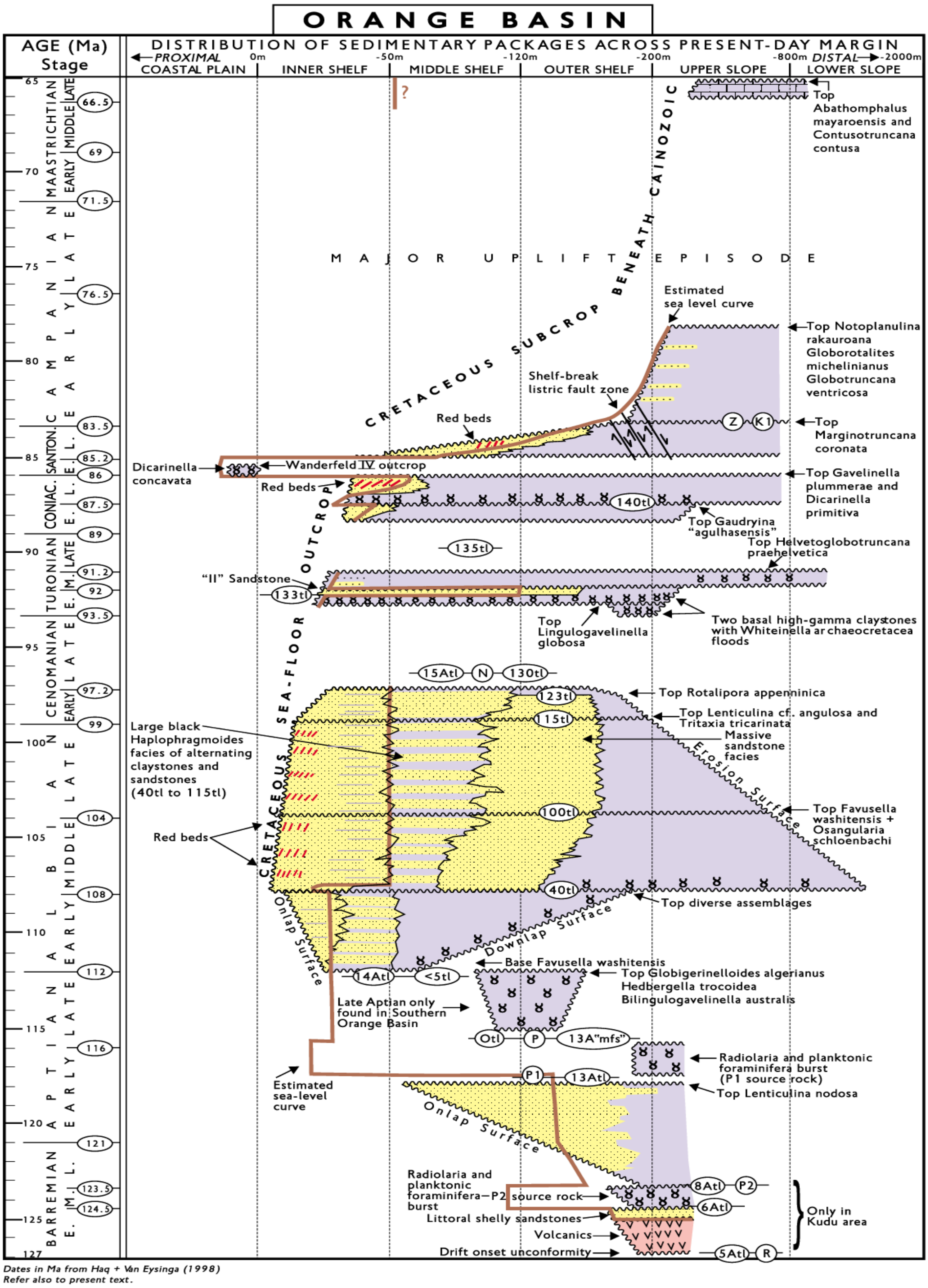


Figure 4.2: Integrated chronostratigraphy and biostratigraphy of Orange Basin (McMillan, 2003)

Late Aptian sediments (approximately 80m thick) were encountered in A-N1 area in the Southern Orange Basin. The remaining part of Late Aptian and Albian sedimentation was widespread in the basin and are represented by claystone / shale/ siltstone and occasional sands deposited under various depositional set up from Upper slope to Outer-middle and inner shelf condition in different parts of the basin. Several minor or localized unconformities were encountered within Albian stage. This is followed by the Late Cretaceous Cenomanian stage sediments.

4.4 Foraminiferal biostratigraphy in the studied wells

The four wells considered for biostratigraphic studies in the present work were drilled with an objective to explore hydrocarbon prospect in the early Cretaceous (Aptian- Albian) and Late Cretaceous (Early Cenomanian stage). Therefore, after crossing the Early Cretaceous boundaries a part of Late Cretaceous (Cenomanian) sediments were also studied in the present work. The following section deals with the foraminiferal biostratigraphy of the four wells.

4.4.1 Well K-E1

The exploratory well K-E1 is the northern most of the four studied offshore wells considered in this work. The well was spudded in 323m water depth (McAloon, 1991). The prime objective to drill this well was to explore shelf sandstones in the Upper Cretaceous as beneath this the interbedded shales were considered as the source rock sequence. The well was drilled up to a depth of 4133.7m and the final status was dry well with minor gas show in certain intervals.

As mentioned in the well completion report the two seismic horizons (unconformity surfaces) within the studied interval are 15At1 at 3025m in Cenomanian top and 14 B_2t1 (Early Cenomanian). Well cuttings between the interval 2930m to 4130m were processed in the laboratory. The sample interval chosen in this work is mainly based on careful consultation of the well completion report (McAloon, 1991). The chronostratigraphic marker horizons 15At1 and below covering the reservoir units. Only one conventional core (CC#1, 3747.5m to 3753.9m) was cut in this well and samples from the argillaceous beds were processed for foraminifera microfossil study.

A total of 53 cutting and core samples were selected mainly from the argillaceous intervals and avoiding the sandstone units. Microfossils are always better preserved in fine argillaceous samples (shale, claystone and silty units) and this gives optimum recovery. Dry well cuttings were studied for lithological details and minute changes in consecutive samples were recorded. Presence of carbonaceous particles, red coloration (oxidation) and presence of calcareous matter and pyritised grains were also recorded before processing the samples in the laboratory. Conventionally 20 grams of samples were processed and all foraminifera and any other microfossils (micro gastropods, pteropods, ostracods and Radiolaria along with algal matters) were sorted and kept the microfaunal slides.

The foraminifera microfossils were grouped under different categories based on their test composition (agglutinated, calcareous and planktonic groups) and morphology. This method helped in generic identification of the foraminifera and further identification until species level. The planktonic foraminifera are important for assigning the stage boundaries and their last appearance datum (LAD). While using cutting samples due to caved particles normally first appearance (FA) data of planktonic foraminifera were not considered.

Morpho grouping of foraminifera were extremely useful for paleo-ecological studies and paleoenvironmental analysis. This has been discussed in chapter five of this thesis.

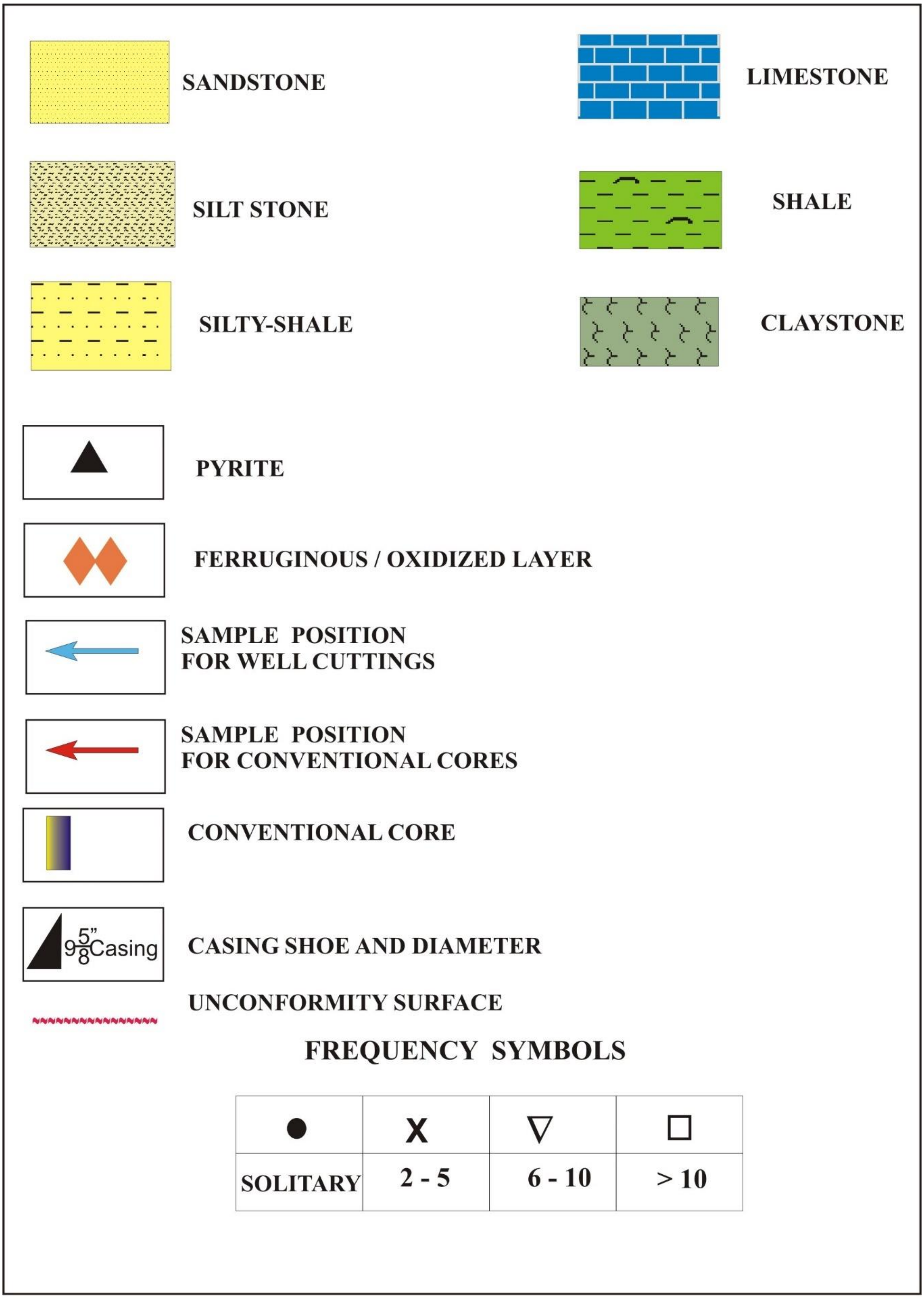


Figure 4.3: Symbols used in this report.

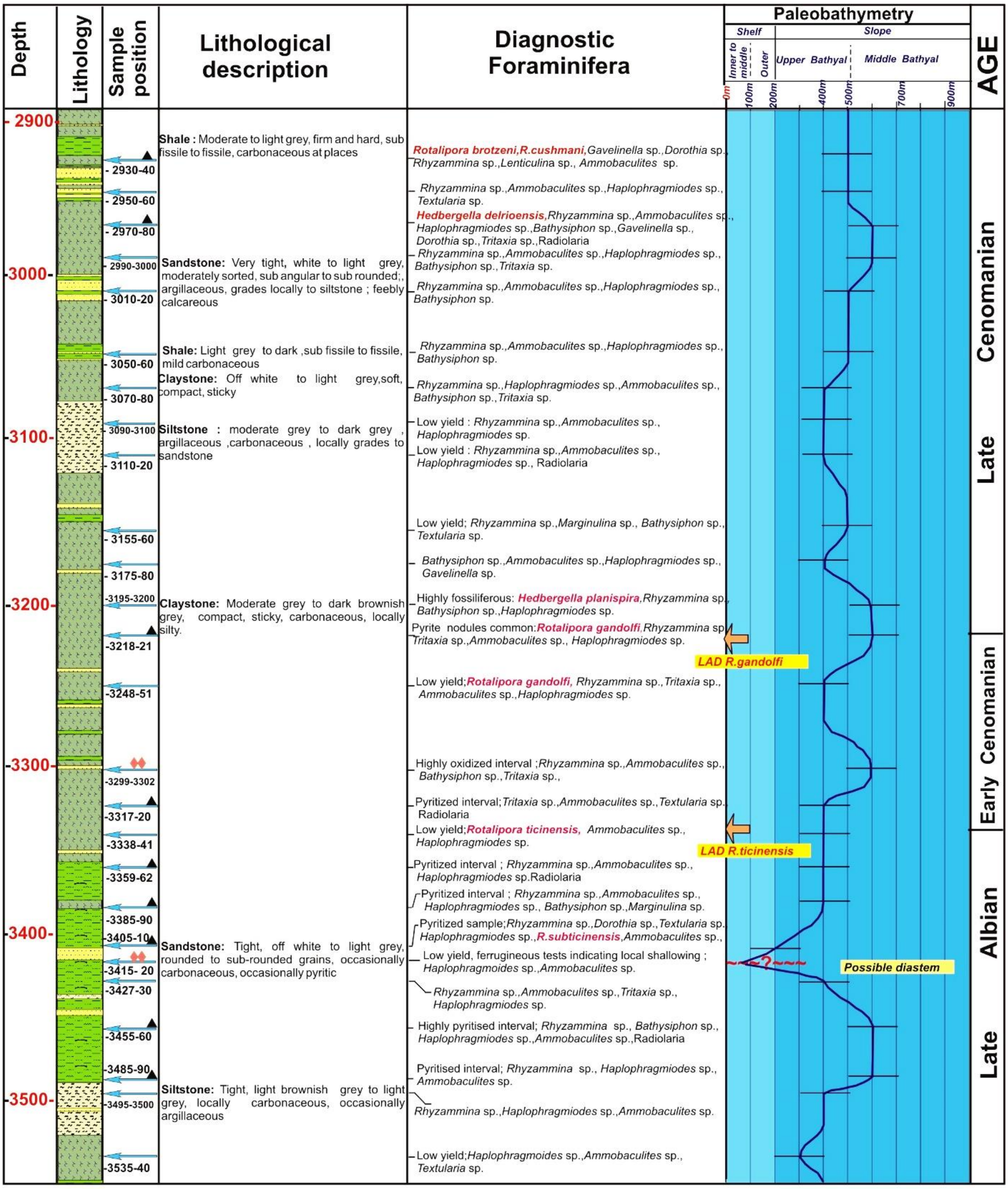


Figure 4.4: Foraminifera assemblage and interpreted paleobathymetry between the interval 2900m – 3550m in well K-E1, Orange Basin, Offshore South Africa.

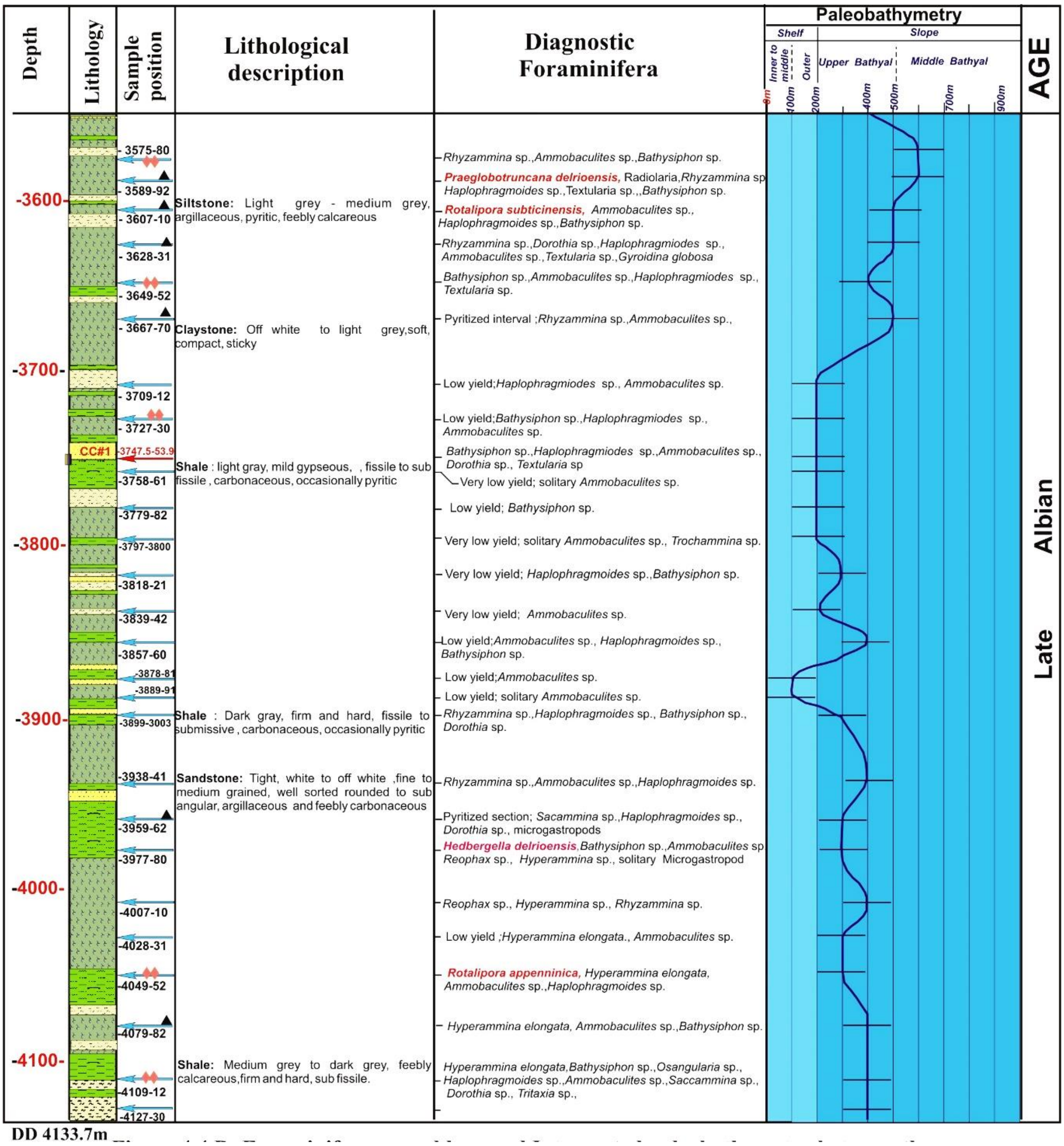


Figure 4.5: Foraminifera assemblage and interpreted paleobathymetry between the interval 3550m – 4130m in well K-E1, Orange Basin, Offshore South Africa.

Sample Interval (m)	FORAMINIFERA ASSEMBLAGE																												
	Haplophragmoides sp	*Bathysiphon sp.*	*Hyperammina elongata*	*Hyperammina sp.*	*Saccammina sp.*	*Ammobaculites sp.*	*Dorothia sp.*	*Tritaxia sp.*	*Reophax sp.*	*Rhyzammina sp.*	*Trochammina sp.*	*Textularia sp.*	*Osangularia sp.*	*Lenticulina angulosa*	*Gyroidina globosa*	*Marginulina sp.*	*Gavelinella sp.*	*Rotalipora appenninica*	*Hedbergella dolreoensis*	*Rotalipora subticinensis*	*Praeglobotruncana delrioensis*	*Rotalipora ticinensis*	*Rotalipora gandolfi*	*Hedbergella planispira*	*Rotalipora brotzeni*	*Rotalipora cushmani*	**Radiolaria**	**Microgastropods**	**Ostracoda**
2930-2940						×	×			∇				×			×								×	•	×		•
2950-2960	×					×				×		•																	
2970-2980	×	×				×		×		□																			
2990-3000	×	×				×	•	•		□							•		•								•		
3010-3020	×	×				×				∇																			
3030-3050	×	•				×				×																			
3070-3080	×	×				×		•		∇																			
3090-3100	•					•				×																			
3110-3120	×					×				×																	×		
3155-3160		×								∇		•				•													
3175-3180	•	×				×											•												
3195-3200	∇	×								□														•					
3218-3221	×					×		×		×													•						
3248-3251		•				•				•													×						
3299-3302		×				×		•		×																			
3317-3320						×		×				×															×		
3338-3341	×					×																•							
3359-3362	×					×				×																	•		
3385-3390	×	•				∇				×						•													
3405-3410	•					•	•			□		•								•									
3415-3420	×					×																							
3427-3430	×					∇		•		□																			
3455-3460	•	×				×				□																	×		
3485-3490	×					×				×																			
3495-3500	×					×				×																			
3535-3540	×					×						×																	
3575-3580		×				∇				□																			
3589-3592	×	•								∇		×									•						•		

Figure 4.6: Foraminiferal frequency (interval 2930m-3592m), Well K-E1, Orange Basin, Offshore South Africa.

	FORAMINIFERA ASSEMBLAGE																												
Sample Interval (m)	*Haplophragmoides sp*	*Bathysiphon sp.*	*Hyperammina elongata*	*Hyperammina sp.*	*Saccammina sp.*	*Ammobaculites sp.*	*Dorothia sp.*	*Tritaxia sp.*	*Reophax sp.*	*Rhyzammina sp.*	*Trochammina sp.*	*Textularia sp.*	*Osangularia sp.*	*Lenticulina angulosa*	*Gyroidina globosa*	*Marginulina sp.*	*Gavelinella sp.*	*Rotalipora appenninica*	*Hedbergella delreoensis*	*Rotalipora subticinensis*	*Praeglobotruncana delrioensis*	*Rotalipora ticinensis*	*Rotalipora gandolfi*	*Hedbergella planispira*	*Rotalipora brotzeni*	*Rotalipora cushmani*	**Radiolaria**	**Microgastropods**	**Ostracoda**
3607-3610	×	•				×														×									
3628-3631	•					×	×			∇		•			•														
3649-3652	×	×				×						•																	
3667-3670						×				×																			
3709-3712	•					•																							
3727-3730	•	•				•																							
3753.51 CC#1	×	•				×	•					×																	
3758-3861						•																							
3779-3782		•																											
3797-3800						•					•																		
3818-3821	•	•																											
3839-3842						×																							
3857-3860	•	•				×																							
3878-3881						×																							
3889-3892						•																							
3899-3902	×	×					×			□																			
3938-3941	•					□				∇																			
3959-3962	×				×		•																						
3977-3980		×		•		×	×		×										•									•	
4007-4010		×		×					×	×																			
4028-4031			•			×																							
4049-4052	×		×			×												•											
4079-4082		×	×			×																							
4109-4112	□	×	×		×	×	•	•					×	×															
4127-4130	×																												

Figure 4.7: Foraminiferal frequency (interval 3601m-4130m), Well K-E1, Orange Basin, Offshore South Africa.

4.4.1.1. Stratigraphic analysis and results

Temporal distribution of foraminifera

Distribution of foraminifera in well K-E1 in the interval (shown in figures 4.6 and 4.7) indicate that throughout the interval agglutinated species are highly dominant compared to calcareous foraminifera. The presence of important age diagnostic planktonic species at certain

stratigraphic levels helped to assign age for the studied section.
In the lower part of the studied stratigraphic section interval from 3797m to the lowest sample depth at 4130m was dominantly a fine argillaceous interval with shale, claystone and shaly siltstones (Figure 4.4 and 4.5). The claystone units were lumpy and compact with dark cement grey in colour, the shales were poorly carbonaceous and highly fissile to sub- fissile. Sandstone units were not very thick, mostly fine to medium grained, subangular indicating moderate distance of transport from the source area. The sands were not very clean and were argillaceous.

This interval is dominated almost entirely by agglutinated foraminifera and calcareous foraminifera are very rare. Only in one sample (3977m-3980m) the presence of solitary micro gastropod was recorded. The agglutinated foraminifera recorded were *Haplophragmoides* sp., *Ammobaculites* sp., *Bathysiphon* sp., *Hyperammina elongata*, *Hyperammina* spp., *Dorothia* sp., *Rhyzammina* sp. and rare *Trochammina* sp. Only in one sample towards the bottom part of this section at 4109m-4112m presence of calcareous benthic foraminifera *Osangularia* sp. and *Lenticulina angulosa* are recorded (Figure 4.7). Presence of planktonic foraminifera species *Rotalipora appenninica* and *Hedbergella delrioensis* (solitary occurrence) were recorded in the shale section in the lower part of this interval.

The overlying interval 3338m -3797m was yet again a dominantly argillaceous interval. However, some intervening sandstone units and frequent thick siltstone beds were common within this interval indicating alternating shallow and relatively deep unstable sea level. Frequent presence of oxidised red coloration in siltstone and sandstone beds at several samples indicates shallowing condition. Pyritised nodules and pyrite coated benthic foraminifera were frequent in shales or claystone units deposited in deeper water condition in upper slope indicating anoxic environment possibly a source with hydrocarbon generation potential. Samples from the solitary conventional core (CC#1 Interval 3747.5m to 3753.9m; Recovery 97%) were studied for their foraminifera content. The core was taken for reservoir studies purpose and is dominated by sandstone with a few shaly intercalation in the upper part. The bottom part is mainly shale. Four selected samples were processed and studied for microfossil content in this core yielded *Ammobaculites* sp. (common), along with *Textularia* sp., *Reophax* sp., *Haplophragmoides* sp. and *Dorothia oxycona* indicating outer shelf to upper bathyal condition (average water depth around 200m).

Like the lower section this entire interval was highly dominated by agglutinated foraminifera with the continuation of similar assemblage. Both *Haplophragmoides* sp. and *Ammobaculites* sp. were common and were present throughout the interval. Presence of *Dorothia* sp. and *Textularia* sp. were noticed in a few samples and were usually with relatively low frequency. *Rhyzammina* sp., a relatively deep-water bathyal environment indicator was present in relatively low frequency in the lower part of this interval but above 3592m there was an abrupt increase in their frequency until 3359m indicating a sharp rise in bathymetry to upper and middle slope environment. The lithology in this interval were claystone and shale indicating deep water facies. Calcareous benthics were very rare and only had a solitary occurrence of *Gyroidina globosa* and *Marginulina* sp. were recorded from two samples. Three important planktonic foraminifera species *Rotalipora subticinensis, Rotalipora ticinensis* and *Praeglobotruncana delrioensis* were recorded in some samples. While *P. delrioensis* was a relatively long ranging plankton (Late Albian to Cenomanian), the other two *Rotalipora* species are index species (Figure 4.21) of Late Albian stage (Caron, M.1985, page. 36).

Age: Within the studied interval 3338m to 4130m presence of planktonic foraminifera was recorded in a few samples. Frequency of these planktonic species are not very good but they were well preserved. The forms recorded were *Rotalipora appenninica*, *Hedbergella delrioensis*, *Rotalipora subticinensis, Rotalipora ticinensis* and *Praeglobotruncana delrioensis*. *Hedbergella delrioensis* was a long ranging planktonic foraminifer (Late Aptian to Coniacian) but all the other planktons present in the studied intervals made their appearance only in Late Albian stage. Therefore, the studied interval cannot be older than Late Albian. On the last occurrence (LAD) of important planktonic foraminifera *Rotalipora ticinensis* the top of Early Cretaceous (Albian stage) was marked at 3338m in well K-E1.

The overlying studied interval between 2900m to 3338m (438m) was a highly claystone rich interval with fissile shale and thin interbedded sandstone/sandstones present indicating periodic deepening and shallow sea level. Towards the top of the interval pyritised grains and foraminifera / radiolarian tests were common, indicating anoxic depositional set up. This interval has yielded deep water agglutinated benthics viz. *Rhyzammina* sp., *Haplophragmoides s*p., *Ammobaculites* sp. and *Bathysiphon* sp. throughout the interval. *Textularia* sp., *Dorothia* sp. and *Tritaxia* sp. were also common in the upper part. Calcareous benthics *Lenticulina angulosa*, *Gavelinella* sp. and solitary occurrence of *Marginulina* sp.

were preserved in the claystone lithology. Pyritised Radiolaria and rare occurrence of Ostracoda were also noticed. Overall, the section indicated an open marine environment.

The recorded planktonic foraminifera species were typical representatives of the Cenomanian stage (lowest stage of Late Cretaceous). The two planktonic species under the genus *Hedbergella,* viz. *H. planispira* and *H. delrioensis* were long ranging planktonic forms. However, the presence of the typical Late Cretaceous Cenomanian planktonic species *Rotalipora gandolfii* in consecutive samples (3218-3251m) indicated toward the lower part of Cenomanian stage i.e. planktonic zone *Rotalipora brotzeni* (Bolli, 1985) while in the uppermost sample interval at 2930m -2940m record of *Rotalipora cushmani* and *R. brotzeni* typical late Cenomanian stage index planktons were present. Therefore, the entire studied interval above 3338m till highest sample at 2930m could be placed under the Cenomanian stage (Late Cretaceous) in well K-E1.

4.4.2 Well K-A3

The exploratory well K-A3 is located approximately 20km SE of well K-E1 (129 km WSW of Hondeklip Bay, Offshore South Africa) was drilled in 219.6 m water depth (Larsen, 1992). The location was drilled as a step-out exploratory well prime objective to explore the sandstone reservoir at the level of horizon 13At1 (Lower Aptian). The well was drilled 4676.85m before reaching the 13At1 horizon due to indication of overpressure condition. The rig was released with the status of well with poor gas show. The information regarding the approximate depths of seismic horizons (unconformity surfaces) within the drilled interval were 15At1 (Late Cenomanian) at 2280m, 14B_2t1 (Early Cenomanian) at 2720m, 14Bt1 (Late Albian) at 3260m and 14At1 (Early Albian) at 3830m respectively.

Two Conventional cores viz.CC#1, interval 2906m-2914.5m (100% recovery) and CC#2, interval 3875.5m -3884m (92% recovery) were available for analysis. Cutting samples for the interval 2310m to 3884m was available for detail biostratigraphic analysis. Cutting samples below 3884m were not available for biostratigraphic analysis. A total of 76 selected cutting samples and 5 core pieces (1 from CC#1 and 4 from CC#2) were also studied.

4.4.2.1. Biostratigraphic analysis and results

Temporal distribution of foraminifera

Frequency distribution of foraminifera in well K-A3 in the studied interval are shown in two figures (4.10 and 4.11). Barring three unfossiliferous samples (at 3480m-3483m,3240m-3243m and 3129m-3132m), mostly from highly arenaceous interval foraminifera species were recorded from all other samples in various frequency and diversity.

The lower part of the section (interval 3030m to 3883.41m) was a long interval dominated by thick sandstone and siltstone units with numerous thin argillaceous units (dominantly shale and claystone). The second conventional core (CC#2, Interval 3875.5m -3884m in the bottommost sample was also dominated by sandstone with minor shale bands. The sandstone units were mostly light grey to white in colour medium to fine sub-angular to subrounded grains. Very fine carbonaceous patches were seen both in the cored samples as well in cuttings. The siltstone units were mostly greyish in colour. Oxidised grains were common in some of the intervals suggesting localised shallowing and short duration exposures (diastem surfaces). Shale and claystones are usually dark to various shades of grey in colour and are sometimes pyritic. (Figures 4.8 and 4.9)

Within this interval, agglutinated foraminifera were extremely dominant and calcareous benthics were extremely rare. Within the agglutinated foraminifera group, faunal diversity was also very poor. *Trochammina* sp., *Ammobaculites* and *Rhyzammina* spp. are present and dominant throughout the interval. *Tritaxia* sp. and *Haplophragmoides* sp. are common in a few depth intervals. The three unfossiliferous samples viz. 3480m-3483m, 3240m-3243m and 3129m-3132m were all from this studied interval.

Age: Presence of planktonic foraminifera species *Hedbergella gorbachikae* was recorded from this interval at 3390m-3393m and its last appearance at 3048m. Since the highest occurrence of the planktonic species *Hedbergella gorbachikae* as per planktonic scale was at middle Albian, the entire interval between 3048m and 3883.41m was placed in the Early to Middle Albian stage.

The overlying interval 2868m-3048m was lithologically similar with coarser clastics (sandstones and siltstones) were dominant with minor shale laminations. The first conventional core CC#1 (2906m-2914 m) was cut towards the top of this interval (Figure 4.8). Most of the sandstone units were fine to medium grained with occasional pyrite grains. Mild carbonaceous streaks were also noticed in the conventional core fragments. The siltstones were grey to brownish grey in colour and often graded to claystone. The few shale units were usually fissile to sub-fissile and are dark grey in colour.

This interval yielded diverse agglutinated foraminifera and good planktonic foraminifera. The presence of agglutinated foraminifera viz. *Haplophragmoides* sp., and *Trochammina* sp. were recorded in almost all samples within this interval. The other agglutinated foraminifera recorded from some of the samples within this interval included *Ammobaculites* sp., *Gaudryina* sp., *Textularia* sp. and rare *Reophax* sp. Solitary specimen on calcareous foraminifera *Lenticulina* sp. are recorded from one sample only . *Rhyzammina* sp. a very common and dominant agglutinated foraminifera from the Early-Middle Albian and as described earlier was noticeably absent indicating a relatively shallower bathymetry during deposition.

Age: The lower part of the interval (Figure-4.8) yielded *Hedbergella planispira*, *Rotalipora ticinensis* and *Rotalipora gandolfii.* While *Hedbergella planispira* is a long ranging form, the other two planktonic foraminifera species viz. *Rotalipora ticinensis* were a species of the Late Albian stage and *Rotalipora gandolfii* first appeared on the Late Albian- Cenomanian stage boundary. Therefore, the top of Early Cretaceous in the well K-A3 was marked at 2868m on the co-occurrence of the two important planktonic foraminifera *Rotalipora ticinensis* and *Rotalipora gandolfii*. The interval 2868m-3048m was therefore placed in Late Albian stage.

The overlying remaining part of the studied interval 2310m-2868m was around 558m thick. Within this interval the lower 210m (2658m-2868m) was lithologically similar with the underlying Late Albian interval. Sandstone was the dominant lithology but argillaceous units were more frequent and siltstone units were common. Sandstones were white to light grey in colour, fine to medium subrounded grains, poorly calcareous with presence of shell fragments in a few samples.

Above 2658m the rest of the section was highly argillaceous with dominant shale section of more than 220m thick between 2310m to 2530m. The shale lithology was characterized by dark to medium grey, fissile to sub-fissile argillaceous unit, mild in carbonaceous at places with pyritised intervals.

The entire interval above the Early Cretaceous top at 3048m was dominated by agglutinated benthics but at some places calcareous benthics were also seen, this indicated that there was more open marine circulation. Presence of several age diagnostic planktonic foraminifera within this interval were recorded and were helpful to demarcate the stage and foraminiferal zones as discussed below.
Trochammina sp., *Ammobaculites* sp. and *Haplophragmoides* sp. are present in all the samples studied within this interval. In a few sample *Tritaxia* sp., *Textularia* sp., *Bathysiphon* sp. were present. Co-occurrence of *Bathysiphon* sp. and *Rhyzammina* sp. (around 2550m) indicated a deeper bathymetry during the time of deposition. There was better diversity of calcareous benthics within this interval. In a few samples the presence of *Lenticulina gaultina* was recorded. Presence of *Epistommina chapmani*, *Nodosaria* sp. and *Dentalina* sp. was reported in a few samples. All of these forms were common in the upper bathyal depth in South African basins.

Planktonic foraminifera diagnostic of different zones of Cenomanian stages were common at many samples within this interval. Although, the frequency for the index planktonic foraminifera recovered are not very good, but they were found to be very important for assigning the geological age. Lithologically the entire interval was dominated by sandstone with alternate shale beds in the lower part (2640m to 2668m) above this sandstone beds were insignificant and dominance of finer clastic siltstone followed by shale was recorded indicating gradual deepening (increase in overall bathymetry). Planktonic foraminifera species *Rotalipora appenninica* were common in many samples in the lower part while *Rotalipora brotzeni* and *R. gandolfii* were also present within 2590m-2868m. The temporal ranges of planktonic foraminifera in this well interval (Figure 4.21) was interesting, while *Rotalipora appenninica* was a planktonic species ranging from last planktonic foraminifera zone (*Rotalipora appenninica* Zone) of Late Albian to part of latest Cenomanian (*Rotalipora cushmani* Zone), the other planktonic foraminifera within the 2590m-2868m interval *Rotalipora brotzeni* was a typical Cenomanian planktonic species also continued till part of *Rotalipora cushmani* zone. The typical index planktonic species *Rotalipora gandolfii* was a typical Early Cenomanian planktonic foraminifer and its Last Appearance at 2610m marked the top of Early Cenomanian in this well. The presence of important planktonic foraminifera above 2610m were *Rotalipora cushmani* and *Praeglobotruncana gibba*. The co-occurrence of these two planktonic species at 2390m and continuous occurrence of *Rotalipora cushmani* an index plankton of late Cenomanian (*Rotalipora cushmani* Zone) conformed the age of the section above the Early Cenomanian top (interval 2610m to 2310m) as Late Cenomanian.

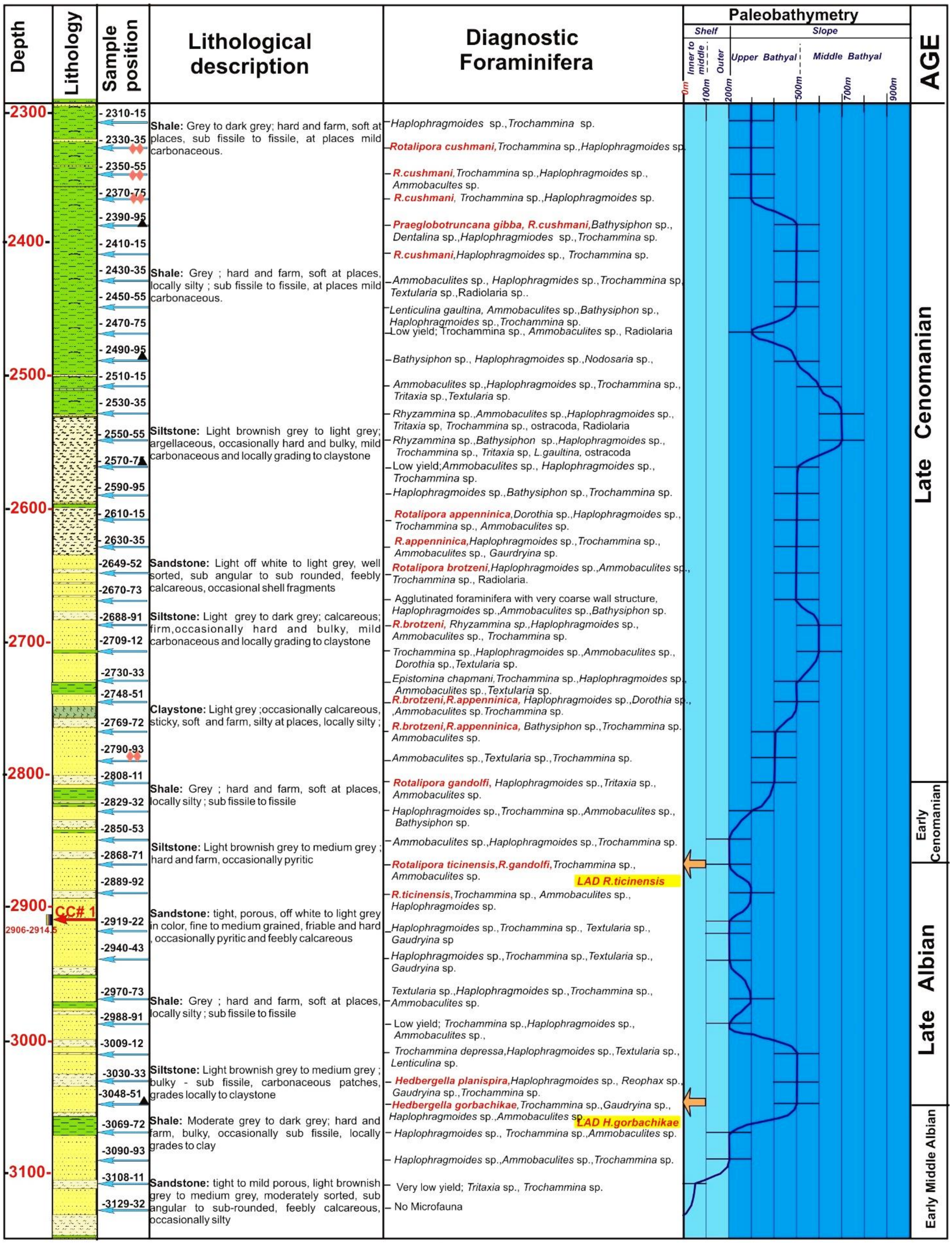


Figure 4.8: Foraminifera assemblage and interpreted paleobathymetry between the interval 2300m – 3150m in well K-A3, Orange Basin, Offshore South Africa.

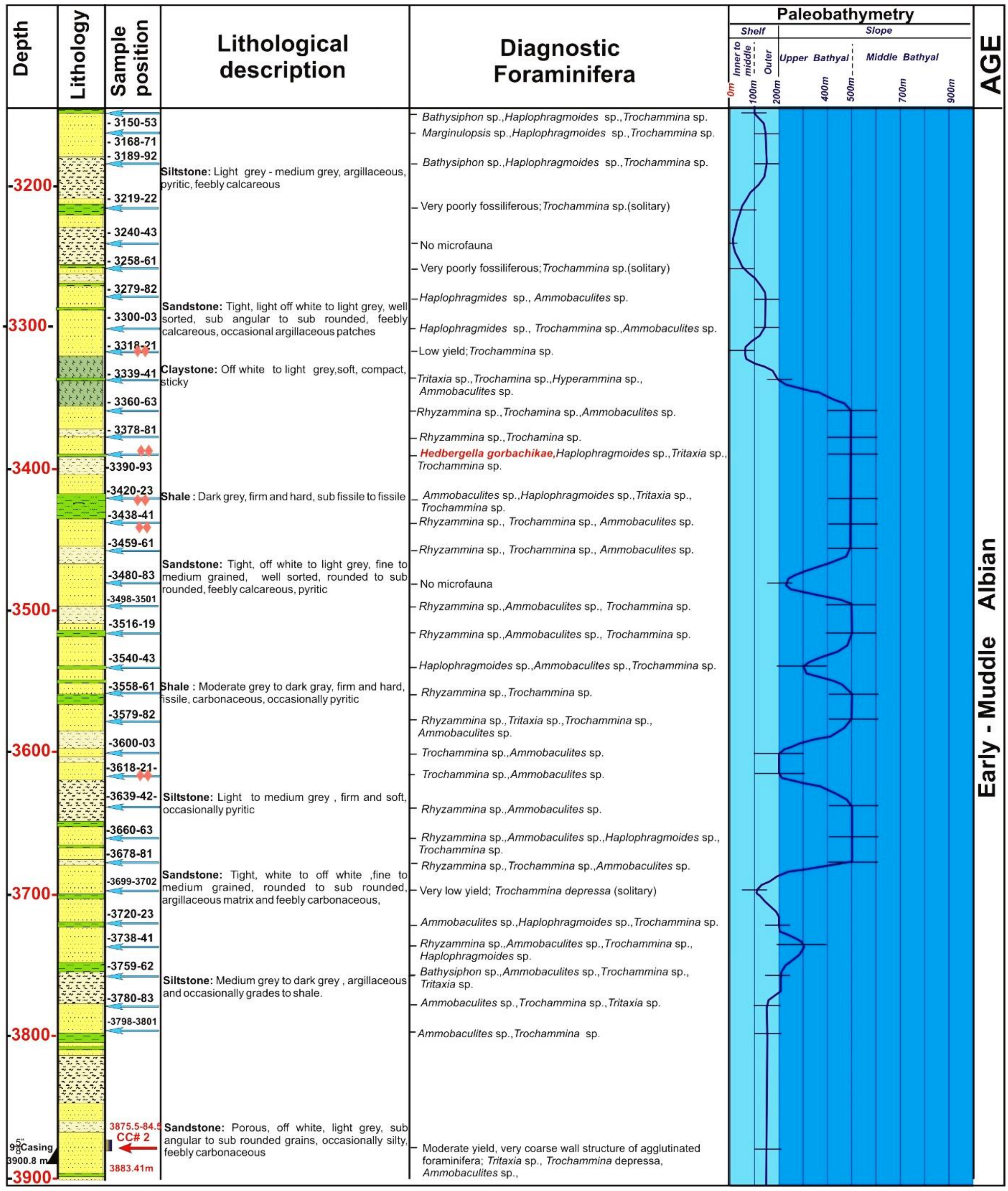


Figure 4.9: Foraminifera assemblage and interpreted paleobathymetry between the interval 3150m – 3900m in well K-A3, Orange Basin, Offshore South Africa.

	FORAMINIFERA ASSEMBLAGE																										
Sample Interval (m)	*Trachammmina deoressa*	*Trochammina* sp.	*Ammobaculites* sp.	*Tritaxia* sp.	*Bathysiphon* sp.	*Rhyzammina* sp.	*Haplophragmoides* sp.	*Gaudryina* sp.	*Reophax* sp.	*Textularia* sp.	*Dorothia* sp.	*Marginulinopsis* sp.	*Lenticulina* sp.	*Lanticulina gaultina*	*Epistommina chapmani*	*Nodosaria* sp	*Dentalina* sp.	*Hedbargella gorbachikae*	*Hedbergella planispira*	*Rotalipora ticinensis*	*Rotalipora gandolfi*	*Rotalipora appenninica*	*Rotalipora brotzeni*	*Rotalipora cushmani*	*Praeglobotruncana gibba*	Radiolaria	Ostracoda
2310-2315		●					●																				
2330-2335		×					●																	×			
2350-2355		×	×				×																	×			
2370-2375		×	×				×																	×			
2390-2395		×	×		×		×							●			×							×	●		
2410-2415		∇	×		●		∇																	×			
2430-2435		×	×				×			×																●	
2450-2455		×	×		●		×							●												●	
2470-2475		●	×																							●	
2490-2495			●		×		×							●		●											
2510-2515		∇	×	×			∇			●																	
2530-2535		●	×	×		×	×																			×	●
2550-2555		×	●	●	×	●	×							●													●
2570-2575		×	×				●																				
2590-2595		×			●		×																				
2610-2615		×	×				×				●											×					
2630-2635		×	×				∇	×														●					
2649-2652		×	∇		×		∇																×			●	
2670-2673			∇		×		∇																			●	
2688-2691		∇	×		●	●	×																●				
2709-2712		∇	×		●		×				●															●	
2730-2733		●	∇				×			×					●												
2748-2751		×	∇				×			×	●											●	●				
2769-2772		×	●		●																	●	●				
2790-2793		×	×	●																							
2808-2811			●				×			●											●						
2829-2832		×	×		×		×																				
2850-2853		●	×				●																				
2868-2871		●	×																	●	●						
2889-2892		●	●				×													●							
2907.03 CC#1	●								●	●																	
2919-2922		●					×	×		●																	
2940-2943		●	×				×	×																			
2970-2973		×	∇				×			●																	
2988-2991		×	●				●																				
3009-3012		×					×			●			●														
3030-3033		×					●	×	×										●								
3048-3051		×	×				×	×										●									

Figure 4.10: Foraminiferal frequency (interval 2310m-3051m), Well K-A3, Orange Basin, Offshore South Africa.

Sample Interval (m)	*Trachammmina deoressa*	*Trochammina* sp.	*Ammobaculites* sp.	*Tritaxia* sp.	*Bathysiphon* sp.	*Rhyzammina* sp.	*Haplophragmoides* sp.	*Gaudryina* sp.	*Reophax* sp.	*Textularia* sp.	*Dorothia* sp.	*Marginulinopsis* sp.	*Lenticulina* sp.	*Lanticulina gaultina*	*Epistommina chapmani*	*Nodosaria* sp	*Dentalina* sp.	*Hedbergella gorbachikae*	*Hedbergella planispira*	*Rotalipora ticinensis*	*Rotalipora gandolfi*	*Rotalipora appenninica*	*Rotalipora brotzeni*	*Rotalipora cushmani*	*Praeglobotruncana gibba*	Radiolaria	Ostracoda
	FORAMINIFERA ASSEMBLAGE																										
3069-3072		×	×				×																				
3090-3093		×	×				×																				
3108-3111		●		●																							
3129-3132						N	O						MICROFAUNA														
3150-3153		●			●		●																				
3168-3171		×					×					●															
3189-3192		×			●		●																				
3219-3222		×																									
3240-3243						N	O						MICROFAUNA														
3258-3261		●																									
3279-3282			×				×																				
3300-3303		●	×				×																				
3318-3321		×																									
3339-3341		∇	∇	×																							
3360-3363		×	×			□																					
3378-3381		●				∇																					
3390-3393		∇	×	×			∇											●									
3420-3423		∇	∇	×			×																				
3438-3441		●	×			□																					
3459-3462		×	∇			□																					
3480-3483						N	O						MICROFAUNA														
3498-3501		×	×			□																					
3516-3519		×	×			∇																					
3540-3543		×	×				●																				
3658-3661		×				∇																					
3679-3682		×	×	×		□																					
3600-3603		×	×																								
3618-3621		●	●																								
3639-3642			×			●																					
3660-3663		×	×			∇	×																				
3678-3681		∇	×			×																					
3699-3702	●																										
3720-3723		×	×				×																				
3738-3741		×	●			●	×																				
3759-3762		×	×	×	●																						
3780-3783		×	×	●																							
3798-3801		×	×																								
3883.41 CC#1	×		×	×																							

Figure 4.11: Foraminifera frequency (interval 3069m-3883.41m), Well K-A3, Orange Basin, Offshore South Africa.

4.4.3 Well K-A2

The exploratory well K-A2 was drilled to explore the Lower/ Early Cretaceous prospect at a level of the 13At1 reflector. The well is located SW of borehole K-A3. The prospects drilled in this location finally penetrated tight, water saturated, channel fill sandstone reservoirs. The well was drilled to a depth of 5829.7m and the rig was released with a status of well with poor gas shows (Soekor, 1991). The information regarding the approximate depths of seismic horizons (unconformity surfaces) within the drilled interval are 15At1 (Late Cenomanian) at 2355m, $14B_2t1$ (Early Cenomanian) at 2740m, 14Bt1 (Late Albian) at 3300m, 14At1 (Early Albian) at 3910m and 13At1 (Early Aptian top) at 5343m respectively.

Two conventional cores viz. CC#1, interval 3982.1m-3991.85m (99% recovery) and CC#2, interval 4076.1m-4083.1m (79% recovery) were available for analysis. Well cutting samples for the interval 3479m to 5790 m were only available for detail biostratigraphic analysis. Lithologically many samples were highly arenaceous (dominated by sandstone lithology). A total of 88 selected cutting samples and 10 core pieces (4 from CC#1 and 6 from CC#2) were processed in the laboratory. The samples from argillaceous units within the major reservoir intervals were studied in detail. Samples below 5790m were not available for examination. Within the total studied interval several samples were dominated by 100% sand and most of them were devoid of microfossils. Moreover, presence of ferruginous particles as well as pyritised anoxic intervals were also noticed at several places. The integrated litho-biostratigraphic details are shown in Figures 4.12, 4.13 and 4.14 respectively and samples wise distribution of microfossils are presented in Figures 4.15 and Fig 4.16.

4.4.3.1. Biostratigraphic analysis and results

Temporal distribution of foraminifera

As discussed in the previous paragraphs, the examined well section was highly dominated by arenaceous units (very tight sandstone and siltstone) with minor shaly beds and few calcareous lenses. Oxidised material (mainly in sand or siltstone samples) were extremely common indicating frequent short term near exposure /diastem surfaces. Presence of pyritised foraminifera as well as dark anoxic patches were also present in the studied section.

The lower part (Figure 4.12 and Figure 4.13)of the studied interval 4980m-5790m was a tight siltstone dominated interval with frequent presence of thick sandstone. Very thin calcareous bands and rare shaly units were also present. Frequent red coloration in these arenaceous unit as well as presence of shallow water agglutinated foraminifera in very small frequency was characteristic for this entire interval. The overall agglutinated frequency, assemblage characters along with the lithology suggested a relatively shallow water deposition with minor fluctuations at a few intervals. No age diagnostic foraminifera were recorded from this interval. The thirteen well cuttings analysed indicated that agglutinated foraminifera with low frequency and diversity were present in eight samples while five samples were devoid of any microfossil (Figure 4.15). No planktonic and calcareous benthic foraminifera were recorded in this interval. The agglutinated foraminifera with low frequency included *Haplophragmoides* sp., *Trochammina* sp., *and Ammobaculites* sp. with rare presence of *Saccammina* sp., *Bathysiphon* sp. and *Rhyzammina* sp.

The overlying interval 4098m-4980m was lithologically similar with the lower interval discussed above with dark grey to grey siltstone, at places argillaceous and frequent presence of disseminated pyrite (at 4920m-4980m and 4659m-4773m) was recorded. Foraminifera and other microfossils present in these intervals were also quoted with pyrite indicating an anoxic condition. Oxidised layers are common (4440m -4491m and in a few places in the younger interval (Figure: 4.12 and 4.13). Most of these oxidised intervals were devoid of microfauna or were characterized by poor faunal frequency indicating very shallow condition of deposition or close to a possible unconformity surface. The entire studied section although was not very rich in foraminifera but overall agglutinated foraminiferal diversity and frequency was much better than the underlying section already discussed. Samples from 27 intervals (including CC#2) were examined in which 4 samples were found to be devoid of foraminifera (Figure 4.16). The bottom part of the interval 4869m-4959m dominance of *Rhyzammina* sp. along with *Haplophragmoides* sp., and *Bathysiphon* sp. indicated an increase in bathymetry to uppermost upper bathyal condition but above this a sudden fall in the bathymetry was also observed. Above 4710m the agglutinated assemblage was dominated by *Ammobaculites* sp. and *Haplophragmoides* sp. with less frequent *Trochammina* sp., *Bathysiphon* sp., *Saccammina* sp. and solitary radiolarian test. The deposition took place in quite shallow water environment possibly in outer shelf position. Many of these unfossiliferous or poorly fossiliferous intervals were characterized by red oxidised clastic grains indicating shallow condition in a marginal to inner shelf environment. The shallow to upper bathyal fluctuating continued within this interval from the underlying interval as revealed by the faunal composition.

The uppermost interval 3450m-4098m lithology was again dominated by argillaceous siltstone but in the lower part good development of sandstone units were highly visible (Figure 4.12). The two conventional cores (CC#2, 4076.1m-4083.1m, 79% recovery with siltstone/silty sale in the bottom and sand in the top; CC#1, 3982.1m-3991.85m, 99% recovery with mainly sandstone and very minor siltstone/shale lenses) were obtained from this uppermost interval. Due to highly arenaceous (mainly massive sandstone units) nature of the lower part within this interval the faunal recovery was extremely poor between 3888m-4098m in all 17 processed samples. Eleven samples were found to be devoid of any foraminifera and poor foraminifera recovery including the samples from the two conventional cores. Frequent presence of oxidised and ferruginous layers indicates shallow depositional condition and an unconformity just below the base of the first conventional core (CC#1). *Haplophragmoides* sp., *Ammobaculites sp*., occasional *Trochammina* sp., rare *Bathysiphon* sp. and *Rhyzammina* sp. were recorded. The low foraminifera frequency, occasional oxidised layer and lithology indicated a shallow water depositional environment within inner to middle shelf position.

Above 3888m, the interval till the highest sample depth at 3479m the lithology was dominated by argillaceous siltstone. Minor shale and sandy units were present, but overall faunal frequency suggested an increase in water depth due to rising sea level. A total of 5 samples (out of 31 processed samples) within this interval were found to be devoid of foraminifera. The only planktonic foraminifera species was recorded between 3772m-3864m. Lower part of this interval between 3772m and 3864m yielded only planktonic foraminifera in rare occasion (Figures 4.12 and 4.13). The co-occurrence of *Rotalipora subticinensis* and *Ticinella primula* at 3861m- 3864m suggests this sample interval was within the middle / late Albian stage (*Rotalipora subticinensis* Zone). The other two records of planktonic foraminifera viz. *Globigerinoides bentonensis* and *Hedbergella planispira* were long ranging planktons not much helpful to demarcate stage boundaries. Presence of *Rhyzammina* sp., *Bathysiphon* sp., *Hyperammina* sp. and *Haplophragmoides* sp. along with these planktons suggested a deepening of sea towards upper bathyal condition. Above this interval agglutinated foraminifera *Rhyzammina* sp. was common in several consecutive sample intervals. Presence of this agglutinated foraminifera was indicative of a deeper bathymetry within upper bathyal (slope, mostly more than 400m).

Age: As discussed above, presence of age diagnostic planktonic foraminifera was rare in well K-A2. The only important planktonic foraminifera assemblages *Rotalipora subticinensis* and *Ticinella primula* were recorded from samples of 3861m-3864m interval suggests Middle to Late Albian age. Above this interval although two other planktonic foraminifera viz. *Hedbergella plaispira* and *Globigerinoides bentonensis* were recorded, both are long ranging planktonic species and are not much helpful in assigning age boundaries.

Data available from Unpublished Well Report (Soekor, 1991) indicated that the Seismic Horizon 14Bt1 (Late Albian top) was at 3300m depth in well K-A2. This was much above the highest sample interval studied in this well. Based on the planktonic assemblage co-occurrence of *Ticinella primula* and *Rotalipora subticinensis* (at 3861m-3864m) the entire interval from 3910m (seismic marker 14At1) to 3450m section was placed within Middle to Late Albian sub-stage in this well.

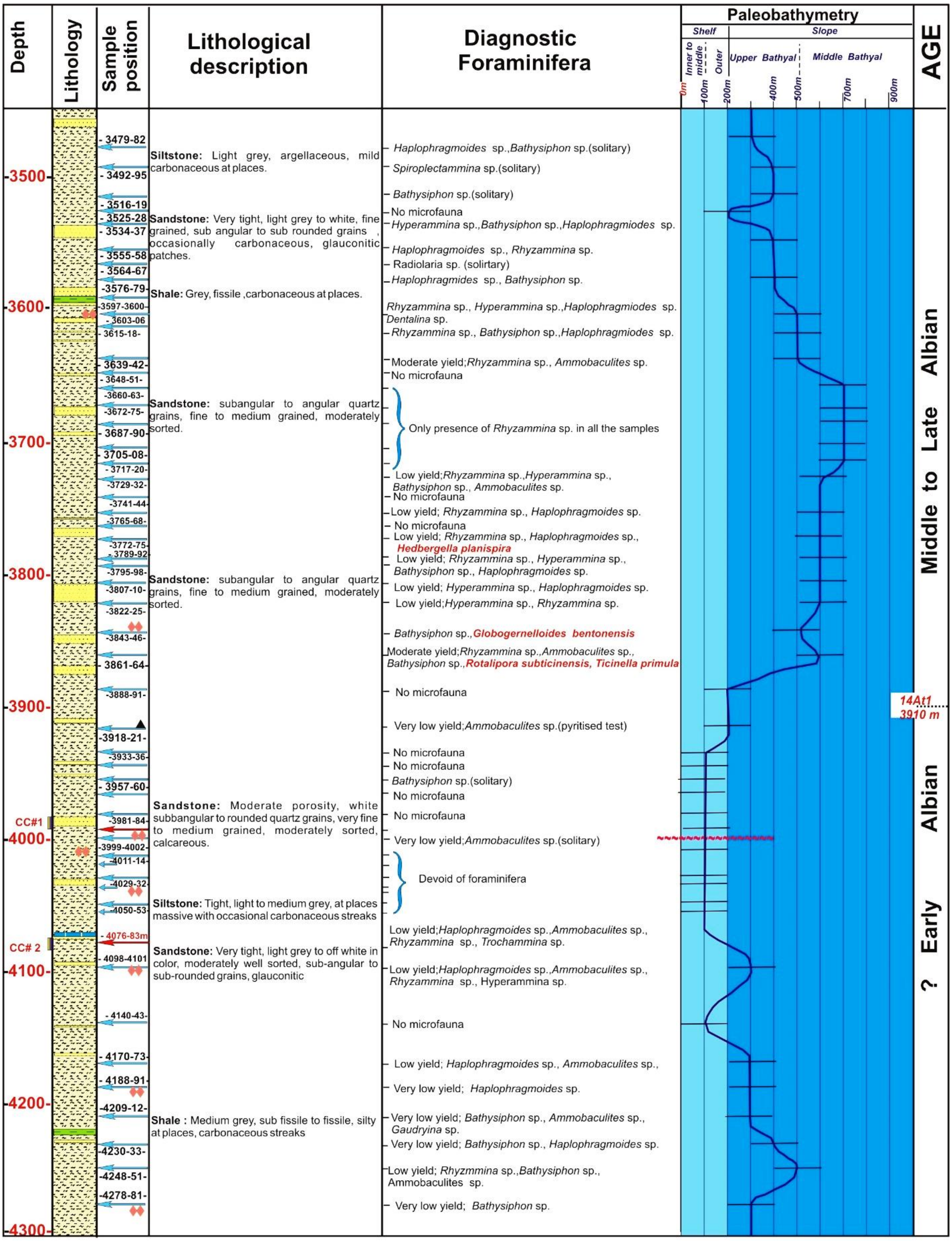


Figure 4.12: Foraminifera assemblage and interpreted paleobathymetry between the interval 3450m – 4300m in well K-A2, Orange Basin, Offshore South Africa.

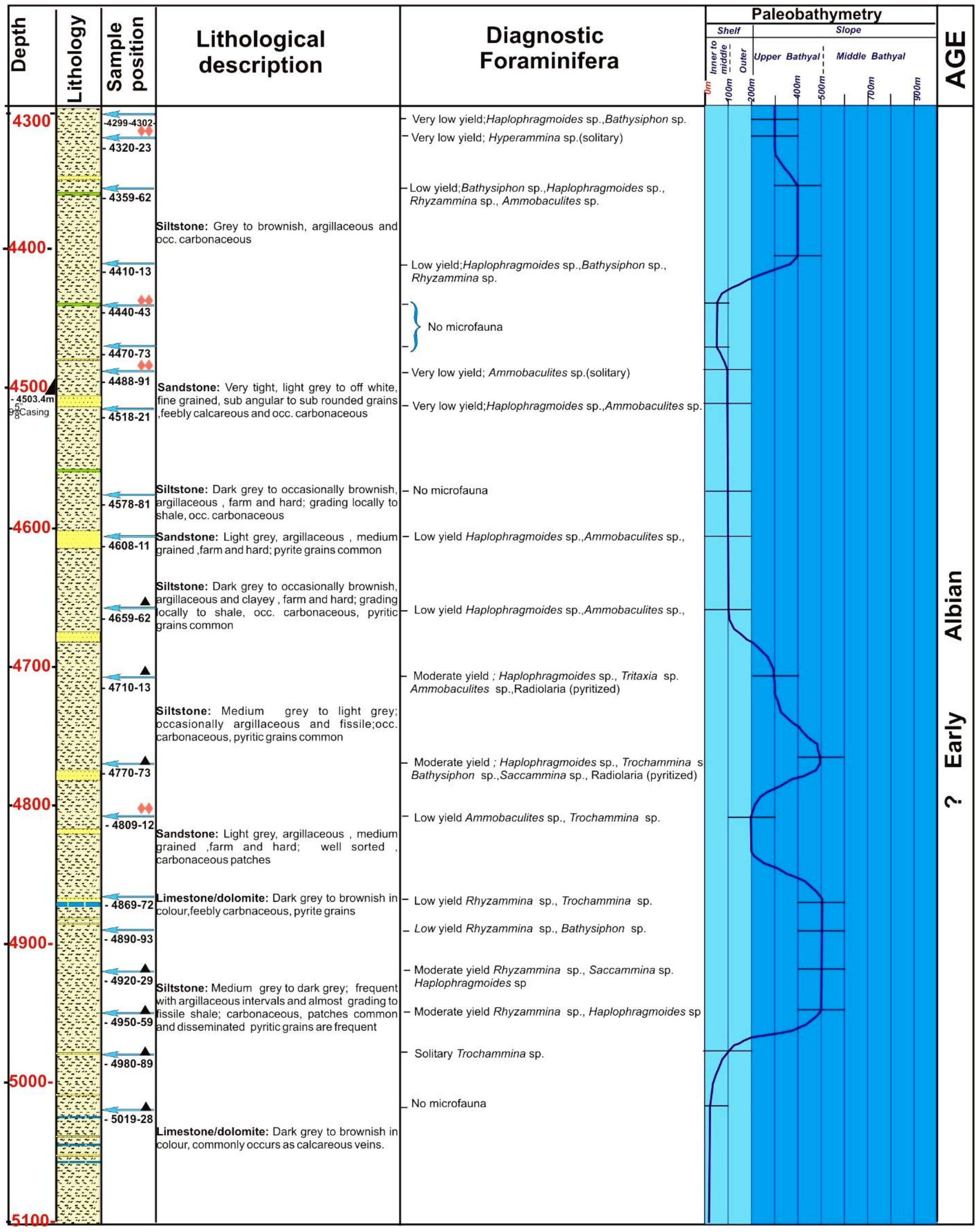


Figure 4.13: Foraminifera assemblage and interpreted paleobathymetry between the interval 4300m – 5100m in well K-A2, Orange Basin, Offshore South Africa.

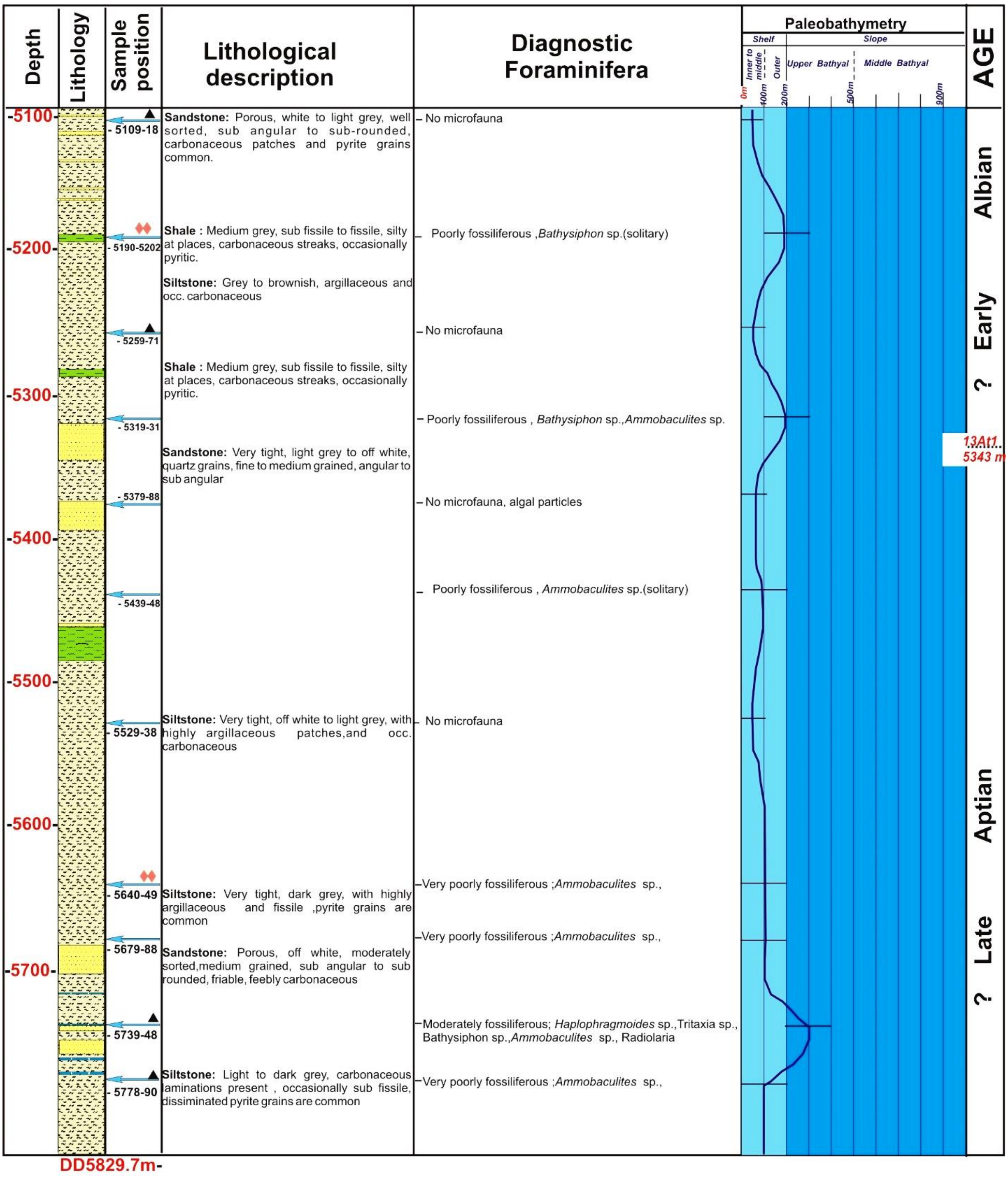


Figure 4.14: Foraminifera assemblage and interpreted paleobathymetry between the interval 5100m – 5790m in well K-A2, Orange Basin, Offshore South Africa.

									FORAMINIFERA ASSEMBLAGE							
Sample Interval (m)	*Haplophragmoides* sp	*Bathysiphon* sp.	*Saccammina* sp.	*Trochammina* sp.	*Ammobaculites* sp.	*Rhizammina* sp.	*Tritaxia* sp.	*Hyperammina* sp.	*Gaudryina* sp.	*Spiroplectammina* sp.	*Dentalina* sp.	*Rotalipora subticinensis*	*Ticinella primula*	*Globogerinoides bentonensis*	*Hedbergella planispira*	Radiolaria
3479-3482	×	×														
3492-3495										●						
3516-3519		●														
3525-3528		N	O			M	I	C	R	O	F	A	U	N	A	
3534-3537	●	●						×								
3555-3558	×					●										
3564-3567																●
3576-3579	×	●														
3585-3588	●	●														
3597-3600	×					×		V			●					
3603-3606	×	●				●		×								
3615-3618	●	●				×										
3618-3621						●										
3639-3642					●	□										
3648-3651	N	O			M	I	C	R	O	F	A	U	N	A		
3660-3663						×										
3672-3675						×										
3687-3690						×										
3705-3708						×										
3717-3720						●										
3729-3732		●			●	×		×								

Sample Interval (m)	*Haplophragmoides* sp	*Bathysiphon* sp.	*Saccammina* sp.	*Trochammina* sp.	*Ammobaculites* sp.	*Rhizammina* sp.	*Tritaxia* sp.	*Hyperammina* sp.	*Gaudryina* sp.	*Spiroplectammina* sp.	*Dentalina* sp.	*Rotalipora subticinensis*	*Ticinella primula*	*Globogerinoides bentonensis*	*Hedbergella planispira*	Radiolaria
3741-3744		N	O			M	I	C	R	O	F	A	U	N	A	
3753-3756	●					×										
3765-3768		N	O			M	I	C	R	O	F	A	U	N	A	
3772-3775	×					∇									●	
3777-3780	●					×										
3789-3792	●	●				×		●								
3795-3798	N	O			M	I	C	R	O	F	A	U	N	A		
3807-3810	×							×								
3822-3825						×		×								
3843-3846		●												●		
3861-3864		×			×	×						●	●			
3888-3891	N	O			M	I	C	R	O	F	A	U	N	A		
3918-3921					×											
3933-3936	N	O			M	I	C	R	O	F	A	U	N	A		
3942-3945	N	O			M	I	C	R	O	F	A	U	N	A		
3957-3960		●														
3966-3969	N	O			M	I	C	R	O	F	A	U	N	A		
3981-3984	N	O			M	I	C	R	O	F	A	U	N	A		
3993-3996					●											
CC#1	●				●											
3999-4002					●											

Figure 4.15: Foraminiferal frequency (interval 3479m-4002m), Well K-A2, Orange Basin, Offshore South Africa.

F O R A M I N I F E R A A S S E M B L A G E																
Sample Interval (m)	*Haplophragmoides* sp	*Bathysiphon* sp.	*Saccammina* sp.	*Trochammina* sp.	*Ammobaculites* sp.	*Rhyzammina* sp.	*Tritaxia* sp.	*Hyperammina* sp.	*Gaudryina* sp.	*Spiroplectammina* sp.	*Dentalina* sp.	*Rotalipora subticinensis*	*Ticinella primula*	*Globogerinoides bentonensis*	*Hedbargella planispira*	Radiolaria
4011-4014		N	O			M	I	C	R	O	F	A	U	N	A	
4017-4020																
4029-4032		N	O			M	I	C	R	O	F	A	U	N	A	
4035-4038																
4050-4053		N	O			M	I	C	R	O	F	A	U	N	A	
4053-4056																
CC#2	×			•	•	•										
4098-4101	×				•	•		•								
4140-4143		N	O			M	I	C	R	O	F	A	U	N	A	
4170-4173	×				•											
4188-4191					•											
4209-4212		•			•				•							
4230-4233	•	•														
4248-4251		•			×	×										
4278-4281		•														
4299-4302	×	•														
4320-4323								×								
4359-4362	×	×			×	×										
4410-4413	×	×				•										
4440-4443		N	O			M	I	C	R	O	F	A	U	N	A	
4470-4473		N	O			M	I	C	R	O	F	A	U	N	A	
4488-4491					•											
4518-4521	•				•											
4578-4581		N	O			M	I	C	R	O	F	A	U	N	A	
4608-4611	×				•											
4659-4662	×				•											
4710-4713	×				•		•									•
4770-4773	∇	•	•	×												
4809-4812				•	•											
4869-4872				×		×										
4890-4893		×				∇										
4920-4929	×		•			∇										
4950-4959	×					∇										
4980-4989				•												
5019-5028		N	O			M	I	C	R	O	F	A	U	N	A	
5109-5118		N	O			M	I	C	R	O	F	A	U	N	A	
5190-5202		•														
5259-5271		N	O			M	I	C	R	O	F	A	U	N	A	
5319-5331		•			•											
5379-5388		N	O			M	I	C	R	O	F	A	U	N	A	
5439-5448					•											
5529-5538		N	O			M	I	C	R	O	F	A	U	N	A	
5640-5649					×											
5679-5688				×		×										
5739-5748				•	•											
5778-5790	×	•	•	×												×

Figure 4.16: Foraminiferal frequency (interval: 4011m-5790m), Well K-A2, Orange Basin, Offshore South Africa.

4.4.4 Well K-H1

The exploratory wildcat well K-H1 is the southern most of the four offshore wells used in the present work. The well was spudded in 342m water depth (New, 1989) and was drilled to a depth of 4268m. The prime objective to drill this well was to explore hydrocarbons stratigraphically trapped within a sequence of prograding low strand system tracts in the Early Albian. The well however, did not encounter any significant reservoir and was finally released as a dry well.

As per information available in the well completion report of K-H1, the Albian-Cenomanian boundary is marked at 3248m and below this up to the drilled interval the succession was placed under Albian stage. This is the first Exploratory well drilled in the central Orange Basin and is the first test well on Seismic Stratigraphy Modelling in this area.

Only one conventional core, CC#1, interval 3066m-3082.7m (98% recovery) was cut in this well. Selected pieces of the conventional core and well cutting samples for the interval 2729m to 3923m were available for detail biostratigraphic analysis. No samples between siltstone rich 3685m-3785m interval (100m) and 3082m-3188m (106m) were available analysis. Therefore, the interpretation of paleobathymetry within these intervals were mainly based on lithological characters as recorded in the well completion reports. A total of 50 selected samples including the cored interval were processed for foraminiferal biostratigraphic studies in this well. The samples from argillaceous units within the major reservoir intervals were studied in detail. Samples below 3923 m were not available for examination. The lower part of the studied interval between 3200m-3923m (Figure 4.17), arenaceous lithology (mainly argillaceous siltstones and minor sand units were dominant with argillaceous claystone units. Above 3200m till the highest sample at 2717m claystone units were more frequent. All the samples were found to be rich in microfauna comprising of agglutinated, calcareous benthic (mainly in the upper claystone rich interval) and planktonic foraminifera. Disseminated pyrite grains and microfossils were common in the upper clay rich interval (Figure 4.18).

4.4.4.1. Biostratigraphic analysis and results:

Temporal distribution of foraminifera

The integrated litho-biostratigraphy details are shown in Figures 4.17 and 4.18 and the sample wise distribution of microfossils are presented in Figures 4.19 and 4.20 respectively . The lower part of the well section between 3300m and 3923m is lithologically dominated by thick siltstone units and relatively thin sandstone beds. The siltstone lithology was mainly medium grey to slightly dark grey in colour, occasionally olive- green siltstone units were also present. The siltstones were soft, mostly friable, and non-calcareous. Oxidised red coloration or pyritised intervals were absent. The sandstone beds were relatively thin, mostly white to light grey, fine grained and grading to siltstone in most intervals. The relatively less dominant argillaceous lithology comprised of soft and sticky, grey to dark brownish grey claystones rich in microfauna.

Agglutinated foraminifera were common in the lowest interval (3617m -3923m) and calcareous benthics were totally absent. Planktonic foraminifera of typical Albian stage were present within this interval. The agglutinated foraminiferal assemblage comprised of thick walled *Haplophragmoides* sp., *Rhyzammina* sp., *Bathysiphon* sp. and *Ammobaculites* sp. Presence of *Saccammina* sp., *Textularia* sp. and *Trochammina* sp. were also present in a few samples within this interval. Presence of many planktonic foraminifera were recorded (Figure

4.20) and many are typical Albian foraminifera. *Favusella washitensis*, *Ticinella primula*, *Rotalipora ticinensis*, *Rotalipora subticinensis*, and *Hedbergella planispira* all these planktonic foraminifera were confined within this interval. The lowest downhole occurrence of *Rotalipora appenninica* also co-occur with *Hedbergella planispira* at sample interval 3879m-3685m. Above this interval no planktonic foraminifera was recorded until 3653m depth. The lithology was mainly siltstone. However, the same agglutinated foraminifera assemblage was found to be present indicating an upper slope (~ 600m) depositional environment. The rest of the interval from 3300m and 3653m was almost similar in lithology with dominating siltstone /minor sandstone and few dark grey claystone units. Apart from agglutinated foraminifera viz. *Rhyzammina* sp., *Bathysiphon* sp., *Haplophragmoides* sp. (thick walled) and *Saccamina* sp. were common. In a few sample intervals presence of *Dorothia* sp., *Textularia* sp. and rare *Tritaxia* sp. was also recorded. Calcareous benthics which are virtually absent in the lower section already discussed made their appearance for the first time. They are represented by *Lenticulina angulosa* and *Gavelinella* sp., *Dentalina* sp. and *Lagena* sp. Most of these calcareous benthics are indicative of upper bathyal environment. Also, for the first-time other microfossils like Radiolaria and ostracoda appeared in samples from this interval. Two important planktonic foraminifera *Rotalipora appenninica* (Last appearance datum) and *Rotalipora gandolfii* were present in this interval indicating Early Cenomanian stage.

The uppermost section between 2700m to 3300m is dominated by claystone but frequent presence of argillaceous siltstone and sandstones was also common (Figure 4.17). The only conventional core CC#1, Interval 3066m-3082.7m (98% recovery) was from this section. Unlike the lower section (Albian) anoxic claystone/ argillaceous siltstone were frequent in this section. The overall lithology in the post Albian clay dominated interval and its foraminifera content suggests a deeper bathymetry.

Agglutinated foraminifera particularly deep bathymetry indicator microfauna were extremely common in this section. *Rhyzammina* sp., *Bathysiphon* sp., *Haplophragmoides* sp. were dominant particularly in the claystone lithology. *Hyperammina* sp., *Ammobaculites* sp. and less frequent *Dorothia* sp., *Textularia* sp. and *Reophax* sp. were also present. Among the calcareous benthics *Gavelinella* sp. and *Lenticulina angulosa* and *Nodosaria* sp. and *Gyroidina* sp. were also common in several samples. Ostracoda (smooth walled) and radiolarian test were frequent in these samples.

Typical age diagnostic and planktonic zone marker foraminifera species were recorded in this interval. They were represented by *Rotalipora appenni*nica, *R. gandolfii, R. brotzeni, R. reicheli, Praeglobotruncana delrioensis* and *Helvetoglobotruncana praehelvetica*. Most of these forms were helpful to demarcate the sub-stages within Cenomanian as discussed below.

Age: Presence of planktonic foraminifera were recorded from a number of intervals in the well K-H1. Their frequency per sample was not very good but, they were important in dating the succession.

In the lower part of the studied interval between 3679m to 3923m presence of planktonic foraminifera was very common. However, no samples between 3685m to 3785m (100m span) were available for analysis. The only planktonic foraminifera from the two samples at 3917m-3923m and 3911m-3917m has yielded *Favusella washitensis* a typical Early Cretaceous (Albian marker species). *Favusella washitensis* appeared in the Lowest Albian planktic zone (*Ticinella primula* Zone) and continued until the Middle Cenomanian (*Rotalipora reicheli* Zone). In South African basins *Favusella washitensis* first appeared in Middle - Albian (McMillan, 2003, p.558). Above this interval the presence of *Ticinella primula* and *Rotalipora ticinensis* and *Rotalipora appenninica* was recorded in a few samples while the 100m interval from where no samples were available for analysis. While *Ticinella primula* is an Early to Middle Albian planktonic species (*Ticinella primula* Zone to *Rotalipora ticinensis* zone) the other planktonic element *Rotalipora ticinensis* ranged between (*Rotalipora ticinensis* zone and *Rotalipora appenninica* zone (Middle to Late Albian substages). The co-occurrence of *Rotalipora ticinensis* and *Rotalipora appenninica* at 3679m-3685m marked the Late Albian top in this well. Due to non-availability of continuous samples the top of Albian was tentatively marked at 3679m in this well and the entire section below this placed within the Middle to Late Albian age.

Above 3679m presence of planktonic foraminifera were recorded in a few samples. *Rotalipora appenninica* continued from the lower Late Albian section (3588m-3591m) till 2981m-2987m sample position. However, *Rotalipora appenninica* was a relatively long ranging planktonic foraminifera which continued from Late Albian *Rotalipora appenninica* zone to part of highest planktonic *Rotalipora cushmani* zone of Cenomanian stage. Therefore, presence of this planktonic species alone was not sufficient to assign stage or zonal position in stratigraphy. Within the same marine section other important planktonic foraminifera were also recorded. Presence of *Rotalipora gandolfii* an index species of Early Cenomanian at 3323m-3329m indicated the entire interval between 3323m to 3679m belongs to Early Cenomanian age. Similarly, the presence of *Rotalipora brotzeni* in the only conventional core (CC#1) at 3080.58m provided an indication of the middle part of Cenomanian. This was further confirmed by the record of another middle Cenomanian index planktonic foraminifera *Rotalipora reicheli*. Due to non-availability of well cuttings of about 116m argillaceous siltstone and claystone interval just below the Conventional core (3082m -3188m) and absence of planktonic foraminifera in the interval 2798m and 2963m precise determination of boundaries between early and middle and the top of middle Cenomanian could not be established. Above 2963m to the youngest studied interval 2729m-2735m the claystone dominant section showed the presence of typical last Cenomanian planktonic assemblage comprised of *Rotalipora cushmani*, *Praeglobotruncana delrioensis* and *Helvetoglobotruncana praehelvetica* all have common occurrence in the *Rotalipora cushmani* zone of Late Cenomanian.

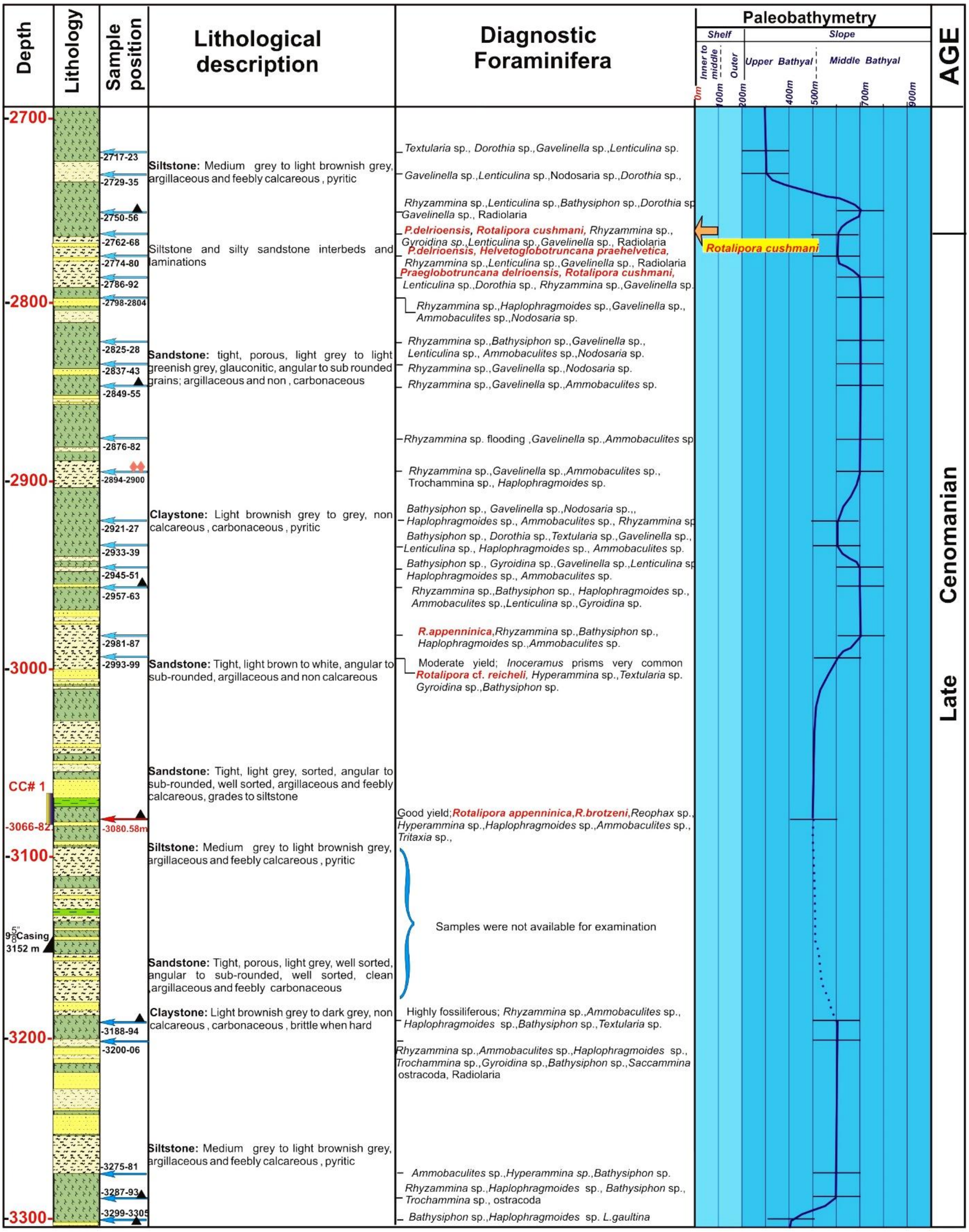


Figure 4.17: Foraminifera assemblage and interpreted paleobathymetry between the interval 2700m – 3300m in well K-H1, Orange Basin, Offshore South Africa.

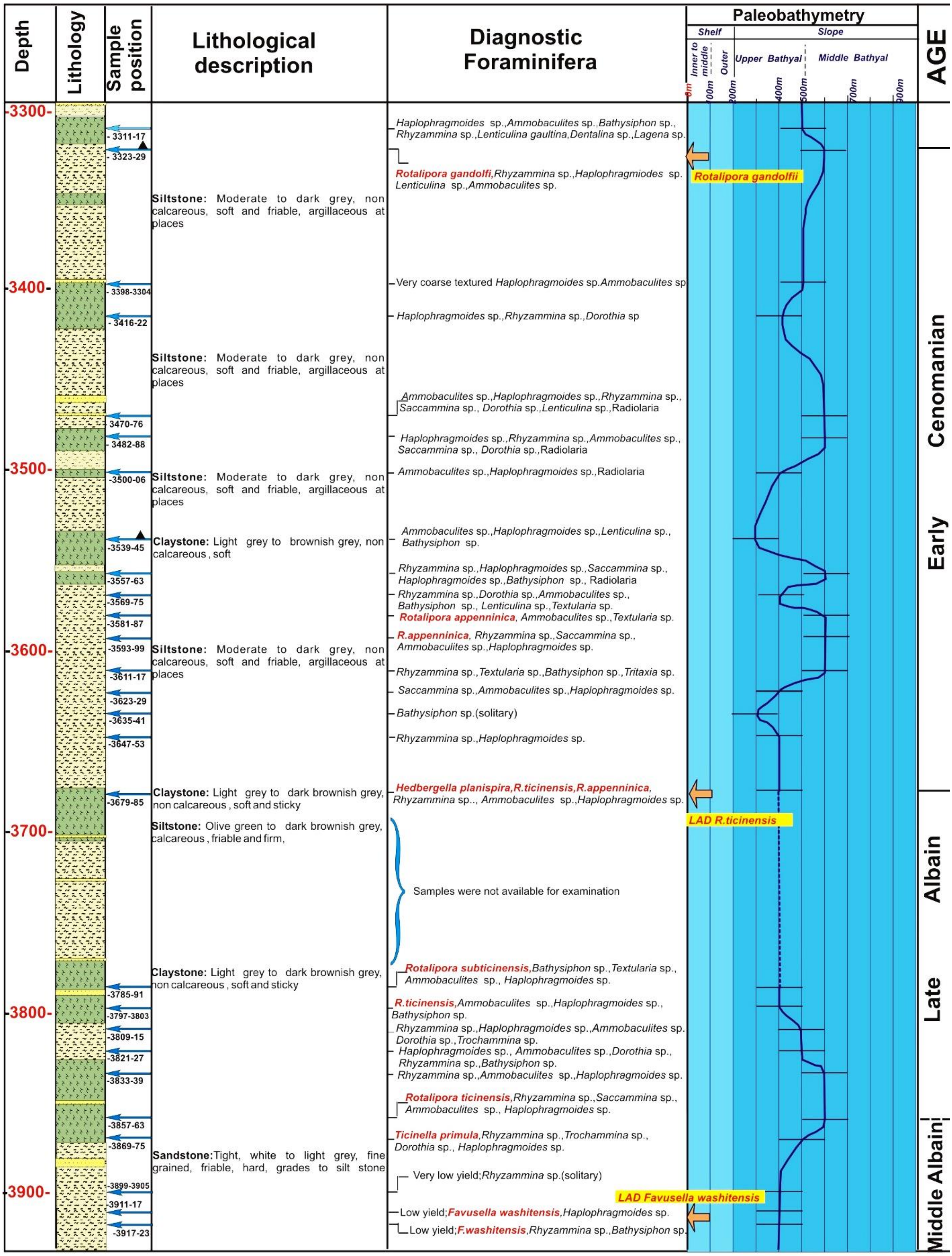


Figure 4.18: Foraminifera assemblage and interpreted paleobathymetry between the interval 3300m – 3923m in well K-H1, Orange Basin, Offshore South Africa.

	FORAMINIFERA ASSEMBLAGE																																
Sample Interval (m)	*Rhyzammina* sp.	*Bathysiphon* sp.	*Haplophragmoides* sp.	*Trochammina* sp.	*Dorothia* sp.	*Ammobaculites* sp.	*Saccammina* sp.	*Textularia* sp.	*Tritaxia* sp.	*Hyperammina* sp.	*Reophax* sp.	*Gavelinella* sp.	*Lenticulina angulosa*	*Dentalina* sp.	*Lagena* sp.	*Gyroidina* sp.	*Nodosaria* sp.	*Favusella washitensis*	*Ticinella primula*	*Rotalipora ticinensis*	*Rotalipora subticinensis*	*Hedbergella planispira*	*Rotalipora appeninnica*	*Rotalipora gandolfi*	*Rotalipora brotzeni*	*Rotalipora reicheli*	*Rotalipora cushmani*	*Praeglobotruncana delrioensis*	*Helvetoglobotruncana praehelvetica*	Ostracoda	Radiolaria	Microgastropods	Scaphopods
2729-2735					●							×	●				×																
2750-2756	□	×			×							∇	∇																	×			
2762-2768	×											×	●			×											●	●		●	×		
2774-2780	×											∇	×															●	●	×			
2786-2792	∇				●							×	×				×										●	×		×			
2798-2801	□		∇			×						×					●																
2825-2828	□	●				×						∇	×				×																
2837-2843	□											×					×																
2849-2855	∇					●						×																					
2876-2882	□					×						×																		●			
2894-2900	□		×	●		●																											
2921-2927	×	×	×			×						∇					×																
2933-2939	×	×	×		×	×		●				×	×																	×			
2945-2951			∇			×						×	×			∇														×	×		
2957-2963	□	×	∇			×							×			×																	
2981-2987			×			×																	●							×	×		
2993-2999	×	×						×		×						●										●				×	×		
CC#1			∇			×			×	×	×												●		●								
3188-3194	□	×	×			×		×																									
3200-3206	×		×	×		×	●									×														×	×		
3275-3281	×	×	×	×		×																								×			
3287-3293	×							×		×			×	×																×	□		×
3299-3305		×	×			×								●																×	×		
3311-3317	×	×	×	×		×							×	×	×																	●	
3323-3329	×		×			×							×											●									

Figure 4.19: Foraminiferal frequency (interval 2729m-3329m), Well K-H1, Orange Basin, Offshore South Africa.

	FORAMINIFERA ASSEMBLAGE																																
Sample Interval (m)	*Rhyzammina* sp.	*Bathysiphon* sp.	*Haplophragmoides* sp.	*Trochammina* sp.	*Dorothia* sp.	*Ammobaculites* sp.	*Saccammina* sp.	*Textularia* sp.	*Tritaxia* sp.	*Hyperammina* sp.	*Reophax* sp.	*Gavelinella* sp.	*Lenticulina angulosa*	*Dentalina* sp.	*Marginulina* sp.	*Gyroidina* sp.	*Nodosaria* sp.	*Favusella washitensis*	*Ticinella primula*	*Rotalipora ticinensis*	*Rotalipora subticinensis*	*Hedbergella planispira*	*Rotalipora appeninnica*	*Rotalipora gandolfi*	*Rotalipora brotzeni*	*Rotalipora reicheli*	*Rotalipora cushmani*	*Praeglobotruncana delrioensis*	*Helvetoglobotruncana praehelvetica*	Ostracoda	Radiolaria	Ostracoda	Scaphopods
3398-3404			×			×																											
3416-3422	×		×		●																												
3470-3476	∇		×		●	∇	×						●																		●		
3482-3488	×		∇		●	×	●																								×		
3500-3506			×			×																									●		
3539-3545		●	×			∇							●																				
3557-3563	×	●	∇			●	●																								×		
3569-3575	×	●			●	∇		×					×																	●			
3581-3587						×																	●	×									
3593-3599	●		●			●	●																										
3611-3617	∇	×	×	×		∇		×	×			●																					
3623-3629		×	×			×																											
3635-3641			●																														
3647-3653	×		×																														
3679-3685	×		×			●														●		●	●										
3785-3791		●	×			×		●													●												
3797-3803		×	●			×														●													
3809-3815	×	●	×	×	×		∇																										
3821-3827	●	●	∇		×	×																											
3833-3839	●		●			●																											
3857-3863	×		●			×	●													●													
3869-3875	●		×	×	●														●														
3899-3905	●																																
3911-3917			×															●															
3917-3923	×	●																●															

Figure 4.20: Foraminiferal frequency (interval 3398m-3923m), Well K-H1, Orange Basin, Offshore South Africa

4.5 DISCUSSION ON BIOSTRATIGRAPHY THE STUDIED WELL SECTIONS

The Orange Basin is the largest among the seven basins of South Africa. This basin lies on the Atlantic margin of South Africa and southern Namibia. It is considered as the most energetic among the seven basins (McMillan, 2003) as it has received the majority of sediments by drainage of interior of southern Africa in Cretaceous period (Late Barremian to

Early Campanian stage). Study of several researchers (Gerrard and Smith, 1982; Munting, 1993; Board and Mills, 1993; Dale and McMillan, 2003 and others) suggests that except for the Kudu area located in the North West side of Orange Basin, the drift sedimentation mostly began 1 million years after the KwaZulu Basin (located along the east coast) and about 3.5 million years after those of Bredasdrop and Pletmos basins located in the South. The Orange Basin is the only basin which has received sediments twice as thick as the contemporary equivalent of the six other basins during the Late Barremian to Early Campanian sediments (McMillan, 2003) due to rapid sediment input.

In the current work none of the wells penetrated the deeper part of early Cretaceous succession. Presence of definite Aptian stage sediments were not found in any of the four wells. The reservoir intervals were dated between Albian (Early Cretaceous) and the younger Cenomanian (Late Cretaceous) sediments. A broad stratigraphic correlation based on the present study is shown in Figure 4.22. The age/stage boundaries are based on the standard planktonic index foraminifera identified in this research. In the absence of index planktonic foraminifera the stage boundaries in the Late Aptian and Early Albian in well K-A2 were marked on the basis of interpreted seismic marker. The ranges of various diagnostic planktonic foraminifera recorded in this work are shown in Figure 4.21.

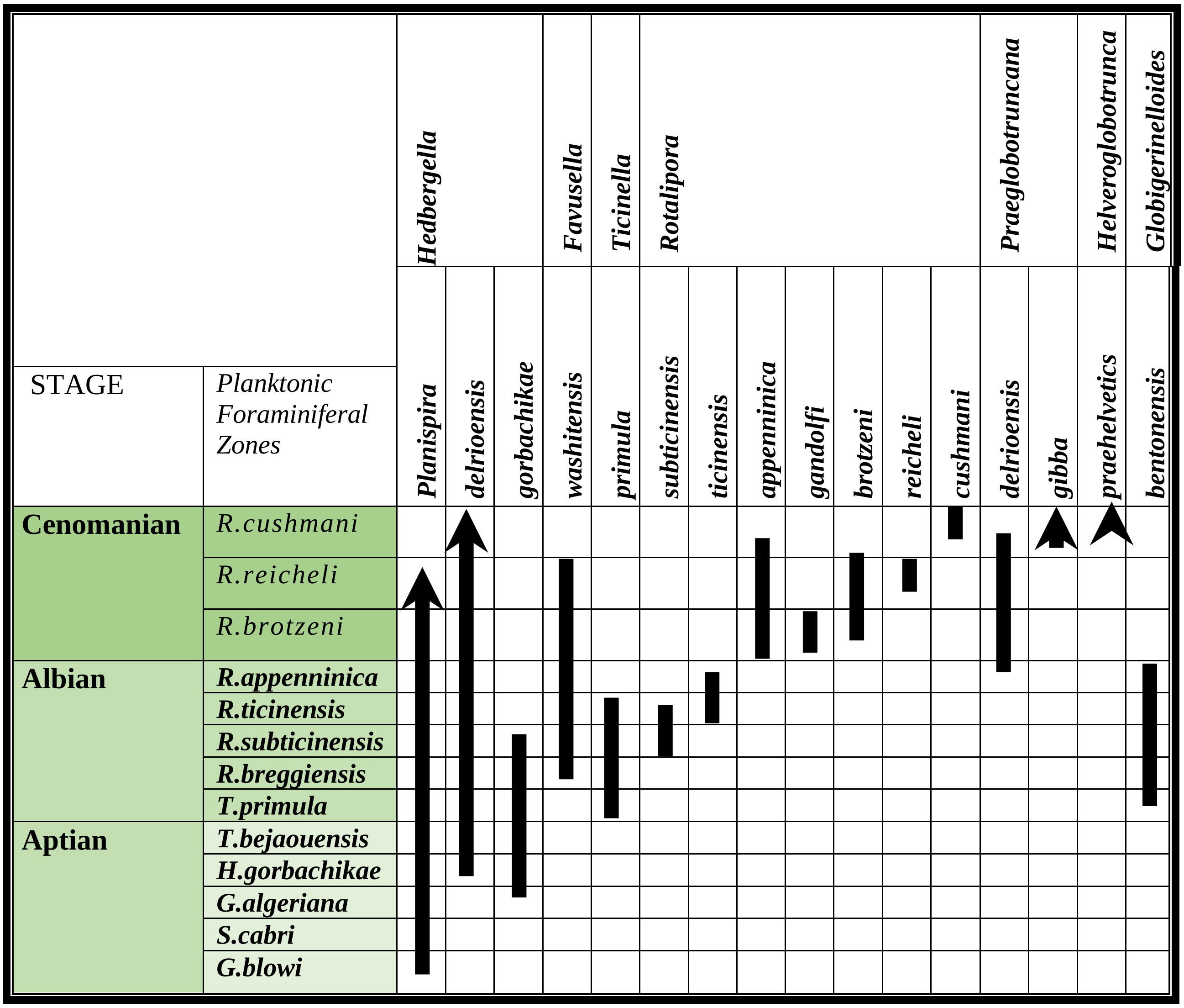


Figure 4.21: Planktonic foraminifera distribution in the studied wells (Zones after Caron, M, 1985).

4.5.1 Barremian to Early Aptian:

As recorded by McMillan (2003), the oldest Early Cretaceous stage sedimentary succession in the Orange Basin belongs to the Barremian stage, represented by basal marine claystone overlying the drift onset unconformity (6At1). These age group of sediments were intersected in Kudu boreholes and are generally devoid of foraminifera. In some rare cases they were feebly fossiliferous however, the benthic assemblages were not age diagnostic. Similarly, in a few locations the Early Aptian was very thin in the Kudu boreholes and in the O-A1 area only. These age group of sediments were not drilled in the study area.

Stage	Age	K-A3	K-A2	K-H1	K-E1
CENOMANIAN	**Late Cenomanian**	2300m-2808m	Not studied	2762m-3323m	2900m-3218m
	Early Cenomanian	2808m-2868m		3323m-3679m	3218m-3338m
ALBIAN	**Late Albian**	2868m-3069m	3450m-3910m	3679m-3869m	3338m-4130m (+)
	Middle Albian	3069m-3400m		3869m-3923m (+)	Not drilled
	Early Albian		3910m-* 5343m *	Not studied	Not drilled
APTIAN	**Late Aptian**	Not drilled	5343m *-5790m (+)	Not drilled	Not drilled

Figure 4.22: Stratigraphic correlation between the four well sections studied in the present work. Substage/age boundaries are based on biostratigraphic criteria (*Intervals /depths are based on seismic markers)

4.5.2 Late Aptian:

Out of the four studied wells only well K-A2 possibly penetrated the Late Aptian succession. However, this age connotation is based only on seismic horizon 13At1 marked at 5343m depth and below. This interval of a thickness of more than 447m (5343m-5790m+) is a highly dominant clastic association comprising of very tight siltstone and sandstone with very minor shale layers. The entire interval is poorly fossiliferous with presence of only long ranging agglutinated foraminifera in a few samples. No age diagnostic planktonic foraminifera of Late Aptian affinity was recorded in this well. The presence of these agglutinated benthic foraminifera indicates a shallow environment of deposition mostly in the middle to outer shelf environment.

4.5.3 Albian

Albian is the uppermost of six main divisions of the Lower Cretaceous Series, representing rocks deposited worldwide during the Albian Age, which occurred between 113 million and 100.5 million years ago. Albian sediments overlie the Aptian and are overlain by sediments belongs to Cenomanian time. The sediments of Albian stages were deposited between 113 Ma to 100.5 Ma. This stage is stratigraphically subdivided into Early, Middle and Late Albian substages.

4.5.3.1. Early Albian

Record of Early Albian sediments in well K-A2 based was based on seismic markers between 14At1 (3910m) and 13 At1 (5343m). In well K-A3 presence of Early Albian was indicated by the presence of the planktonic species *Hedbergella gorbachikae* which appears in Late Aptian worldwide but this species was long ranging and its highest occurrence was recorded in the Middle Albian. Moreover, the speculated interval in well K-A3 is highly arenaceous and no other diagnostic planktonic foraminifera of definite Early Albian affinity was recorded. Therefore, the early Albian boundary could not be demarcated precisely in this well. In both the wells the interpreted Early Albian sections are dominated by arenaceous lithology mostly deposited in the outer shelf environment with minor deepening in a few interval. Presence of pyrite nodules at several sample intervals in these sections indicated anaerobic conditions of deposition (Basov and Krasheninnikov, 1983) which prevented development of bottom life to some extent.

4.5.3.2. Middle Albian

The Middle Albian foraminiferal assemblage has been recorded in well K-H1 and are also present in well K-A2 and K-A3. This interval was not drilled in K-E1 well (Figure 4.22). According to McMillan (2003), presence of the planktic form *Favusella washitensis* is important in Middle Albian interval in South African basins. This planktonic species is usually long ranging in other parts of the world but it usually becomes extinct towards in Middle Albian in most South African basins. In well K-H1 the presence of *Favusella washitensis* was recorded in consecutive intervals followed by *Ticinella primula* at 3868m. The top of Middle Albian is tentatively marked at 3869m. In well K-A3, the top of Middle Albian is demarcated at 3069m on the Last Appearance of *Hedbergella gorbachikae*. This extinction of this planktonic species is within the Middle Albian *Rotalipora subticinensis* Zone in the plankton scale (Figure 4.21). In well K-A2 the co-occurrence of *Rotalipora subticinensis* and *Ticinella primula* at 3861m-3864m sample interval confirm the presence of Middle Albian age sediments however, due to the high arenaceous nature of the sediments no other planktonic foraminifera were recovered. The only planktonic foraminifera above this sample depth are *Globigerinelloides bentonensis* (Early to Late Albian) and very long ranging planktonic foraminifera *Hedbergella planispira*. Presence of these two planktonic forms are not of much help to decide the Middle Albian top in well

K-A2 and thus the entire interval above the Early Albian (depth 3910m / marker horizon 14At1) was placed under Middle to Late Albian age.

4.5.3.3. Late Albian

In well K-A3, the Late Albian section is highly dominated by sandstone units with very thin shale and siltstone beds. Age diagnostic planktonic foraminifera are rare. The conventional core CC#1 was cut within this interval. Towards the top of this interval presence of *Rotalipora ticinensis* (in two samples) and *Rotalipora gandolfi* indicated the top of Late Albian (marked at 2868m). Therefore the Late Albian in this well was 180m thick. Due to highly arenaceous nature of this entire interval only presence of agglutinated benthics were recorded and they usually indicate outer shelf to upper bathyal condition. In well K-H1, the Late Albian section is mainly dominated by argillaceous lithology (mainly claystone) with subordinate argillaceous siltstone units. Presence of sandstones was rare. The lithology itself indicates a deeper depositional set up. No well cuttings were available for examination for 100m siltstone dominant interval (3685m-3785m) in this well. Presence of relatively deep water agglutinated foraminifera (viz. *Rhyzammina* spp., *Dorothia* sp. and *Haplophragmoides* sp.) were recorded in most of the studied samples. Planktonic foraminifera, viz. The claystone rich intervals has yielded *Rotalipora ticinensis*, *R. subticinensis*, *R. appenninica* and *Hedbergella planispira* within the argillaceous interval. The last appearance of *Rotalipora subticinensis* at 3679m demarcates the Early Cretaceous top (top of Late Albian) in this well. Therefore, the Late Albian interval (3859m to 3679m) is about 180m thick in this well.

In the Northern-most well K-E1 the thickness and lithological association of Late Albian succession is very much different in comparison to the area discussed in K-H1 and K-A3 area. Thickness of the Late Albian interval was very thick (3338m- 4133m+) i.e. more than 795m. Lithologically, the entire interval was dominated by claystone and shale with numerous fine sandstone and siltstone units at various stratigraphic levels. The only conventional core CC#1 (3747.5m – 3754m) was cut in this interval. Benthic foraminifera assemblage in the middle part of this thick interval (3427m-3600m) suggest deep water middle slope environment otherwise outer shelf to upper slope condition prevailed in the major part of this section. Frequent presence of pyritised foraminifera tests and disseminated pyrite grains in the upper part suggests anaerobic condition. Presence of oxidised ferruginous particles indicates that local shallowing is more common in arenaceous units leading to formation of diastem surface at 3415m-3420m depth. Planktonic foraminifera species viz. *Rotalipora appenninica*, *Rotalipora subticinensis*, *Rotalipora ticinensis*, *Hedbergella delrioensis* and *Praeglobotruncana delrioensis* were recorded in many samples. Some of these planktonic foraminifera viz. *Praeglobotruncana delrioensis* are long ranging (Caron, 1985) but *Rotalipora subticinensis* and *Rotalipora ticinensis* were recorded in the other wells in this present study and elsewhere in other southern African basins. On the highest occurrence (LAD) of *Rotalipora ticinensis* the Late Albian top (Early Cretaceous -Late Cretaceous boundary) was marked at 3338m in this well.

4.5.4 Cenomanian

Cenomanian is the earliest or lowermost of six main divisions of the Late Cretaceous representing rocks deposited worldwide, which occurred between 100.5 million and 93.9 million years ago. Cenomanian stage rocks overlie the Albian stage and were overlain by Turonian stage sediments. McMillan (2003) preferred to use two stratigraphic subdivisions in Cenomanian (Early and Late Cenomanian), the same nomenclature is followed in this work.

4.5.4.1. Early Cenomanian

The Early Cenomanian interval was studied in three wells K-A3, K-H1 and K-E1. In well K-A3, this interval (2808m-2868m) is only 60m thick. The section is characterized by mixed lithology of fine to medium grained sandstone and siltstone in the lower half and becoming argillaceous towards the top indicating gradual deepening. The Early Cenomanian sediments were deposited in outer shelf to shallow part of upper bathyal environment. The Early Cenomanian planktonic index species *Rotalipora gandolfii* (confined to the *Rotalipora brotzeni* Zone of Early Cenomanian) was present within this interval. The last occurrence of *Rotalipora gandolfi* marked the Early Cenomanian top in this well.

In the North Westerly located well, K-E1, the Early Cenomanian was approximately 120m thick (3218m-3338m) with a lithology entirely dominated by claystone with very minor thin sandstone layers. The last appearance of the characteristic planktonic foraminifera *Rotalipora gandolfi* at 3218m marked the top of Early Cenomanian in this well. Presence of *Rhyzammina* sp. along with *Tritaxia* sp. and *Bathysiphon* sp. indicates that the claystone dominated sediments were deposited in upper bathyal to middle bathyal environment with very minor fluctuations during this period.

In the southern well K-H1 the Early Cenomanian section was much thicker compared to K-A3. The 356m thick section (3323m -3679m) was dominated by siltstone with an occasional brownish to grey claystone. Presence of planktonic assemblages *Rotalipora appenninica* and *Rotalipora gandolfii* are recoded. Last appearance of *Rotalipora gandolfi* at 3323m marked the top of Early Cenomanian in this location. The agglutinated benthic assemblage suggested a highly fluctuating sea level during the time of deposition of the entire section. Presence of agglutinated foraminifera *Rhyzammina* sp. along with *Bathysiphon* sp. and calcareous benthic foraminifera *Lenticulina* sp. suggested deeper water conditions of deposition within the Upper bathyal almost reaching middle bathyal at some intervals.

4.5.4.2. Late Cenomanian

This is the uppermost interval studied in the three wells K-A3, K-E1 and K-H1. As already mentioned, that for well K-A2 Cenomanian section was not studied for the foraminiferal analysis. In the southern well K- H1 the top of the Late Cenomanian was demarcated at 2762m. In this well the Late Cenomanian is 561m thick (2762m-3323m). The only conventional core CC#1 (3362m-3082m) was cut within this age group of sediments. The lithology of the Late Cenomanian in this well was interesting. The lower 2981m-3323m (342m thick) interval was dominated by an arenaceous unit sandstone and siltstone the upper 219m (interval 2762m-2981m) was rich in claystone and argillaceous siltstone. The benthic foraminiferal assemblage indicates gradual increase in water depth from upper bathyal to middle bathyal towards the top of Late Cenomanian. Presence of deep water agglutinated benthics like *Rhyzammina* sp., and *Bathysiphon* sp. along with deep water Calcareous benthics like *Lenticulina angulosa* and *Gavelinella* sp. were frequent in the claystone rich upper part of Late Cenomanian in this well. Planktonic foraminifera viz. *Rotalipora appenninica*, *R.brotzeni*, *R.cushmani*, *Praeglobotruncana delrioensis and Helvetoglobotruncana praehelvetica* were present in several samples (Figure 4.17). Many of these planktonic foraminifera ranged within the Cenomanian stage. The Last Appearance of the index planktonic species *Rotalipora cushmani* at 2762m marked the Late Cenomanian top in this well.

Located in the center of the studied are in well K-A3 the Late Cenomanian section was more than 478m thick (2330m -2808m). In this well the lower 160m interval was dominated by arenaceous units represented mainly by sandstone and siltstone with minor shale/clay beds. Above 2550m the lithology was mainly argillaceous represented by shale. The agglutinated benthic foraminifera assemblage and frequency suggested that the deposition took place mainly in upper bathyal to occasional middle bathyal (slope) environment. Rich planktonic foraminifera assemblage viz. *Rotalipora appenninica*, *R.brotzeni*, *R.cushmani* and *Praeglobotruncana gibba* were recorded in this interval. Last appearance of *Rotalipora cushmani* at 2330m depth marked the tentative upper boundary of Late Cenomanian in this well.

In the North-western well K-E1 is more than 318 m (2900m+ to 3218m) thick. The entire studied interval was dominated by shale/claystone lithology with presence of argillaceous siltstone and sandstone units towards the central and upper part. The deep water agglutinated benthics and almost similar to the well K-H1. The benthic foraminifera association dominated by *Rhyzammina sp*. and *Bathysiphon* sp. throughout the studied interval and presence of *Dorothia* sp. and *Tritaxia* sp. in some interval suggested deposition in the upper part of bathyal to middle bathyal slope (600-800m). Four different species of planktonic foraminifera were present in the studied interval. The two species *Hedbergella planispira* and *Hedbergella delrioensis* were long ranging forms which continued from Aptian to Turonian stages. Co-occurrence of the two other planktonic foraminifera *Rotalipora brotzeni* and *Rotalipora cushmani* were indicative of the uppermost planktonic zone of Late Cenomanian. Examination of some more samples of the section above the sample depth was necessary to ascertain the Late Cenomanian top in this well.

5. CHAPTER FIVE: PALEOECOLOGY AND DEPOSITIONAL ENVIRONMENT

5.1 Introduction

Usefulness of marine microfossils to reconstruct the paleoenvironment and paleodepth is commonly known. One of the main objectives in this work was to predict the changing pattern of deposition in the Cretaceous reservoirs in the area under consideration within the Orange Basin. Foraminiferal assemblages have been widely used for paleoenvironmental reconstruction in the Mesozoic and Cenozoic of sedimentary basins throughout the world. Several researchers have worked on this subject area for almost last half a century (Sliter, 1972, 1975; Sliter and Baker, 1972, Olsson, 1977; Eduardo and Hart, 1990; Nagy, 1992; Haggart et.al, 2013 and others).

In the present study an attempt has been made to outline general paleoenvironmental distribution patterns of the Cretaceous foraminiferal morphogroups from Albian to Cenomanian stages where most of the reservoir units were located. The following paragraphs deals with the behavior pattern of fossil foraminifera, their morphological groupings based on external test morphology and paleodepth analysis

5.2 Paleoecology of foraminifera

Paleoecology is the study of interactions between organisms and their environments across geological times. This branch of science is interdisciplinary and therefore, interacts with and depends on various fields' viz. Paleontology, ecology, climatology and biology. Usually palaeoecological studies are based on the assumption that 'Present *is the key to the past*'.

Foraminifera, like other marine micro-organisms have been affected by the environment and past oceanographic conditions. The distribution of foraminifera, their evolution and extinction in an area within the ocean basin depends on a number of important factors. These factors are not necessarily only related to ocean depth Some of these factors like stability of the ocean environment, amount of dissolved oxygen in water, oxygen cut-off condition (i.e. anaerobic situation and development of anoxia), salinity of ocean water, temperature of water along with availability of dissolved $CaCO_3$, nutrient, bottom condition and type of substrate, restricted or open sea condition related with wave and current activity.

5.3 Foraminifera trophic groups

Foraminiferal trophic (feeding strategies, dwelling habits and niche patterns) structures appear to be influenced by environmental conditions such as bathymetry (water depth), sedimentation rate, food resources, oxygen availability, temperature, food resources. Benthic foraminifera possess a number of feeding strategies (Eduardo and Hart, 1990). In the Cretaceous time the benthic foraminifera communities of the South African basins thrived on feeble calcareous but predominantly siliciclastic substrate and were not light dependent. They can be classified (Figure 5.1) under the following groups

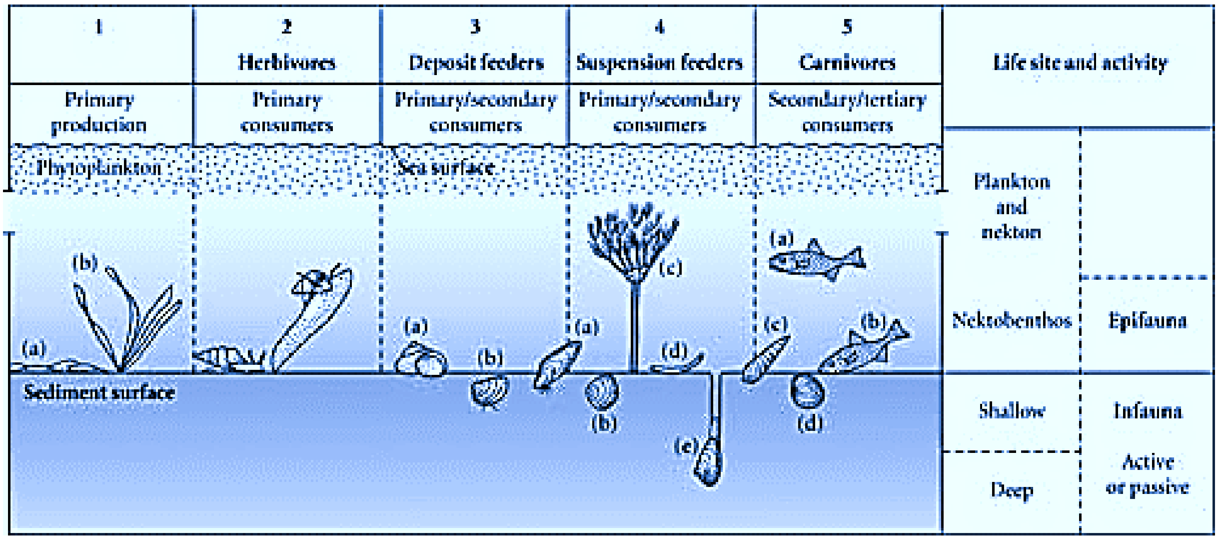


Figure 5.1: Trophic groups, activity of benthic fauna and their life strategy (Benton et al., 2013)

1. Passive Epifaunal Herbivores: They possess irregular, flattened or low to high trochospiral morphology, usually are attached or temporarily attached to hard substates and feed on phytoplankton or bacteria and organic detritus. Usually they are found only below the photic zone.
2. Deposit feeders: This group of foraminifera feed over the substrate (i.e. epifaunal) in or near the water-sediment interface (shallow burrowers) or live within the substrate (infaunal). This group diversify rapidly on soft fine grained organic rich clay or mud rich in abundant food material. The deposit feeders are of two different types:

a) Infaunal deposit feeders: They feed on organic matter particle or bacteria. Morphologically they have elongate tests that helps the specimen to penetrate the organic matter rich soft sediment (mud or silt) using minimum strength.
b) Epifaunal deposit feeders: This group could be active herbivores (feed on algae/diatom and bacteria), omnivores (feed or algae/bacteria as well as animal matters or organic matter) and carnivores (feed on zooplanktons). They have very slow locomotion and have a wide variety of test morphology. They also prefer a soft muddy substate.
c) Suspension feeders: This group survive on fine suspended organic matter or re-suspended organic matter from the near bottom water layer. This group are predominant in the area where the sedimentation rate is either very high or extremely low in middle to lower slope environment (Angel, 1988). Morphologically the Suspension feeders have long, tubular test, which they partially burry in the sediments and have large number of branches (Lipps, 1983).

5.4 Foraminiferal morphogroups and inferred life strategy

In the present work the classification under different morphotypes and mode of life strategy is adopted to understand the preferred living condition and paleo depositional depth. The classification adopted here is based on the classical work of several researchers (Claudia et.al, 2011; Lob and Mutterlose, 2012; Talib et al., 2016; Settoyamamaya et al., 2017; Hetam, 2017 and others).

The classification of different morphogroups are predominantly based on the external morphology such as arrangement of chambers, coiling pattern and general test structure. The application of different morphogroups is based on basic concepts used by Jones and Charnok (1985) and Jones (1986). For the benthic foraminiferal life habitat and feeding strategy in relation to test morphology classical work of several researchers viz. Brandy (1964), Murray (1989) and Kaminski et al. (1988) were consulted in this work. The foraminifera genera were classified in groups based on Loeblich and Tappan (2013).

5.4.1 Foraminiferal morphogroups in the present work

Distinctive morphological features in fossil foraminifera tests are influenced by the overall ecological condition (depositional environments) viz. sedimentation rates, oxygen concentration, temperature and salinity, depth of deposition (paleobathymetry), dissolved calcium carbonate plus availability of food resources.

Foraminiferal test morphology and wall structure composition plays an important role for deployment of pseudopodia in the feeding process. This has extensively been discussed by several researchers (Lipps, 1975; 1976; Jones and Charnock, 1985). The morpho grouping of foraminifera is based on models as proposed by several researchers viz. Cetean ei.al. (2011), Frenzel (2000) and others.

In the present study, morpho-groupings as adopted in Settoyamamaya (2011) was followed. The groupings were carried out separately for agglutinated and benthic foraminifera recoded in the four studied well sections (K-A2, K-A3, K-E1 and K-H1) of Orange Basin for the Cretaceous reservoir interval. The detailed account of different morphogroups are presented in Figure 5.2 (agglutinated benthic) and Figure 5.3 (calcareous benthic) respectively. As previously discussed in Chapter 4, the diversity of benthic foraminifera is moderate in the studied intervals. A brief description of the morphogroups and their life strategy, nature of host sediments and depth distribution are discussed in the following paragraphs.

5.4.2 Agglutinated foraminifera

This group of foraminifera are exclusively benthic microfossils and are distributed in sediments from Cambrian to the present time. They are widespread in clastic sediments deposited in marine and brackish environments. Their external wall structures are comprised of sedimentary grains in comparison to other groups which secrete their test material. Some of these benthic agglutinated foraminifera are selective of their test material and their arrangement. Due to their long range, they are not very useful for precise age dating but they are very important paleoenvironment and paleodepth indicator. They occur in very shallow marine (marginal marine and brackish water) to very deep marine environment. They are dominant in Cretaceous and Tertiary clastic sediments (flysch facies). In the present work the following morphotypes (Figure 5.2) have been recorded:

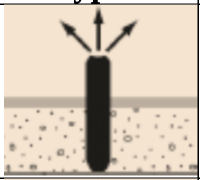
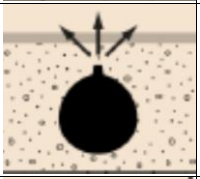
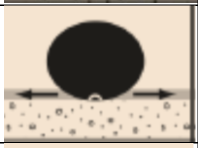
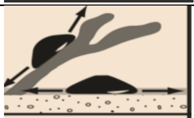
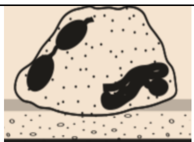
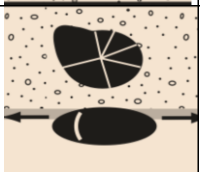
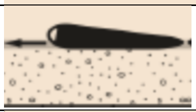
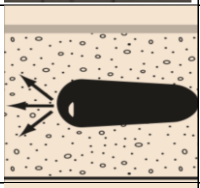
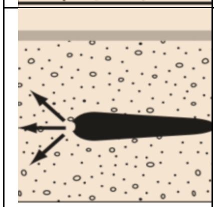
Morpho-group	Morpho-type		Test Form	Life Position	Feeding strategy	Environment	Genera
A1			Tubular	Erect Epifauna	Suspension feeding	Tranquil bathyal to abyssal with low organic flux	*Bathysiphon* *Rhyzammina*
A2	A2a		Globular	Shallow Infauna	Suspension and/or Passive deposit feeding	Common in bathyal and abyssal	*Hyperammina* *Saccammina*
	A2b		Rounded Trochospiral and Streptospiral	Surficial Epifauna	Active deposit feeding	Shelf to deep marine	NOT RECORDED
			Planoconvex Trochospiral				*Trochammina*
A3	A3a		Flattened Trochospiral	Surficial Epifauna	Active deposit feeding	High energy lagoon and estuary	NOT RECORDED
			Flattened Trochospiral and Streptospiral				
	A3b		Flattened irregular	Surficial Epifauna	Suspension feeding	Upper bathyal to abyssal	
A4	A4a		Rounded planispiral	Surficial Epifauna and/or Surficial infauna	Active deposit feeding	Inner shelf to upper bathyal	*Haplophragmoides*
	A4b		Elongate Keeled	Surficial Epifauna	Active deposit feeding	Shelf to marginal marine	*Spiroplectammina*
	A4c		Elongate subcylindrical	Deep Infauna	Active deposit feeding	Inner shelf to upper bathyal with increasing organic matter flux	NOT RECORDED
			Elongate tapered, uniserial and multiserial				*Ammobaculites* *Reophax* *Textularia* *Tritaxia* *Dorothia* *Gaudryina*

Figure 5.2: Agglutinated foraminiferal morphogroups and morphotypes (modified after Cetean et al., 2011)

Morphogroup (A1):

Tabular or branching morphotypes, unilocular

Inferred mode of life: Epifauna, attached to the sea floor or embedded in soft ocean floor sediment (substrate), suspension feeders

Substrate: Fine grained sandstone/ siltstone and siliceous mud

Distribution: Bathyal

Taxa: *Bathysiphon* and *Rhyzammina*.

Record in the present work: Representative of both the genera *Rhyzammina* and *Bathysiphon* are found in the claystone/ shale and argillaceous siltstone rich intervals in all the four wells but are absent in sandstone rich intervals.

Morphogroup (A2): Variable morphotypes, includes low trochospiral, rounded to sub arcuate periphery sometimes half buried in the sediments. Two subgroups are recognized in the present study;

- **Submorphogroup (A2a):** Single, globular chamber, unilocular

Inferred mode of life: Epifaunal to shallow infaunal (half buried test in the soft sediment), Suspension and/or Passive deposit feeding

Substrate: Fine grained sands and siliceous mud

Distribution: Bathyal

Taxa: *Saccammina* and *Hyperammina*

Record in the present work: Both the genera *Saccammina* and *Hyperammina* are found in the argillaceous siltstone rich intervals in all the four wells but are present only in a few samples.

- **Submorphogroup (A2b)**: low trochospiral to planispiral, periphery rounded and often sub arcuate.

Inferred mode of life: Epifaunal and active deposit feeders

Substrate: Fine sand and siliceous muds

Distribution: paralic, outer neritic to middle bathyal.

Taxa: *Trochammina*

Record in the present work: The genus *Trochammina* is not very common in the studied intervals and are found in siltstone intervals in a few sample depths only. The other member under of the submorphogroup with rounded trochospiral and streptospiral morphology was not recorded in this study.

Morphogroup (A3): Flattened morphotypes, including flattened trochospiral, planispiral, streptospiral and irregular varieties (A3a andA3b types) were not recorded any of the samples studied in this work.

Morphogroup (A4): Elongate morphotype with various chamber arrangements and coiling patterns, uniserial to multiserial and multilocular. Presence of the following three sub morphogroups were identified:

- **Submorphogroup (A4a):** Rounded planispiral, spherical to subspherical morphotypes.
  Inferred mode of life: Surficial epifauna or shallow infauna, active deposit feeders
  Substrate: Fine grained sand and siliceous muds
  Distribution: paralic: Outer neritic to middle bathyal.
  Recorded taxa: *Haplophragmoides*
  Record in the present work: The genus *Haplophragmoides* is very common in the studied intervals in all the four well intervals common in argillaceous siltstones and claystone and a few cases in sand dominated intervals. They are present in good frequency in many samples in throughout Albian and Cenomanian. They have higher frequency in the Cenomanian due to hypoxic episodes in the outer shelf and upper slope (Koutosoukos et.al, 1990).

- **Submorphogroup (A4b):** Elongate keeled and flattened morphotypes, varied chamber arrangement and coiling mode. Uniserial and multiserial.
  Inferred mode of life: Surficial epifauna and deposit feeders
  Substrate: Fine grained calcareous and siliceous muds
  Distribution: shelf to marginal marine
  Recorded taxa: *Spiroplectammina*
  Record in the present work: Very rare, recorded in a solitary sample from the Late Albian siltstone section well K-A2.

- **Submorphogroup (A4c):** Elongate tapered morphotype, varied chamber arrangement and coiling mode; Uniserial and multiserial.
  Inferred mode of life: Deep epifauna and active deposit feeders
  Substrate: Fine grained calcareous and siliceous muds
  Distribution: inner shelf to upper bathyal

Recorded taxa: *Ammobaculites, Reophax, Textularia, Tritaxia, Dorothia* and *Gaudryina*

Record in the present work: *Gaudryina* is absent in well K-A2, less common in K-A3, but are present only in a few samples in the other two wells. *Reophax* is very rare in K-A3, K-H1 and K-E1 and absent in K-A2. *Tritaxia* and *Textularia* are recorded only in a few samples in Late Albian and Cenomanian stage silty sediments. *Ammobaculites* are very common and are present in various frequencies more common in outer shelf siltstone intervals) in all the wells except in well K-A2.

5.4.3 Calcareous – hyaline foraminifera

In calcareous benthic foraminifera mostly secrete calcareous tests composed of calcium carbonate ($CaCO_3$). The calcareous tests are usually made up of calcite or aragonite depending on the species. The test contains an organic matrix, which can sometimes be recovered from fossil samples. Several different wall structures within the calcareous tests are known viz. porcelaneous, hyaline, fusulinids, aragonitic etc. In deeper water condition below the carbonate compensation depth (CCD) they are not found. The calcareous benthic groups have been distributed from Silurian to Recent sediments. Some of the foraminifera have an age preference but have useful local zonal classification. These forms are common in shelf environment, a few have been recorded from deeper environment. In the present study only nine calcareous benthic genera have been recorded. They were not frequently present in the studied intervals. The detailed account of different morphogroups, morphotypes, habitat, feeding strategy with preferred depth distribution (Figure 5.3) are discussed in the following section.

Morphogroup (C1): This morphogroup includes low to high trochospiral and with planoconvex and concavo-convex calcareous benthic foraminifera. Elongate morphotype with various chamber arrangement and coiling pattern, uniserial to multiserial and multilocular. Presence of the following three sub morphogroups were identified:

- **Submorphogroup (C1a):** Low trochospiral to nearly planispiral morphotypes. Biconvex with broadly rounded periphery.

  Inferred mode of life: Epifaunal or shallow infaunal, active deposit feeders.

  Substrate: Siliceous muds

  Distribution: paralic: Outer neritic to bathyal.

  Recorded taxa: The only recorded benthic under this submorphogroup is *Gyroidina*.

  Record in the present work: Common in a few samples in Late Cenomanian (well K-H1) and solitary presence in Late Albian (well K-E1), absent in K-A2 and K-A3.

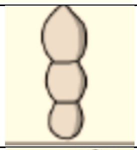
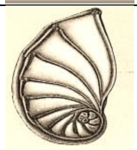
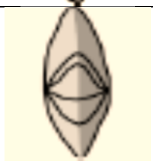
Morpho-group		Morpho-type	Test Form	Life Position	Feeding strategy	Environment	Genera
C1	C1a		Low trochospiral Biconvex	Epifaunal to shallow infaunal	Active deposit feeders	Outer neritic to bathyal	*Gyroidina*
	C1b		Planoconvex Rounded Trochospiral	Epifaunal	Active deposit feeders	Neritic to upper bathyal	*Gavelinella*
	C1c		Planispiral flattened	Epifaunal	Active deposit feeders	Neritic	Not recorded In this study (e.g.: *Spirillina*)
C2	C2a		Elongated uniserial	Shallow infaunal	Deposit feeders	Neritic to upper -middle bathyal	*Nodosaria Dentalina Marginulina*
	C2b		Elongated flattened	Shallow infaunal	Active deposit feeders		*Marginulinopsis*
C3	C3a		Biconvex (lenticular) to almost planispiral	Epifauna	Active deposit feeders	Middle-outer neritic and upper bathyal	*Epistomina Osangularia*
	C3b		Biconvex (lenticular) planispiral	Epifaunal to deep infaunal	Active deposit feeders	Neritic and upper -middle bathyal	*Lenticulina*

Figure 5.3: Calcareous benthic foraminiferal morphogroups and morphotypes (modified after Frenzel, 2000)

- **Submorphogroup (C1b):** Planoconvex to rounded trochospiral, usually a plano or concave umbilicus with a convex spiral side.

  Inferred mode of life: Epifaunal usually the concave umbilical face half buried in the substrate, active deposit feeders.

  Substrate: fine grained calcareous or siliceous muds

  Distribution: paralic: Neritic to upper bathyal.

  Recorded taxa: The only recorded benthic under this submorphogroup is *Gavelinella*.

  Record in the present work: Common in a few samples in Late Cenomanian of well K-E1; very good frequency in the early and late Cenomanian of well K-H1, and solitary presence in Late Albian (well K-E1), absent in K-A2 and K-A3 wells.

- **Submorphogroup (C1b):** Representative foraminifera under this morphogroups are planispirally coiled, discoidal -flattened. However, this forms were not recorded in any of the well sections. This morphogroups usually prefer shallow neritic condition.

Morphogroup (C2): Calcareous benthic foraminiferal assemblage under this morphological group are typically elongated forms with high length to width ratio suitable for predominantly epifaunal mode of life. Two distinct Submorphogroup were recognised under this category:

- **Submorphogroup (C2a):** Elongate uniserial, straight to slightly arcuate morphotype.

Inferred mode of life: Epifaunal or shallow infaunal deposit feeders

Substrate: Fine sands, siltstones and calcareous or siliceous muds

Distribution: paralic: Neritic to upper-middle bathyal.

Recorded taxa: *Nodosaria*, *Dentalina* and *Marginulina* are three representatives present in the studied wells.

Record in the present work: All the three benthic foraminifera under this group are present only in a few intervals in the studied wells. Very rare presence of *Marginulina* sp. have been recorded only in two claystone samples of Late Cenomanian age from well K-E1. *Dentalina* was recorded from only a few samples of Late Cenomanian age of well K-H1 and solitary presence in K-A3, while single occurrence was recorded from Late Albian (?) of well K-A2. Similarly *Nodosaria* was recorded only in a few Late Cenomanian intervals of K-H1 and K-A3 wells.

- **Submorphogroup (C2b):** Elongate flattened, slightly arcuate morphotype.

Inferred mode of life: Shallow infaunal deposit feeders.

Substrate: Fine sands, siltstones and calcareous or siliceous muds.

Distribution: paralic: Neritic to upper-middle bathyal.

Recorded taxa: *Marginulinopsis is* the only representative under the subgroup.

Record in the present work: Very rare presence of *Marginulinopsis* was noticed in only one sample from the sandstone lithology in Well K-A3 possibly belongs to Middle Albian.

Morphogroup (C3): Foraminifera assemblage under this morphological group are typically planispiral or low trochospiral with bi-convex and lenticular test. The periphery of the tests are subarticluate to carinate. Epifaunal mode of life with active feeding life strategy. Two distinct submorphogroup were recognized in this category:

- **Submorphogroup (C3a):** The forms are nearly planispiral to low trochospiral and compressed, usually biconvex and subarcuate periphery.
  Inferred mode of life: Epifaunal and active deposit feeders
  Substrate: Fine grained sands, siltstones and calcareous or siliceous muds
  Distribution: paralic: Middle to outer neritic and upper bathyal.
  Recorded taxa: *Epistomina* and *Osangularia*
  Record in the present work: In four studied well section record of this submorphogroup was found to be extremely rare. In one Late Cenomanian sample from well K-A3, solitary.
  Presence of *Epistomina* was recorded from argillaceous sandstone. Similarly Osangularia was recorded from one argillaceous sandstone sample which was assigned Late Albian age in the present work.

- **Submorphogroup (C3b):** The forms are typical lenticular morphotype and are biconvex with arcuate periphery.
  Inferred mode of life: Epifaunal to shallow infaunal and active deposit feeders.
  Substrate: Fine grained sands and calcareous or siliceous muds.
  Distribution: Neritic and upper-middle bathyal.
  Recorded taxa: *Lenticulina*
  Record in the present work: Except for well K-A2 *Lenticulina* is present at various stratigraphic levels in the remaining three wells. They are present in a number of samples in well K-H1 from the fine argillaceous units dated as Cenomanian, in K-E1 and K-A3 wells they were recoded from Late Cenomanian and Late Albian samples.

5.5 Paleobathymetry and environment of deposition

The fossil microfaunal record particularly, while working with marine sediments is controlled by several geological factors including dissolution of calcium carbonate tests below Carbonate Compensation Depth (CCD) which may vary from basin to basin, post depositional changes or factors involving diagenesis and mixing of microfauna due to erosional factor of older sedimentary rocks. While working with drilled cuttings special care is to be taken to avoid cavings from younger horizons. However, in the present study all these factors were considered and care was taken to avoid contamination in the laboratory while processing. The foraminifera and other microfossil association recorded in this work can be considered as locally derived and free from large scale post-mortem transport and mixing.

In the present work the depth distribution of benthic foraminifera from each sample interval was studied and estimated based on their worldwide distribution after consulting previously quoted publications. These include classical and well know contribution of several researchers on benthic foraminiferal paleoecology viz. Murray (1989), Sikora and Olsson (1991); Leckie and Olson (2003) and others. Based on the recoded distribution of the benthic assemblages in the four studied well sections (frequency distribution from the samples in each well and corresponding lithology as mentioned in chapter four) assessments of paleodepth were made. The major foraminiferal trophic resources and interpreted bathymetric distribution of these microfauna in the Cretaceous succession is summarized in Figures 5.4 and 5.5 respectively.

Against each sample interval in all the four wells, possible paleodepth was estimated and was plotted against the sample positions. Joining the central point of each depth distribution line sample wise, from lower to higher intervals, provides an idea of the sea level fluctuation in each well. This has been discussed in detail in Chapter 4 and illustrated through the figures 4.4, 4.5, 4.8, 4.9, 4.12, 4.13, 4.14, 4.17 and 4.18 respectively.

As mentioned by McMillan (2003) after the creation of the basin around earliest Cretaceous time sedimentation was initiated in this basin above the volcanoclastic sediments. The oldest sediments belong to the middle- Late Barremian stage followed by Aptian sedimentation. However, none of the four wells considered in the present research penetrated this older age group of sediments. In the subsurface drilled section only in one exploratory well K-A2, possibly the Late Aptian sediments was encountered. However, the Late Aptian age connotation is based on the position of the seismic horizon 13At1 in this well. The highly arenaceous succession is in general is poorly fossiliferous (Figure 4.14). The succession comprises dominantly of argillaceous siltstone with fine grained sandstone and rare shale units. Paucity of fauna and their assemblage and poor frequency indicates a middle to outer shelf environment of deposition. Presence of a few agglutinated foraminifera indicate and absence of calcareous benthics suggest a hyposaline environment. This condition continued in the Early Albian within the studied area (as observed in the two nearby wells K-A2 and K-A3) which shows marked similarity in the nature of sea level rise and fall.

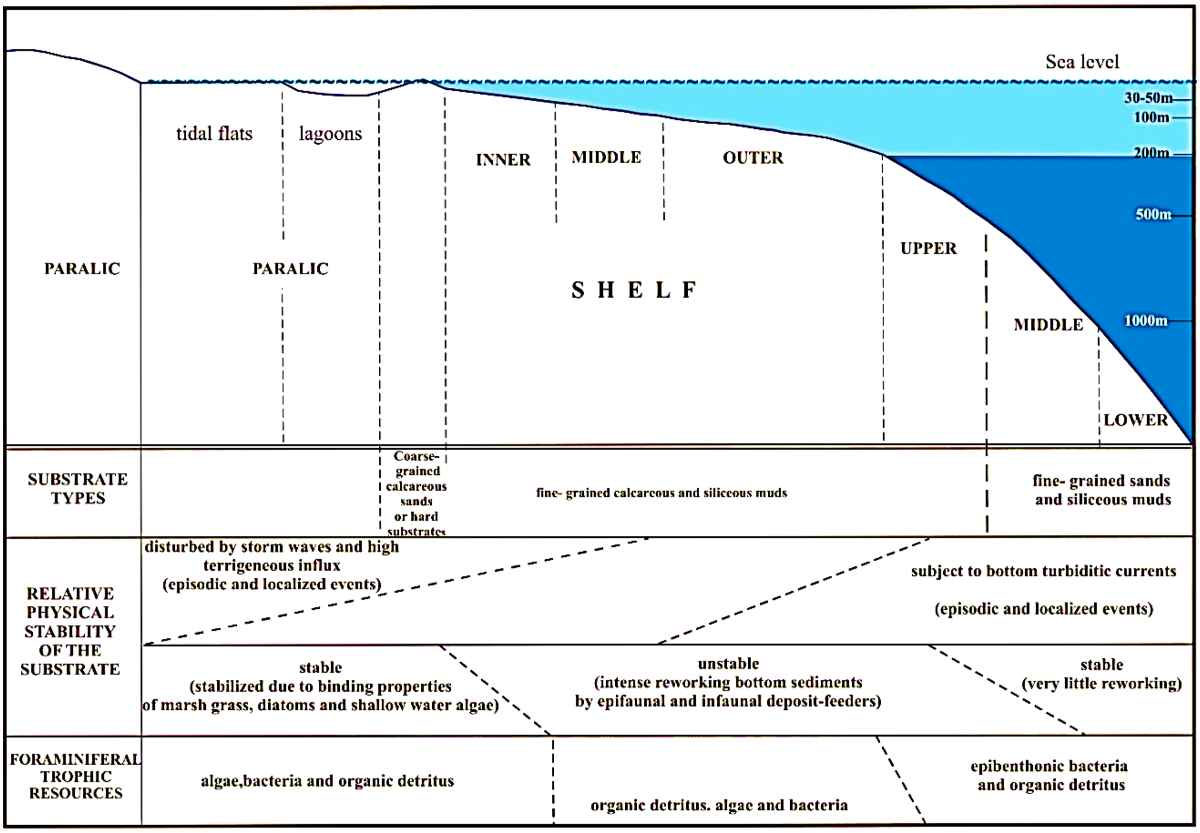


Figure 5.4: Major foraminifera trophic resources and substrate in the marine environment (inferred for the studied Cretaceous sections of the Orange Basin).

Figure 5.5: Benthic foraminifera bathymetry distribution of the studied Cretaceous sections of the Orange Basin.

The shallow marine condition of Late Aptian continued in the lower part of Early Albian in both the localities followed by occasional increase in bathymetry to upper bathyal level. This is evidenced by the presence of upper bathyal agglutinated benthics in a few samples. The sediments deposited under upper bathyal condition are highly argillaceous (shale/ silty shale) in both wells. A few relatively thin sandstone units present in both the wells within the Early to Middle Albian interval are texturally fine to medium grained, clay-like in nature and are very tight with feebly carbonaceous. The low frequency of the agglutinated benthics preserved in these sandy units are indicative of very shallow environment of deposition mostly fluctuating between inner-middle to outer shelf condition. Extreme shallowness in some of the intervals in indicated by rare presence of absent of fauna or presence of leached foraminifera and reddish coloration in the fossil tests as well as oxidised grains indicates short periodic exposures or possible erosional surface especially in Early Albian in well K-A2 (Figure 4.12). Towards the top of Early Albian and in the Middle Albian sea level started rising throughout the area as evidenced by dominant shale / claystone lithology and presence of upper bathyal agglutinated foraminifera. The deposition took place in well oxygenated open marine condition as indicated by presence of planktonic foraminifera and calcareous benthics in a few intervals for the first time in these studied intervals. The increased bathymetry trend continued in the Late Albian in the studied are with minor shallowness towards the Late Albian– Cenomanian boundary (interpreted diastem surface well K-E1, Figure 4.4A). Otherwise, throughout Late Albian the sediments were deposited in upper bathyal to middle bathyal (slope environment). The Cenomanian sediments in general throughout the area (studied in wells K-E1, K-H1 and K-A3) were deposited in deeper water condition; lithologically claystone / shale and argillaceous siltstones are very dominant with anoxic condition (evidenced by disseminated pyrite grains and dark shale lithology), thin sandstone units locally grading to clayey siltstones are also present at a few intervals in all the three wells. The benthic foraminiferal assemblage in the Cenomanian sediments, in all the wells, indicates deposition in marine slope under the upper bathyal to middle bathyal environment.

6. CHAPTER SIX: SUMMARY AND CONCLUSIONS

Four exploratory wells (K-E1, K-A2. K-A3 and K-H1) all located in the continental margin of Orange Basin, Western Offshore, South Africa were studied for demarcation of stage boundaries and understanding of depositional environment for the Cretaceous reservoir bearing intervals. Minor or insignificant gas shows were noticed in the three wells K-E1, K-A2 and K-A3, while the southernmost well K-H1 had no significant reservoirs encountered.

Prior to the present work, no detailed account of temporal behavior of marine microfossil group foraminifera were available for the studied area. A broad outline of foraminifera biostratigraphic analysis involving the seven major basins were available from the study carried out by McMillan (2003).

The present study used planktonic foraminifera for demarcation of various stage boundaries within the Cretaceous drift succession. Although presence of large number of planktonic foraminifera were not present in all the well sections, their occasional records helped to identify various stage/ substage limits and recognise standard planktonic zones between Albian to Cenomanian stages within the Cretaceous.

None of these wells penetrated the earliest part of Cretaceous age group of sediments (Barremian to Early Aptian) in this area. Possibly only one studied well K-A2 encountered the Late Aptian stage sediments. However, the interval is dated on the basis of the position of the seismic marker. This section was devoid of any planktonic foraminifera. The lithology was mainly sandstone-siltstone dominant with low frequency of relatively shallow water agglutinated benthics were present which suggested deposition in the shallow marine shelf.

The Albian stage sediments were encountered in all the four exploratory wells and in some of the wells it was possible to distinguish the Early- Middle and Late Albian substages divisions on the basis of foraminiferal zonal species. In well K-A2, the section above the Late Aptian interval continues to be dominated by arenaceous units and about 1433m thick interval Early Albian succession were sparsely fossiliferous and devoid of age diagnostic planktonic foraminifera. Presence of a possible hiatus towards the top of the Early Albian was recorded with highly ferruginous nature of siltstone/ sandstone units. In the adjacent well K-A3, similar shallow depositional environment and lithology association was recorded in the lower part of Early Albian with periodic rise in sea level during the Middle Albian. The Early Albian section was not drilled in the northern and southern located wells, K-E1 and K-H1.

A gradual rise in the sea level was noticed in the Middle Albian in well K-H1 indicated by the dominance of upper bathyal agglutinated benthics and gradual increase in planktonic foraminifera which indicated an open marine circulation. Argillaceous lithology represented by claystone and argillaceous siltstone supported these observation. In the central area (well K-A2 and K-A3) similar patterns of sea level rise was noticed. The Middle Albian interval was not drilled in the southern well K-E1.

The rising sea level with periodic fluctuation within the upper bathyal condition continued in the studied area during Late Albian. During this time around 200m (+) thick sediments were deposited in the central and southern part of the study area (wells K-A3 and K-H1) but was much thicker in the northern well (K-E1) where deposition was much faster. The stage /substage boundaries in all the wells was demarcated due to presence of several important planktonic foraminifera.

The top of the Early Cretaceous (Late Albian) was successfully marked in wells K-E1, K-A3 and K-H1 on the last appearance of *Rotalipora ticinensis* in all the three wells. The central area where K-A3 is located was structurally much higher compared to the other two.

Deposition in the Late Cretaceous Cenomanian stage sediments in the three sites took place in much deeper water depth (upper bathyal -partly middle bathyal) as revealed by their faunal composition and associated lithology. The lithology in K-E1 and K-H1 sites located far from the basin edge received mainly claystone with minor fine-grained clayey sand and siltstone. The thin sandstone units were very tight, occasionally clayey with low permeability, could not be considered as good reservoir. Comparatively in the central area (site K-A3), presence of arenaceous units were better developed in the later part of Cenomanian stage. The deposition of the Cenomanian sediments were mostly in the upper bathyal (slope area). The presence of index planktonic foraminifera in all the three wells indicated open marine conditions and the associated benthics indicated minor changes in bathymetry during Cenomanian throughout the studied area.

Paleoecological studies based on foraminiferal morphogroup analysis carried out for the first time in this basin. The work based on morphological characters of the two benthic foraminifera groups viz. agglutinated and calcareous benthics helped assign paleodepth against sample position. The study indicated that some of the deep-water benthic foraminifera viz. *Rhyzammina* and *Bathysiphon* were distributed mainly in claystone rich intervals in the four wells. Their distribution and frequency may have been useful for short local correlation, however, some wells were to be studied in the equivalent sections. Anoxic conditions prevailed as indicated by pyrite coated benthics, this suggests occasional restricted environment. Due to this, the frequency of the planktonic foraminifera was less abundant in the Albian sediments throughout the studied area. Absence or very rare presence of calcareous benthics also indicated deposition in restricted deeper water environment in Albian. The situation changed gradually towards the later stage of Late Albian and in Cenomanian with more open marine condition prevailed and increase in frequency and diversity in both the planktonic and benthic foraminifera.

The reservoir units in the Late Aptian and early part of Albian were sandstone and siltstone. They were mostly texturally immature and were transported from the eastern to north-eastern direction of South African landmass. The paleo-bathymetric analysis indicated shallow marine deposition in the inner to middle shelf. Some of these sandstone units were thick but were very tight with relatively poor reservoir quality. In the relatively younger section i.e. Late Albian - Cenomanian stages fine grained sandstones and siltstones sandwiched in the deep water thick argillaceous sections were present. The foraminiferal studies indicated that these arenaceous units were deposited in a slope environment (upper bathyal). These minor units were mixed with claystone and have poor reservoir properties.

The work was carried out with certain limitations. One of the main constraints was availability of continuous samples from the drilled wells. Most of the wells were drilled more than 30 years ago and the wells are quite deep with very big interval. A major part of the biostratigraphy work involved isolation of microfauna from the processed samples and this can only be carried out by manual procedure. However, all attempts were made to study the samples at regular intervals in each well. The results from this research can be further refined after studying some more wells from the nearby localities.

In summary, this work involving foraminiferal studies helped to subdivide the stratigraphic section into different stage and substage boundaries and predict the depositional environment in which the arenaceous reservoirs were deposited and contributes in understanding the reservoir quality in the studied locality of Orange Basin.

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