SAKARYA UNIVERSITY
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THE PETROLEUM AND NATURAL GAS POTENTIAL OF GHANA

M.Sc. THESIS

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DECLERATION

I declare that all the data in this thesis was obtained by myself in academic rules, all visual and written information and results were presented in accordance with academic and ethical rules, there is no distortion in the presented data, in case of utilizing other people's works they were refereed properly to scientific norms, the data presented in this thesis has not been used in any other thesis in this university or in any other university.

Salamatu Bannib LAMBON

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LIST OF SYMBOLS AND ABBREVIATIONS

AAPG	: American association of petroleum geologist
AFFZ	: Agulhas - Falkland fracture zone
API	: American petroleum institute
ARCO	: Atlantic Richfield company limited
Bbl	: Billion barrels of litters
BBC	: British broadcasting corporation
Bopd	: Barrels of oil per day
CARS	: Central African rift system
CO_2	: Carbon dioxide
CIGMR	: Cote d'Ivoire - Ghana marginal ridge
CNR	: Canadian natural resources limited
CFZ	: Chain fracture zone
CH_2	: Methylene
CH	: Benzene
EBSCO	: Elton Bryson Stephens corporation
EqRS	: Equatorial Atlantic rift system
E	: East
EEI	: Extended elastic impedance
FFZ	: Florianopolis fracture zone
ft^3	: Cubic feet
GOG	: Gulf of Guinea
GOC	: Gas – oil contact
GNPC	: Ghana national petroleum corporation
H / C	: Hydrogen carbon ratio
H_2O	: Water
HI	: Hydrogen index

km	: Kilometre
Km^2	: Kilometres square
LPD	: Liquified petroleum gas
m	: Meters
Ma	: Million years
mB	: Millions of barrels
MBOE	: Million barrels of oil
mm/yr	: Millimetres per year
Mmbbls	: Million Barrel
n.d.	: No date
N	: North
O/C	: Oxygen carbon ratio
OPEC	: Organization of petroleum exporting countries
OWC	: Oil – water contact
PI	: Production index
PCIAC	: Petro Canada international assistance corporation
RFZ	: Romanche fracture zone
Ro	: Reflectivity of vitrinite
Rb - Sr	: Rubidium- Strontium
S	: South
SAGE	: Sarah and George journal
SARS	: South African rift system
SEG	: Society of exploration geophysics
Sq. km	: Square kilometres
S/C	: Sulphur carbon ratio
SDR	: Seaward dipping reflectors
SP	: Spontaneous Potential
SPE	: Springfield exploration and production
TEN	: Twenewboa, Enyenra and Ntomme
Tmax	: Total maximum

TOC	: Total oxygen content
TTI	: Time -temperature Index
USA	: United States of America
USGS	: United States geological survey
UAC	: African and Oriental Petroleum Corporation
W	: West
WAM	: West African margin
WAOFCO	: West Africa oil and fuel company
WARS	: West African rift system
2D	: Two dimensions

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SUMMARY

Keywords: Plate Tectonics, Sedimentary Basins, Ghana, Qualitative Analysis, Petroleum and Natural Gas Potential, South Atlantic Ocean.

The research was conducted to determine the Petroleum and Natural Gas Potential of Ghana using secondary data sources. One of the aims of the research was to determine the role of plate tectonics and the opening of the South Atlantic Ocean played in the accumulation of petroleum and natural gas in the Gulf of Guinea in general and Ghana in particular. The research was conducted using systematic review approach of qualitative research method. The data sources used in this study were focused on peer-reviewed journals, conference articles, books, thesis works, reports and other sources relevant to this study. The results of the study show that Ghana has four sedimentary basins, one inland (Voltaian) and three offshore basins (Tano, Saltpond, and Keta). The Tano basin has source rock of Cenomanian, Turonian and Albian ages which serves as the major plays in the Tano Basin. The reservoir sands are of upper Cretaceous times making the Turonian turbidite sandstones (slope fan) and Albian sandstones (tilted faults). The Albian shale series, Cenomanian shale series, and Turonian shale series serve as the seal plays in the Tano basin with the trapping mechanisms mainly both structural and stratigraphic as well as post-transitional anticlinal traps (fault-block). Major discoveries have been made in different parts of the Tano Basin. The first economical valued discovery in the Tano Basin was made in 2007 in the Jubilee field (Mahogany-1 discovery) which estimated to have recoverable reserves of 1.2 billion barrels of oil. The potential source rock in the Saltpond basin is the Devonian shales (Takoradi shales) and the main reservoir rocks of the Saltpond basin are the sandstones of the Takoradi sandstone formation which are of Devonian to Carboniferous of age. The Saltpond has both structural and stratigraphic trapping mechanisms with the reservoirs sealed by the Takoradi shale formation. The Saltpond is the second prolific basin which has been estimated to have a total reserve of about 7.5 million barrels of oil. The Keta basin has the Devonian shales, Lower Cretaceous shales and Late Cretaceous shales as the main source rocks and the reservoir rocks are of Albian, Late Cretaceous and Tertiary of age and the trapping mechanisms are both structural and stratigraphic. The Keta basin which is after the Saltpond basin has not proven to have any recoverable reserves due to less exploration work in it. The possible petroleum system known in the Voltaian is the Oti Group made of sandstones, shales, and siltstones. The Voltaian which is an inland basin has also not proven to have any recoverable reserves due to the complexity of the geology.

GANA’NIN PETROL VE DOĞAL GAZ POTANSİYELİ

ÖZET

Anahtar kelimeler: Levha Tektoniği, Sedimanter Havzalar, Gana, Kalitatif Analiz, Petrol ve Doğal Gaz Potansiyeli, Güney Atlantik Okyanusu.

Araştırma ikincil kaynaklardan elde edilen veriler kullanılarak Gana'nın petrol ve doğalgaz potansiyelinin belirlenmesi için gerçekleştirilmiştir. Araştırmanın amaçlarından biri genel olarak Gine Körfezi'nde ve özellikle Gana'da petrol ve doğal gaz birikiminde plaka tektoniğinin ve Güney Atlantik Okyanusu'nun açılışının rolünü belirlemektir. Araştırma nitel araştırma yönteminin sistematik gözden geçirme yaklaşımı kullanılarak yürütülmüştür. Bu çalışmada kullanılan veri kaynakları hakemli dergiler, konferans makaleleri, kitaplar, tez çalışmaları, raporlar ve bu çalışma ile ilgili diğer kaynaklara odaklanmıştır. Çalışmanın sonuçları Gana'nın bir iç kara (Voltaian) ve üç deniz havzası (Tano, Saltpond ve Keta) olmak üzere dört sedimanter havzaya sahip olduğunu göstermektedir. Tano havzasında önemli yer kaplayan Senomaniyen, Mesozoik ve Albiyen yaşlı kaynak kayalarına sahiptir. Rezervuar kumları Mesozoik türbidit kumtaşlarını (eğimli fan) ve Albiyen kumtaşlarını (eğik faylar) oluşturan Üst Kretase yaşlıdır. Albiyen şeyl serisi, Senomaniyen şeyl serisi ve Mesozoik şeyl serisi yapısal, stratigrafik kapanım mekanizmaları ayrıca geçiş sonrası antiklinal kapanları (fay bloğu) ile Tano havzasında yalıtım olarak rol oynamaktadır. Tano Havzası'nın farklı yerlerinde önemli keşifler yapıldı. Tano Havzası'ndaki ilk ekonomik değerli keşif 2007 yılında 1,2 milyar varil petrol elde edilebilecek rezerve sahip olduğu tahmin edilen Jubilee sahasında (Mahogany-1 keşif) gerçekleşti. Saltpond havzasındaki potansiyel kaynak kaya Devoniyen şeylleridir (Takoradi şeylleri) ve Saltpond havzasının ana rezervuar kayaları Devoniyen-Karbonifer yaşlı Takoradi kumtaşı formasyonunun kumtaşlarıdır. Saltpond, Takoradi şeyl formasyonu tarafından kapanan rezervuarlar ile hem yapısal hem de stratigrafik kapan mekanizmalarına sahiptir. Saltpond yaklaşık 7,5 milyon varil petrol rezervine sahip olduğu tahmin edilen ikinci üretken havzadır. Keta havzası ana kaynak kayası olarak Devoniyen şeylleri, Alt Kretase şeylleri ve Geç Kretase şeyllerine sahiptir ve rezervuar kayaları Albiyen, Geç Kretase ve Tersiyer yaşlıdır ve kapanım mekanizmaları hem yapısal hem stratigrafiktir. Saltpond havzasından sonraki Keta havzasında elde edilebilir bir rezervin olduğu daha az araştırma çalışmaları dolayısıyla kanıtlanmamıştır. Voltaian'da bilinen olası petrol sistemi, kumtaşları, şeyller ve silttaşlarından oluşan Oti Grubu'dur. Bir iç havza olan Voltaian'ın da jeolojinin karmaşıklığı nedeniyle elde edilebilir bir rezerve sahip olduğu kanıtlanmamıştır.

CHAPTER 1. INTRODUCTION

1.1. General Introduction

Petroleum is a complex naturally occurring liquid derived from the thermal alteration of fossil fuels which is extracted from specific geological formations in the earth's crust (NEED, 2018; Investopedia, 2019). The chemical component that makes up petroleum are mainly hydrogen and carbon often known as hydrocarbons (Fagan, 1991) and other elements such as nitrogen, sulphur and oxygen (Walters, 2006). Natural gas is also generated from hydrocarbons extracted from shale formations which are colourless and odourless in their natural state. Although other forms of natural gases such as methane, nitrogen, carbon dioxide etc. exist in the atmosphere (American Gas Association, 2019; The Economic times, 2019). Petroleum and natural gas are usually not used in their pure forms but rather processed and extracted into fuels such as petrol, diesel, kerosene, LPD gas etc.

Since the ancient times, petroleum and natural gas discoveries have been made and used in medicine, in wars, lighting homes and other purposes but due to lack of advanced technology and equipment much exploration has not been done in regard to that until the early 1900's when explorers had ideas and ways of extracting which has advanced up to present. Due to increasing demand to energy resources, the search for petroleum and natural gas over the years have increased enormously. Advanced technology and equipment have been developed over the years to help explore, extract, produce and refine petroleum and natural gas for economic gain.

According to the U.S. Energy information Administration, the world's leading producers of petroleum in 2018 are U.S, Saudi Arabia, Russia, Canada, China, Iraq, Iran, United Arab Emirates, Brazil and Kuwait. The production sums up to a total of 100.85 million barrels per day making a total of 70% of the world's petroleum production globally.

Africa as a continent plays a great role in the global production of petroleum and natural gas. About 30 of the 54 countries in Africa produce oil and natural gas. Currently, Africa accounts to about 9.4% of the total world's oil. Africa produces about 8.7 million barrels per day (Carpenter, 2015). According to Ikenwa, 2019, the leading countries in petroleum production are Nigeria, Angola, Algeria, Liberia, Egypt, Sudan, Equatorial Guinea, The Republic of Congo, Gabon and South Africa.

Ghana which is the first Sub-Saharan African country to gain its independence, discovered their first oil in 1896 but discovery of commercial quantity of petroleum was in 2007. Ghana has four sedimentary basins of which one is inland and the other three are offshore. The inland basin is the Voltaian basin and the offshore basins are Tano, Saltpond and Accra-Keta basins. Currently, the most prolific basin in Ghana which has huge accumulations of hydrocarbons is the Tano basin although exploration works are ongoing in the Saltpond and Keta basins for hydrocarbon potential. Ghana witnessed their first oil production in 2007 in the Jubilee field of the Tano basin at rate of about 55,000 barrels per day with an increase to 120,000 barrels per day within six months (BBC News, 2010). In 2019, production has increased to about 196,089 barrels per day with an expected increase in production to 420,020 barrels per day by 2023 (Public Relation Unit, 2019).

1.2. Statement of Problem and Justification of the Study

Ghana has many natural resources including, Oil, gold, wood, bauxite, iron, etc. Except for the oil discovered in 2007 (which is of economic value), Ghana's remaining natural resources are well documented and published to raise awareness among Ghanaians and the international community.

Most Ghanaian geoscientists in general and the Ghanaian public are not well informed about Ghana's true oil potential. This lack of information leads to different stories about the oil potential in Ghana, and the public are over or under demanding in terms of economical support and development from the state. Due to the lack of extensive published documents summarizing all the geological and geoscientific aspects of oil in Ghana, scientists and students of geoscientific faculties in Ghana and other parts of the world have difficulties obtaining information on Ghana's oil potential.

This research tried to solve this problem by providing detailed information on Ghana's oil and gas potential. Using the concept of geological formation and plate tectonics, this work provides to the public, academicians and students interested in oil and gas industry with a detailed understanding of Ghana's gas and oil potential. This study deals comprehensively with the potential of Ghanaian oil and gas from a geoscientific point of view.

1.3. Purpose and Objective of the Study

The main aim of this thesis is to research and present a geoscientific document on the potential of Ghana's oil and natural gas from secondary data sources. The following objectives have been drafted to help achieve the above aim.

A. To determine the petroleum and natural gas potential of Ghana using the concept of plate tectonics (the role of the opening of the Atlantic Ocean (Plate Tectonics) in determining the oil and natural gas potential).

B. To use the regional geology of the coastal belt of Gulf of Guinea to determine the petroleum and natural gas potential of Ghana.

C. To use local geology and geological structures within the Ghanaian borders to determine the petroleum and natural gas potential of Ghana.

1.4. Scope of the Study

The study is a literature-based research using the previously published papers, reports, maps, etc. as data sources. The method of data collection was a systematic review that extracted and summarized information on the potential of oil and gas in Ghana and on the role of plate tectonics in the accumulation of oil and gas from various sources in a structured approach within a theoretical framework. The data sources were mainly from peer-reviewed journals, conferences, books and reports from government organizations and institutions. Books were used to present basic standard knowledge. The time frame considered in this study ranged from the discovery of the first oil in Ghana 1896 to present 2020. The research was limited to the geoscientific aspect of Ghana's oil and natural gas potential. The research focused on the global, regional and local aspects of hydrocarbon potential. Much attention was given to the four basins in Ghana. The geological structures influencing the formation, maturation and migration of petroleum were studied and documented in this work. These structures were correlated to the current structures within the basins of Ghana. From these factors, the current hydrocarbon potential of Ghana was estimated.

This thesis is organized into six chapters. Chapter one is the introduction. Chapter two contains the research methodology. Chapter three contains the theories of petroleum formation, Global tectonics and its role in petroleum accumulation narrowing it to opening of the South Atlantic Ocean to the equatorial section and to Ghana. Chapter four contains the previous research about the sedimentary basins in Ghana as well as the study area. Chapter five contains results and discussion. Finally, Chapter six contains the conclusion and recommendations related to the research.

CHAPTER 2. RESEARCH METHODOLOGY

2.1. Chapter Introduction

This chapter explains how the data for this thesis work were obtained and the method used writing of the thesis. The main aim of this chapter is to give information about the research method used in this thesis and give needed information for anyone to be able to perform similar research work.

2.2. Methodological Approach

As it was stated in Chapter 1, the main aim of this thesis is to research the oil and natural gas potential of Ghana. Speaking of oil and natural gas potential research in the field of geophysics naturally require acquisition of geophysical data, processing of those data and interpreting the data to determine the oil and natural gas potential of the field or the block. Geophysical data such as seismic data acquisition is mostly conducted by oil and gas companies and/or oil and gas service companies. However, obtaining these data for scientific research is nearly impossible since the ethics of scientific research requires publishing research results, but these companies have acquired the data for their commercial purposes. Sharing their data to the world means losing their competitive advantages to negotiate with governments and other companies. Therefore, they do not make the data available for researchers unless after taking all the advantages from the data and sometimes they do not give it out at all. Therefore, to do a research about the oil and natural gas potential of a country not a single basin or even a block is very difficult, if one wants to depend on primary data. Because of these difficulties secondary data option was opted for in this research.

To achieve the aim and objectives as stated in Chapter 1, a qualitative approach of research was adopted. Systematic review approach of qualitative research method was used in preparing this thesis work. A systematic review method is a summary of the literature in a field that uses explicit methods to perform a comprehensive literature search and critical appraisal of individual studies. The qualitative systematic review is also known as qualitative evidence synthesis. In summary, qualitative systematic review method is used to compile research sources and writing materials for this thesis. The major aim of the used qualitative systematic review was to investigate the petroleum and natural gas potential of Ghana. Qualitative systematic review was adopted to narratively synthesize the findings and evidence of the petroleum and natural gas potential in the sedimentary basins of Ghana.

As stated in Chapter 1, the research problem is the lack of extensive published and non-published geoscientific research on the potential of the oil and natural gas in Ghana. To address this problem, answerable research questions were drafted. The answers to these questions were organized into various chapters of the thesis. The answerable research questions drafted are;

A. Is there any published complete book or article about the complete oil and natural gas potential of Ghana?
B. What lead to the discovery of the first oil exploration work in Ghana?
C. What are the differences between the mode of exploration during the first discovery of oil in Ghana and that of the present?
D. What are the parameters for that control oil and natural gas formation and are these parameters found in the rock formations beneath Ghana.
E. Which geological formations and structures are associated with oil and natural gas and are some of the formations and structures found within the geology of Ghana?
F. What role do plate tectonics play in oil and gas formation or creation? Do plate tectonics play major role in the oil and gas of Ghana?
G. How does the opening of Atlantic Ocean affect the potential of oil and gas in Ghana?
H. How does the regional geology and geological structure within the Gulf of Guinea affect the oil and natural gas potential of Ghana?

I. Is the oil and natural gas potential of Ghana similar or greater than or less than that of Nigeria?

J. Which kind of reservoirs are available in Ghana and what are their capacities?

K. Which of the four basins of Ghana has high oil and natural gas potential?

L. What is the oil and natural gas reserve capacity and how long can the oil and natural gas be produced?

M. Are there any country(s) which have the same geology as Ghana where economical oil and natural gas were found?

N. What are the other discoveries made after the 2007 oil and gas discovery in Ghana?

O. Which oil and gas companies discovered the oil and gas?

P. Are there any geophysical publications about the oil and gas in Ghana? If yes, what are the results?

Q. What is the ranking of the potential oil and gas sedimentary basins in Ghana?

R. What are some of the oil and gas discoveries made in Africa especially West Africa?

S. What are the possible formations in which the oil and gas discoveries were made in West Africa?

T. What are the recoverable reserves discovered within West Africa?

U. What is the ranking of Africa and West Africa in global oil and gas discoveries?

V. What is the rank of Ghana in West Africa and global oil and gas discoveries?

W. What is the general geology of Ghana? Are there any sedimentary basins in Ghana? If yes, do they have oil and gas potentials?

X. Are there similar sedimentary basins formed across in South America and Africa during the opening of the Atlantic Ocean?

2.3. Method of Data Collection

In order to produce quality and more informative research work, data were obtained from different types of sources and criteria.

2.3.1. Data source

The data used for this research were obtained from citation indexes, bibliographic database, hand searching and Grey literature.

A. Citation indexes: Data was obtained by tracking references, authors included in the reference list of their publication. Example of citation indexes used includes Web of Science, Scopus and Google Scholar.
B. Hand searching: Page by page of relevant journals, conferences and other publications of interest were conducted.
C. Bibliographic database: it was used because it contains a lot of literature related to every field. Among the bibliographic databases used includes EBSCO, ProQuest, SAGE Online Journal collection, Wiley Online Library, Science Direct, SEG Library, AAPG library, Springer, Elsevier and Semantics Scholar.
D. Grey literature: Grey literature is information produced by governments, academics, businesses and industry in both electronic and print format not controlled by commercial publishing. Grey literature used in this thesis includes thesis, newspapers, reports and Wiki articles.

2.3.2. Data search and data search criteria

In search for data from the various sources as explained in the sources section of this chapter, time was spent in identifying all synonyms and related terms. These synonyms and related terms were used for searching of information in the sources. Among the synonyms used are;

A. oil in Ghana.

B. petroleum in Ghana.
C. Natural gas in Ghana.
D. Gas in Ghana.
E. Petroleum and natural gas in Ghana.
F. Petroleum and gas in Ghana.
G. oil and natural gas in Ghana.
H. Sedimentary basins in Ghana.
I. Profitable sedimentary basins in Ghana.
J. Petroleum and Plate tectonics.
K. Opening of Atlantic Ocean.
L. Basins in South Atlantic Ocean.
M. Profitable basins in West Africa.
N. Role of Plate tectonics in oil accumulation etc.

To be included in this systematic review research, every study or source needed to meet the specific but extensive inclusion criteria that was set up for the purpose only sources that are related to the topic under investigation. The inclusive and exclusive criteria are as below;

Time period: The time period considered for this research begins from 1896 (the first discovery of petroleum and natural gas in gas) to January 2020. Any work published after January 2020 were not considered because it marks the end of data resources search.

Language: The languages for the published and unpublished data sources were restricted to English and Turkish Language. This is due to the inability of the researcher to understand other international languages aside from these two. Although Turkish language was included in the data source, no published or unpublished work was found in this language that was relevant to this research. In some cases, English abstract of some publications in other languages were considered.

Publication: The literature sources is restricted to published and unpublished materials such as books, journal articles, sections of books, case studies, conference proceedings, encyclopedia articles, magazine articles, newspaper articles and news, reports, thesis, webpages and working papers. Excluded from publication types include letters, radio shows and news because of impossibility of finding these sources.

Geographic consideration: Data published particularly about Ghana were given very high priorities. There was no geographical consideration on issues related to general theories, knowledge and issues of petroleum and natural gas.

Aside from the use of synonyms and related forms in data search, Boolean operators and combinations of terms method were used for data search. Boolean operators were used to links terms together either to widen aa search for literature or to exclude terms from the literature search results. The Boolean operators used were OR (was used to search for synonyms and related terms within the search keywords), AND (was used to retrieve literature covering both topics within the search keywords). Lastly, NOT (was used to retrieve only one part of the search keywords and to exclude the other part). Example of AND (Boolean operator) is found in the above identifying synonyms section. For the other two Boolean operators used, the example of search keywords are as follows:

A. Oil or petroleum in Ghana.
B. Oil or natural gas in Ghana.
C. Oil or gas in Ghana.
D. Petroleum or natural gas in Ghana.
E. Sedimentary basins or reservoirs in Ghana.
F. Petroleum basins not hydrological basins.
G. Profitable basins in West Africa not dry basins in West Africa.

2.4. Data Analysis Method

Data as used in this research is defined as texts, tables, maps figures, illustrations, diagrams, quotations and digits obtained from published and non-published sources. Relevant data were obtained from different sources and they were grouped into different themes and patterns. After that the themes were organized into chapters and sections. All obtained data sources such as journal articles, conference proceedings, thesis, reports, Wiki articles etc. were all imported into Mendeley. The desktop version of Mendeley was used for importation of the sources but they were synchronized with cloud storation of Mendeley to prevent any loss of sources. Relevant information or data were highlighted, and notes were taken on the desktop version of Mendeley. Mendeley helped in referencing relevant information or data, and it also assisted in organizing the obtained data according to required themes.

In conclusion, the systematic review approach of qualitative research alongside with all other techniques and methods explained in this chapter, helped the research in coming out with results that addressed the research problems at hand.

CHAPTER 3. THEORITICAL FUNDAMENTALS

3.1. Chapter Introduction

The aim of this chapter is to explain the formation of petroleum and to discuss the structures and parameters of geological formation that controls the formation, migration and accumulation of petroleum and natural gas. Much attention will be given to hydrocarbon systems, but for a general understanding of this chapter, a brief discussion is given below to establish a connection between plate tectonics, basins, and hydrocarbons.

A basin is basically a topographic depression filled with sedimentary rocks. Plate tectonics deals with the relative movement between the plates. The plates as used here are part of the outer shell of the earth, which has been divided into different parts. Some plates are thin, and others are large, but in general all plates are rigid and move relative to each other. As a result of this movement, deformation occurs. In general, this deformation concentrates at the boundaries of the plate. The deformation caused by the relative movement of the plates creates a pelvis. In short, the deformation of the plate boundaries creates basins where hydrocarbons are accumulated.

For petroleum to be formed, there are some important elements and processes as well as favorable conditions, which must occur for the accumulation of oil and natural gas. The most important thing is for a sedimentary basin to be formed. Under favorable depositional condition permits the good preservation of matter.

Hydrocarbon system is a collection of all elements and processes that are essential for hydrocarbon accumulation to exist. The genetic elements of the hydrocarbon systems include;

A. Source rock.
B. Reservoir rock.
C. Trap.
D. Seal.

The processes that are essential for a hydrocarbon accumulation to exits includes;

A. Maturation.
B. Migration.
C. Timing.

These detail discussions of these elements and processes would be considered one by one in the remaining part of this chapter.

3.2. Plate Tectonics

3.2.1. Global tectonics and role of plate tectonics in petroleum accumulation

Plates tectonics has been a concept of debate for decades. There are a lot of intensive studies to understand the continuous motion of plates. Plate are referred to as a large, rigid slab of solid rock and tectonics is a word whose root came from a Greek language which mean “to build”. Plate tectonics is the study of movements of plates and the processes that go on within the Earth (Jpb, 2017). The concept of plate tectonics is related to earth processes of seafloor spreading, lithospheric subduction, continental drift, continental collision and transform faulting which has been changing the world’s geography for the past 180 million years and coincidently the accumulation of approximately 90% of the known oil and natural gas reserves in the World (Thompson, 1976).

According to Doglioni, n.d, numerous theories have been proposed by various authors about the concept of plate tectonics for decades and some of the authors include; Hess, 1962; Vine and Matthews, 1963; Hiertzler, 1968; Condie, 1989. In 1596, Abraham

Ortelius (Dutch map maker) in his work Thesaurus Geographicus proposed that due to the events of floods and earthquakes led to the separation of both North and South America by saying they were “torn away from Europe and Africa” (Müller, 2002). In the 1800s, Alexander von Humboldt (German Explorer) observed the opposing shores (North America and Europe, South America and Africa) between the Atlantic Ocean had some similarities (Kearey et al., 2009). An American physicist F.B. Taylor in 1910 was the first to suggest the concept of continental drift and later by Alfred Wegener in 1912. Taylor proposed that continental drift explained the geometrics and geological similarities along the sides of the continents especially around the Atlantic and Indian Oceans and further stated the drift explained the distribution of the young folded mountain belts and “the origin of the Earth’s plan” (Kearey et al., 2009).

Alfred Lother Wegener, 1915 then later suggested about the continental drift. The science community during that time wasn’t fully convinced about the breakup of Pangea with his theories until Professor Alexander Du Toit of Johannesburg University later proposed that the Pangea first separated into two large masses known as Gondwanaland (Southern hemisphere) and Laurasia (Northern hemisphere) which then continued to breakup into the smaller continents that exist today (Müller, 2002). Du Toit stated that Laurasia (Canada and Asia regions) consist of Europe, North America, Asia and Greenland and Gondwana consist of Antarctica, South America, Madagascar, India, Africa and Australia. The proto- Pacific Ocean or Panthalassa (literally “all ocean”) was surrounding Pangea (Kearey et al., 2009). Wegener worked much on older pre-drift, geological data as well as understood the continuation of older structures and formations of fossil faunas and floras across the continental shorelines in the pre-drift reconstruction (Kearey et al., 2009). These observations lead Wegener to term the continental assembly as Pangaea (known as “all the Earth”). Due to all these evidences, it has been concluded with the theory proposed by Wegener that roughly 300 Ma ago, the earth’s landmasses were squashed into one huge supercontinent known as Pangaea and about 200 Ma. ago, it began to split up (Sumner, 2015).

Kearey et al., 2002 states that Gondwanaland started to breakup during the late Triassic / early Jurassic times about 200 Ma. ago. The North Atlantic started opening about 180 Ma. and the South Atlantic later opened about 130 Ma. Keppie, 2015 as cited by Sumner, 2015 proposed that the Tethys ocean was the driving force behind the breakup of Pangaea.

In the 1960's, Francis Bacon mentioned about the opening of the Atlantic and Indian Oceans which has evolved to the present-day continents and oceans are as the results of the continuous rifting of Laurasia and Gondwanaland (Byrant et al., 2012). The East African rifts, Lake Baikal rift, Russia and the Basin and Range Province, western USA are examples of these rift systems (Bryant et al., 2012).

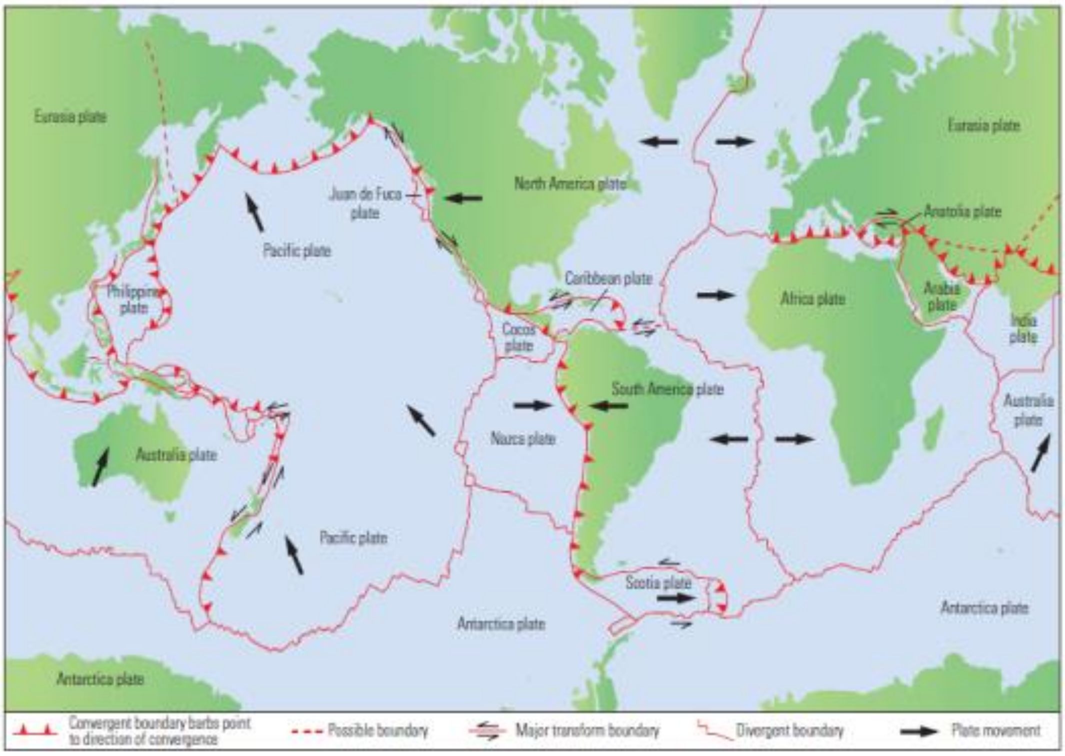

Figure 3.1. Map of the earth showing the relative plate movements at the various plate boundaries (Bryant et al., 2012).

3.2.2. Theories of global tectonics

The theory of global plate tectonics which explains the geological phenomenon of plate motions and plate boundary zones (Niu, 2014). The theory of plate tectonic states that a top hotter, more mobile material is the cause of the movements of the Earth's outermost layers. This has led the layers to be fragmented into large and small plates that are moving relative to each other (Müller, 2002). One of the assumptions of the plate tectonics is that, the plates are rigid and do not deform internally but more relative to each other and therefore explains the earth processes such as magnetism, metamorphism, deformation and earthquakes along the plates boundaries but cannot explain within –plate geological phenomena (Niu, 2014). Müller, 2002 also stated that the events of plate tectonics have spurred some scientific evidences which formulates the theory of plate tectonics. These events are the illustration of the raggedness of the ocean floor. They give information about the geological past, sea floor spreading hypothesis, volcanic activities as well as repeated reversals of the Earth's magnetic field.

In our present day, due to the continuous motion of plate tectonics, the Earth's surface has been separated into seven (7) major plates and several minor ones. Africa, North American, Antarctica, Australian, , South African, Eurasian and Pacific plates are the seven major plates and Adria, Juan de Fuca, Arabia, Cocos, Caribbean, Philippins , Nazca, plates are composed of continental and oceanic lithosphere are the minor ones (Jpb, 2017; Doglingo, n.d.; Dar, 2013).

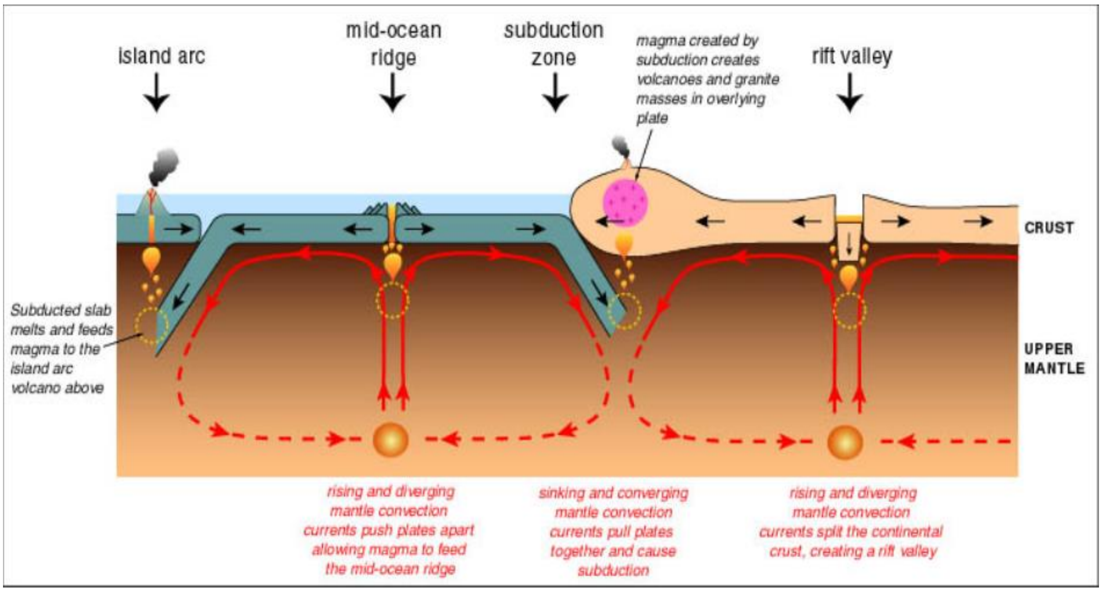

Figure 3.2. An illustration of the concept of plate tectonics theory ongoing on the earth's surface (Dar, 2013).

3.2.3. Driving force of plate tectonics

The Earth is made up of different composition and physical properties such as a viscous mantle, solid central core, the fluid peripheral core, and the solid lithosphere (i.e. Continental and oceanic lithosphere). It is this lithosphere that has separated into the several plates we see today (Jpb, 2017). Niu, 2014 proposed that water bodies (e.g. oceans) are the primary cause of plate tectonics and that water has the highest heating capacity and oceans may have caused the development of the cold and dense oceanic plates. Also, water is an effective weakling agent which facilities subduction initiation (Niu et al., 2003; Niu, 2014). Convection in the mantle is the driving force of the plates that is generated in both the core and mantle (Kearey et al., 2007). Holmes, 1931 as cited in Niu, 2014 first proposed that mantle convection was the driving force for the continental drift. Middleton et al., 1996 as cited by Müller, 2002 stated that tectonic stresses are forces that drive plate tectonics. Chapple and Tullis, 1977 also stated that Morgan, 1971, 1972-b suggested the hotspots at the base of the lithosphere is due to the horizontal flow of material leading to the plate movements. Forsyth and Uyeda, 1975 used the observed motions and geometries of the plates to solve the inverse problem of knowing the relative magnitude of the plate forces and noted that velocity of the plate motion is independent to the size, circumference and ridge length of a plate (Kearey, 2002; Niu, 2014).

The different types of plate forces acting on the lithosphere are the ridge push and slab pull (Bostrom 2000 as cited in Doglioni n.d.). According to Doglioni, n.d. defines ridge push as the potential gravitational energy that causes an increase in the rise of a mid-ocean ridge and slab pull as the mechanical action that allows subduction of a cold plate at lower temperature to a warmer surrounding mantle. This confirmed by a work done in Zoback et al., 1989; Zoback 1992 as cited in Niu, 2014 which involved a Project on the giant World stress map. Therefore, to understand plate motions, subduction zones are of great importance (Niu et al., 2003) and oceanic ridges play as a passive feature (McKenzie and Bickle, 1988; Davis and Richard, 1992; Niu and O'Hara, 2008 as cited in Niu, 2014). Reconstruction of the continents has led scientists to believe that the continents were once fitting each other. For example, the remains of the early Permian reptile Mesosaurus found in both Brazil and South Africa indicates this (Kearey et al., 2002). Another is the widespread dispersal of marine invertebrates (Hallam, 1973 b) as well as ancient faunal province boundaries due to correlation with sutures also explains ancient continents were once together (Kearey et al., 2002).

There are several implications plate motions have on the earth's surface and the most important one is the creation of sedimentary basins along continental margins where fossil fuels are easily deposited. Under favorable conditions, the sedimentary basins tend to preserve resources like petroleum and natural gas. Plate tectonics has played an important role of locating petroleum and natural gas reservoirs which are generated and trapped in sedimentary basins across the globe. Some examples of such basins are the Paris and Michigan basins, Gulf of Aden (Red Sea), the North Sea, Gabon Basin, Los Angeles Basin and others (Kearey et al., 2002).

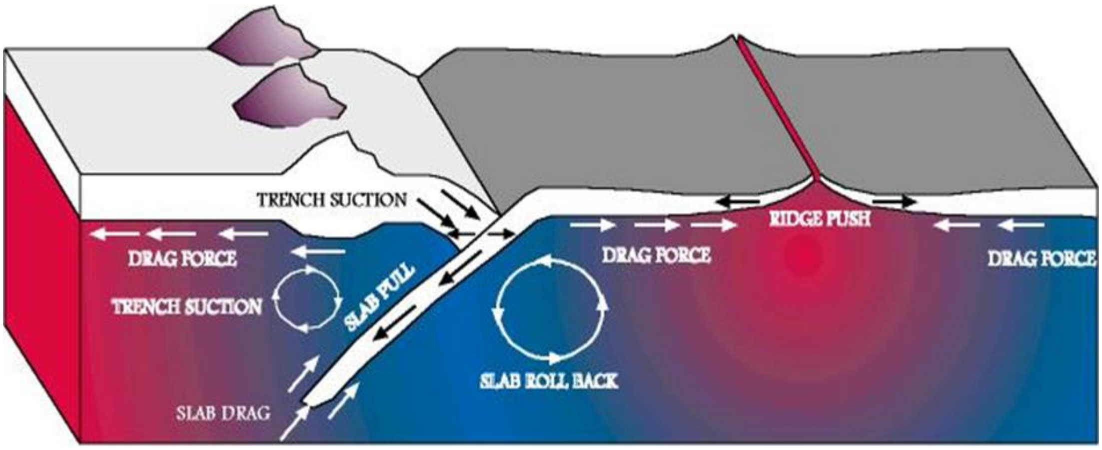

Figure 3.3. The driving forces that control plate tectonics motion (Weil, n.d.).

3.2.4. Plate boundaries

The earth's crust is made up of continental shelves, continental slopes, continental rise, deep- ocean trenches and plate margins (Dar, 2013). The continental shelves make up the 75% of the total ocean and have economic importance due to large reserves of petroleum and natural gas (Busby and Zor, 2012 as cited in Dar, 2013). Plate motions are as a result of both linear movements that may reach up to >20 cm/yr. and vertical components of up to 10 mm/yr. (Jpb, 2017). Plate boundaries are usually outlined by active earthquake epicenters and surrounded by spreading centers, subduction zones and transform faults. The relative motion of plate tectonics has been explained using Euler's theorem (Müller, 2002). The Euler's theorem states that a single angular rotation about a pole is defined by the movement of a section of a sphere across a surface (Müller, 2002; Kearey et al., 2002; Doglingo, n.d.).

According to Assaad, 2009, active tectonic movements (epeirogenic movements and orogenic movements) and passive tectonic movements (large parts of the Precambrian platforms) are the types of tectonic movements known. Examples are in the Alpine-Mediterranean zone of Eurasia, and that of the passive tectonic movements are North America and Russia, central of Africa (the Algerian Saharan platform). The types of plate boundaries are convergent boundaries, divergent boundaries and transform and wrench boundaries (Kearey et al., 2002; Assaad, 2009; Ingersoll, 2012; Dar, 2013; Jpb, 2017, Doglioni, n.d.; Mansor, n.d.).

3.2.4.1. Divergent plate boundaries

They are known as constructive margins because they completely fracture the continental lithosphere. At divergent plate boundaries, the rise of magma from upwelling mantle causes the plates to spread out which causes rifting leading to sea floor spreading creating new oceanic lithosphere. These phenomena can be seen in the mid-Atlantic rift valley which causes two plates to separate from each other (Doglioni, n.d.). The process of plates separating at diverging boundaries is referred to as a rift-to-drift transitional and inter-plate continental margins (Dickson, 1974 b, 1976 a; Ingersoll, 1988; Bond et al., 1995; Ingersoll and Busby, 1995 as cited in Ingersoll, 2012). According to Ingersoll and Busby, 1995, Leeder, 1995 as cited by Ingersoll, 2017 states that the mechanisms that initiate continental rifting experience successful or failed rifting. Successful rifting results sea floor spreading leading to the creation of nascent ocean basins, but failed rifting doesn’t evolve into nascent ocean basins. Not all rifting processes results into oceanic rifts (Doglioni, n.d.; Dietz, 1961 and Hess, 1962 cited in Kearey et al., 2009; Dar, 2013; Ingersoll, 2017).

The divergent plates separate at a rate of 100 to 200 mm/yr. at fast spreading boundaries from rapid spreading and addition of abundant hot magma and lava flows. For example, the East Pacific Rise moves apart at less than 55 mm/yr. with broader and rougher topography and features rift valleys. At ultraslow spreading boundaries, such as the mid-Atlantic ridge, the plates separate at a rate of at less than 20 mm/yr. and causing huge slabs of mantle rock to rise to the ocean floor (Dar, 2013). Assaad, 2009 stated that mid - ocean ridges are created by diverging plate boundaries which can be seen in the Atlantic, Pacific and Indian Oceans. The type of basins created at divergent type settings which may lead to the accumulation of petroleum and natural gas are nascent ocean basins, inter-cratonic basins, active ocean basins and dormant ocean basins (Ingersoll, 2012).

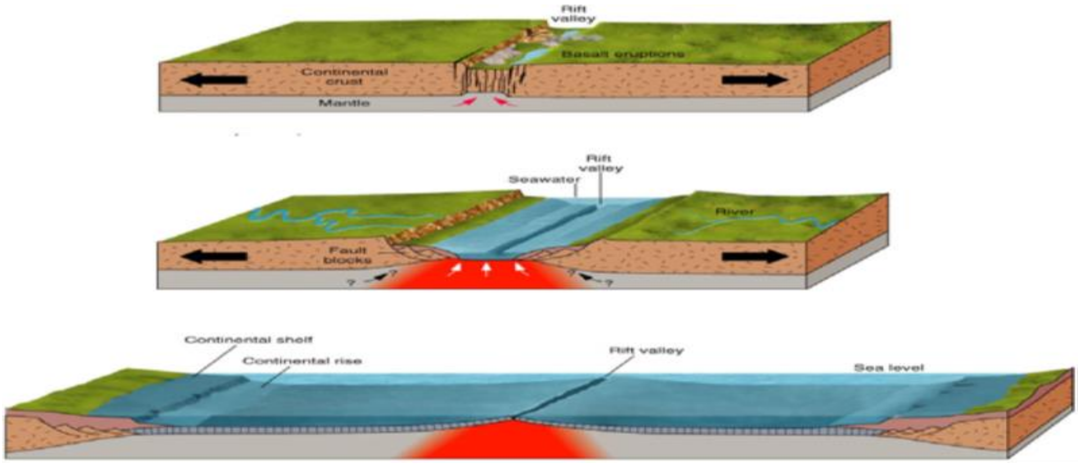

Figure 3.4. Processes involved at divergent plate boundaries on the earth's surface (Dar, 2013).

3.2.4.2. Converging plate boundaries

When two plates of different densities (one heavier - oceanic lithosphere and the other lighter - continental lithosphere) collide into each other causing the heavier plate to sink or subduct into the hot mantle is known as a converging plate boundary (Müller, 2002; Assaad, 2009; Dar, 2013; Doglioni, n.d.). When the subducted slab sinks into the hot mantle, it is partially melted till it goes down as deep as 700 km deep into the earth (Assaad, 2009). The subduction zones create orogens and accretionary prisms (Bally, 1983 as cited in Doglioni, n.d.). This event is evident in the mountain belt of Apennines. Convergence can occur in different ways by either between a continental and oceanic plate, oceanic and oceanic plates and, continental and continental plates (Müller, 2002).

At the oceanic - oceanic convergent plates boundaries, one of the plates (older, denser and colder) tends to be subducted into the mantle (Dar, 2013) and forming a trench. For example, the Mariana trench where the Pacific plate convergences into Philippine plate (Müller, 2002). This subduction processes of this type of convergence also creates volcanoes in the ocean. These volcanoes that are submerged in the ocean over geological time rise above the sea level and form chains of island arcs (Müller, 2002; Assaad, 2009). Examples of these island arcs are the Marianas and Aleutian Islands (Müller, 2002).

When an oceanic plate collides into a continental plate which hardly sinks, the oceanic plate gets subducted downwards into the hot mantle creating coastal mountains (Assaad, 2009; Dar, 2013). According to Müller, 2002, trenches are created at the deepest parts of the ocean floor due to the subduction and this is evident in the pacific rim (ring of fire). Places like the Andes and Cascade Range in the Northwest of the pacific can sustain the earth's volcanic activities due to oceanic-continental convergence (Müller, 2002).

Continental - Continental Convergence Plate Boundary happens when two large continental plates collide into each other head-on neither of them subducting due to having same densities, tend to buckle and push upwards or sideways creating huge and long chain of mountains (Müller, 2002). This phenomenon is witnessed in the Himalayan mountains and Tibetan Plateau.

The events of convergent plate boundaries cause foreland basins are formed at the front of mountain belts and accretionary prisms (Doglioni, n.d.). Ingersoll, 2012 states that retro-foreland, trench-slope, inter-arc, forearc, back-arc, remnant ocean, pro-foreland, hinterland basins and wedge-top are usually formed at converging plate boundaries settings.

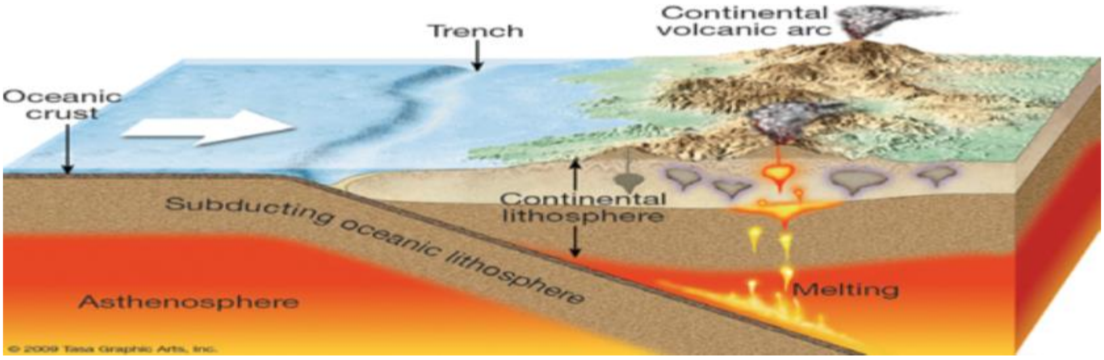

Figure 3.5. Convergent plate boundaries processes (Dar, 2013).

3.2.4.3. Transform plate boundaries

They are zones where the plates slide horizontally or against each other along a transform or deep fault without any subduction or collision (Müller, 2002; Assaad, 2009; Dar, 2013; Doglioni, n.d.). A transform fault is also known as a transcurrent or conservative margins (Doglioni, n.d.). Transform margins have specific characteristics which are strongly triggered by structural damming effects. These effects are a tectonic history influenced by transform motion between two breaking plates, rapid ocean-continent transition, a high input of clastic sediments as a consequence of rapid subsidence, a complex history of uplift and subsidence and active transform tectonics and subsequent sedimentation (Mascle and Blarez, 1987 as cited by Mascle et al., 1997). A Canadian geophysicist J. Tuzo Wilson, 1965 is the one who proposed about the origin of transform fault. Wilson proposed that transform fracture or faults zones connects two spreading centres (diverging plate boundaries) or trenches (converging plate boundaries) (Müller, 2002). Dar, 2013 states that most transform faults occur on the ocean floor, but few occur on continental plates. Spreading ridges and subduction zones or subduction zones and triple junctions are mostly connected by transform faults (e.g., Aldaya and Maldonado, 1996; Barker, 2001; Fournier et al., 2011 as cited in Duarte, 2018). Most of these plate boundaries can be found in ocean basins (Dar, 2013). Example of the ocean floor is that of the transform movements at the mid-ocean ridges in the Atlantic (Romanche and Vema) and Pacific Oceans (Assaad, 2012; Doglioni, n.d.). Large scars of the Northeast Pacific off the coast of California and Mexico are the Clarion, Molokai and Pioneer fracture zones (Müller, 2002). The continental transform fault is the San Andreas fault zone in California (Müller, 2002) and the Alpine, Dead Sea, and North Anatolian faults (Duarte, 2018). These faults are characterized by shallow earthquakes (<50 km. deep) (Müller, 2002). Ingersoll, 2012 indicates that transform plate setting are mostly made up of strike-slip systems as well as trans-tensional, transpressional and trans-rotational basins can be located at transform plate boundaries.

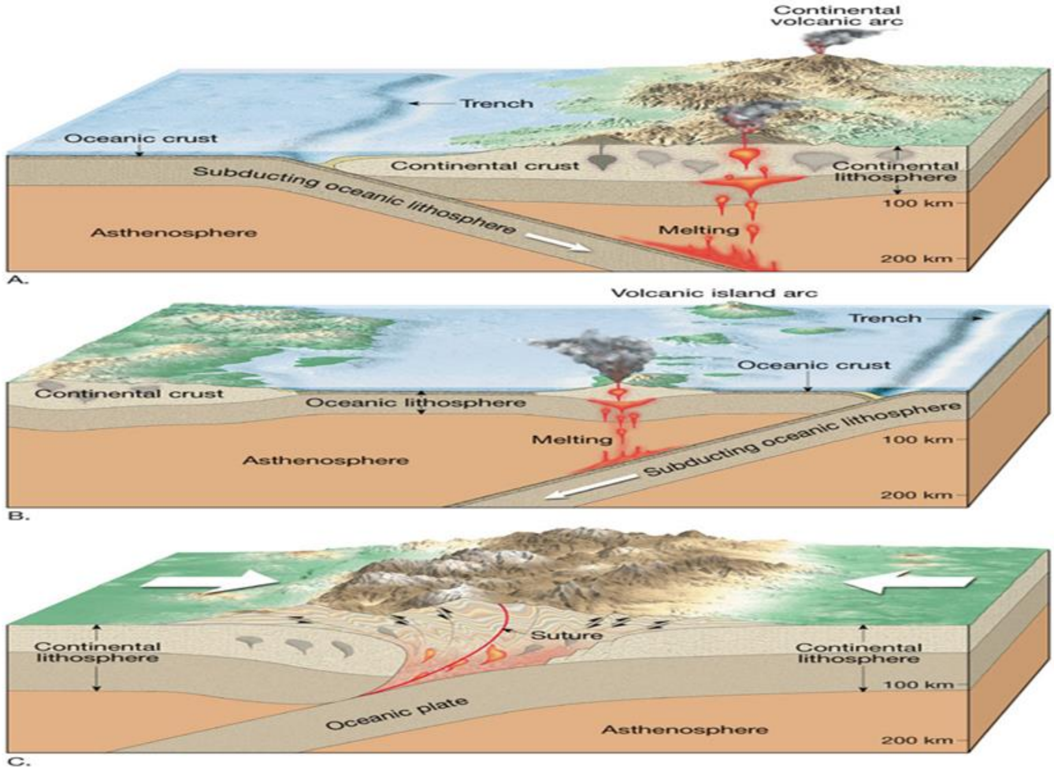

Figure 3.6. Types of convergent plate with the processes they undergo. A. Ocean-Continent. B. Ocean-Ocean and C. Continent-Continent convergent plate boundaries (Leyva, 2015).

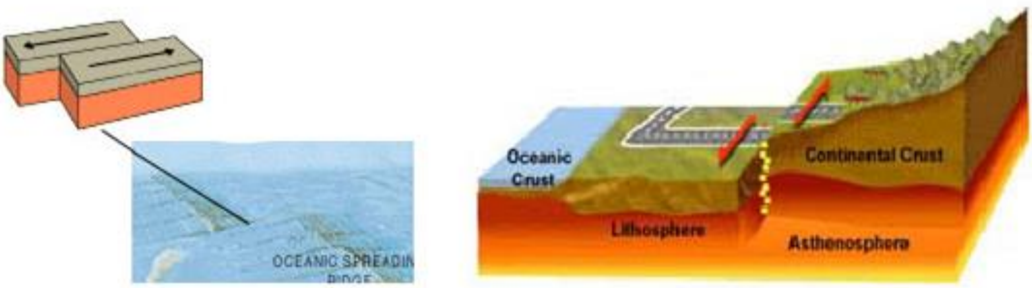

Figure 3.7. Figure 3.7. Transform plate boundary (Dar, 2013).

3.2.5. Plate tectonics and development of sedimentary basins

Sedimentary basins are areas where sediments have accumulated over long periods of time at a significantly greater rate and thickness which has been preserved for long geologic time (Dar, 2013). Sedimentary basin is also defined as an area where the crust subsides or a pre-existing empty basin which can be filled by sediments (Doglioni, n.d.). Bally, 1915 as cited by Dar, 2013 defined sedimentary basins as realms of subsidence containing an amount of thickness of sediments exceeding one km that are still preserved in a coherent form. Assaad, 2012 indicates that a sedimentary basin develops from the process of subsidence of the crust, or from uplift of confined basin margins resulting in an accumulation of prism of strata. Watts et al., 1982 describes sedimentary basins to have occurred through their evolution by epeirogenesis or vertical movements of the earth's crust. Müller, 2002 states that sedimentary basins are either formed in response to regional compression in orogenic belts. These are some definitions and information of the origin of sedimentary basins by different researchers.

Sedimentary basins are usually formed either on the continental crust or they are encountered at plate boundaries. The tectonic setting during its evolution will determine the type of basin formed. The depositional conditions, sequence and the way the plates interact gives a unique history of a basin. Sedimentary basins are primarily formed by thinning of the lithosphere (extensional or trans-tensional tectonics), thermal cooling of the oceanic and continental lithosphere at passive margins, folding of the lithosphere at subduction zone hinges due to slab retreat, or sinking generated by the load of the mountain belt or delta on a continental margin (Doglioni, n.d.). This leads to stratigraphic fill in the basin which takes place due to the nature of depositional activity system (Assaad, 2009). The formation of folded and faulted structures within the basin is related to either tectonic processes or sedimentary evolution. Faults and tilted blocks are the products of extensional deformation while folds and thrust faults are the products of contractional deformation (Assaad, 2009). Most basins are formed on the earth's crust and can be classified by rifted and orogenic settings (Sloss and Speed, 1974; Dickson and Yarborough, 1976; Bally and Snelson, 1980 as cited by Watts et al., 1982; Dar, 2013).

Divergent plate boundaries are dominated by extensional forces are associated to rifted basins (Bally and Snelson, 1980 as cited by Watts et al., 1982; Dar, 2013). the US Atlantic margin basins (Baltimore Canyon Trough, South Caroline Trough) and the

North Sea Basin are examples of rifted basins evident on our modern-day earth (Watts et al., 1982). Convergent plate boundaries dominated by compressional forces are associated with orogenic basins and examples of these are the foreland (Appalachians, Alberta and Ganges) and fore arc (Cook Inlet, Alaska) (Bally and Snelson, 1980 as cited by Watts et al., 1982; Dar, 2013). According to Assaad, 2009 sedimentary basins that can occur at rifted settings after plates have separated from each other, they then tend to be enhanced by thermal decay over time and may be augmented mostly by flexures in response to sedimentary loading and in that of orogenic settings. Plate flexures by plate consumption or local tectonic thickening of crustal profiles as well as sedimentary loading and other thermo-tectonic effects are some of the process that allow further subsidence of a basin.

The rapid rifting phase in an extensional tectonic setting produces extremely prolific source rocks usually when oceanographic circulation and half graben depocenters are starved which can be found in sedimentary basins in Mediterranean Sea ,West Africa, Russian Arctic, East Africa, South China Sea, East Brazil and Gulf of Mexico (Gao, 2012). Gao, 2012 further stated that at the West African and East Brazilian passive continental margin above rift and sag basins is a well-known downslope marine area where prolific source rocks are evident and dominated by gravity-induced thrust, folds and salt structures with a high sealing capacity. This has paved way for extensive oil and natural gas exploration in these areas and huge commercial quantities of petroleum has been found.

3.3. Opening of the South Atlantic Ocean

The Atlantic Ocean is a long sinuous ocean which originated during the Mesozoic following the breakup of the Supercontinent of Pangea (Levin and Gooday, 1999). It is bordered to the west by South American plate and to the east by the African plate with the mid-Atlantic oceanic ridge made of transform faults passing through it. At the northern portion of it is the subpolar Greenland and Norwegian Basins (Levin and Gooday, 1999) and that of the south by the subtropical convergence around 40 o S (Webb, 1996 as cited by Levin and Gooday, 1999).

The opening of the Atlantic Ocean started through the breakup of Gondwana and Laurasia roughly around 300 million years. That of Gondwana leading to the development of the South Atlantic Ocean started up about 130 Ma during the early Cretaceous epoch which separated South American continent from the African continent (Bryant et al., 2012).

The Continental rifting between these two continents started in the south and moved up northward which ended about 20 to 30 million years later during the Aptian and Albian ages (Bryant et al., 2012; Granot et al., 2015). That of the central portion started opening later due to the continental plate being hotter and softer there (Bryant et al., 2012). This led to the creation of extensional domains on the African Continent. The West African Rift System (WARS), Central African Rift System (CARS), the South African Rift System (SARS) and the Equatorial Atlantic Rift System (EqRS) are the domains of extension witness on this modern-day earth's surface (Burke and Dewey, 1974; Fairhead, 1986; Nürnberg and Müller, 1991; Genik, 1992 ;Basile et l., 2005; Heine et al, 2013 as cited in Heine and Burne, 2013).
The Equatorial Segment and Romanche Fracture Zone (RFZ), the Central Segment between RFZ and Florianopolis Fracture Zone (FFZ) hosting the Aptian Salt accumulation, the Southern Segment from the FFZ to the Agulhas- Falkland Fracture Zone (AFFZ) and the Falkland Segment south of the AFFZ are the divisions of the South Atlantic Ocean (Torsvik et al., 2017).

When the Atlantic Ocean finally opened, it rifted South America to the north-western direction and Africa to the north-eastern direction (Bryant et al, 2012). This has caused some events for example the Tristan da Cunha province which is a hotspot widely linking the Parana and Ertendeka flood basalts in Brazil (South America) and Namibia (Africa) (Bryant et al., 2012; Torsvik et al., 2017). This hotspot province is characteristically defined by their rapid eruption between 133 and 180 Ma (Torsvik et al., 2004 as cited by Torsvik et al., 2017). Also, the Rio Grande Rise and Walvis Ridge was formed in the southern portion of the South Atlantic Ocean and Demerara Plateau of Suriname and French Guiana and the Guinea Plateau in West Africa were associated with the breakup in the northern latitudes of the Equatorial South Atlantic Segment, and the coasts of north Brazil, Cote d'Ivoire and Ghana in the southern latitudes of the Equatorial South Atlantic Segment (Bryant et al., 2012). Similar regional sedimentation histories (late Jurassic and the Present epoch) are evidences observed between the African and South American margins. Evidences can be seen from the various rifting stages (Pre, syn and post) where sediments are deposited into sequences of various rock types (Katz and Mello, 2000 as cited by Torsvik et al., 2017). The West African and the Sao Luiz cratonic areas, Imataca and Fallawatra complexes of the Guayana Shield and the Liberian age-province in West Africa, the Caririan Fold Belt (Borborema Province) of northeast Brazil and the Pan-African Belt of Nigeria and Cameroon, the Damara Belt in Southwest Africa and the South African coastal region, and the basement rocks of Uruguay and Buenos Aires province of Argentina are some of the provinces after the pre-drift event between South America and Africa, the Rockelide Fold Belt in West Africa and the Paraguay-Araguaia Belt in Brazil, the Jequid Complex in Bahia, the Ntem Complex of Cameroon and similar rocks in Gabon and Angola, the northern part of the Ribeira Belt (Mantiqueira Province) in Brazil and the West Congo Belt in West Africa and the southern part of the Ribeira Belt (Mantiqueira Province) in southern Brazil and Uruguay (Torquato and Cordani, 1981).

Tectonically, the Atlantic Ocean is less active than the Pacific with very few subduction zones and trenches (Levin and Gooday, 1999). A global data record from seafloor spreading and magnetic anomalies (stripes) has helped in retracing the process of ocean growth since the breakup of Gondwana (Reeves, 2010). Plate tectonic processes alongside geological events that are controlled by geography, climate and basin history have paved way for the discovery of oil and natural gas along the continental shelves and this can be witnessed along the South America and Africa. Some of the discoveries are the matching salt basins from Brazil to Angola and matching turbidite sequences from Ghana to French Guiana (Bryant et al., 2012).

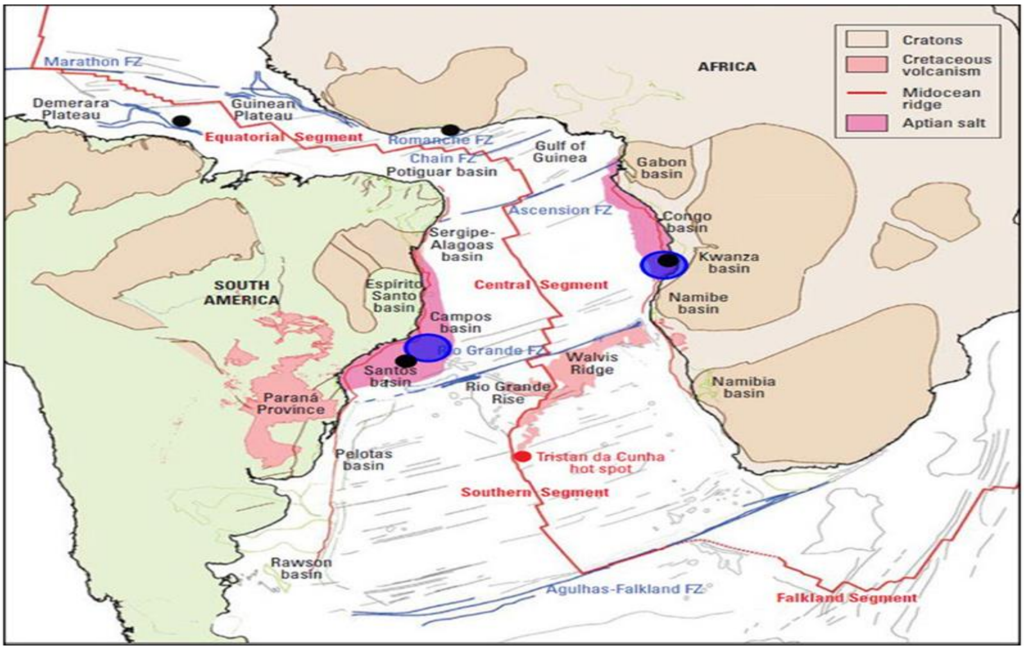

Figure 3.8. Tectonic map of the South Atlantic (Bryant et al., 2012).

3.4. The Petroleum System

As mentioned at the beginning of this chapter about the main components of the petroleum system to the presence of organic rich source rock, reservoir rock, seal and trap alongside processes of maturation, migration and timing under favorable conditions promotes the generation of hydrocarbons. A hydrocarbon system under all the provided excellent conditions such as deposition of organic rich source rock which can generate oil and gas over a long restricted geological time scale can be termed as a petroleum system as indicated in Figure 3 9 (Isinugen, 2012; Al-Hajeri et al., 2009). Zhao et al, 2018 explains the different types of petroleum systems (source petroleum system, tight petroleum system, and conventional petroleum system) based on reservoir qualities which are as explained in Table 3.1.

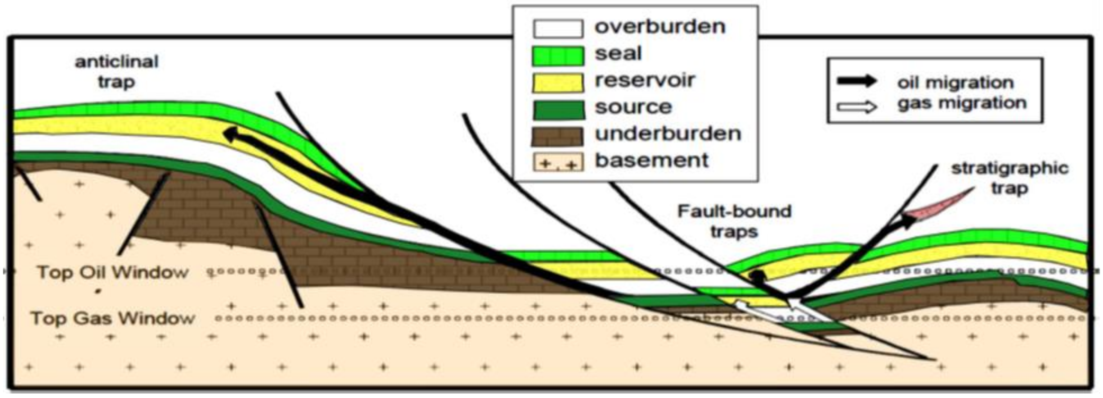

Figure 3.9. Figure 3.9. Illustration of the petroleum system (Isinugen, 2012).

Table 3.1. Explanation of the various types of petroleum system (Zhao et al, 2018).

Types of petroleum systems	Source petroleum system	Tight petroleum system	Conventional petroleum system
Essential elements			
Source rocks	Shales, carbonates, coals	Shales, carbonates, coals	Shales, carbonates, coals
Reservoirs	Source rocks	Tight sandstones and carbonates	Conventional reservoirs
Seals	Self-sealing	Self-sealing; mudstones, carbonates, etc.	Mudstones, carbonates, etc.
Traps	Not required	Non-anticlinal traps are necessary, while anticlinal trap functions for some	Indispensable
Essential processes			
Generation	No particular requirement for timing	After the reservoir gets tight	Prior to or contemporaneous with trap formation
Migration	Insignificant or over short distances	Primary migration is important, and secondary migration is mostly over short distance. Migration is mainly overpressure-driven flow	Both primary and secondary migrations are significant. And secondary migration is commonly buoyancy-driven flow and sometimes overpressure-driven flow
Accumulation	Mostly continuous	Quasi-continuous or discontinuous	Discontinuous
Preservation	Commonly excellent	Moderate to excellent	Critical
Types of accumulation	Mostly continuous	Primarily quasi-continuous, and secondarily discontinuous	Discontinuous
Typical accumulation	Shale oil and gas	Tight oil and gas	Conventional reservoirs

3.4.1. Source rock

Source rocks are rocks that generate oil and gas. Source rocks consist mainly of organic rich fine-grained sedimentary rocks and has generated or can generate hydrocarbons. The types of hydrocarbons generated by a source rock depends on the source of the organic matter and on maturation. Most source rocks are shale, sandstones and carbonates (Engler, 2005). Maturation is the thermal processes that act on organic rich source rocks to generate liquid and gaseous hydrocarbons (Tissot and Welte, 1984). The generated hydrocarbons vary by the degree of thermal alteration and the type of source rock. Migration of hydrocarbons is divided in two, namely; Primary migration (Tissot and Welte, 1984, Selley, 1992, Leythaeuser, 1983) and Secondary migration (Walters, 2006). Primary migration is the expulsion of thermally matured hydrocarbons from kerogen rich source rocks and secondary migration is the movement of hydrocarbons away from the source rock along the top of carrier beds (Leythaeuser, 1983; Tissot and Welte 1984; Selley, 1992; England 1994, Walters 2006, Dolson 2016).

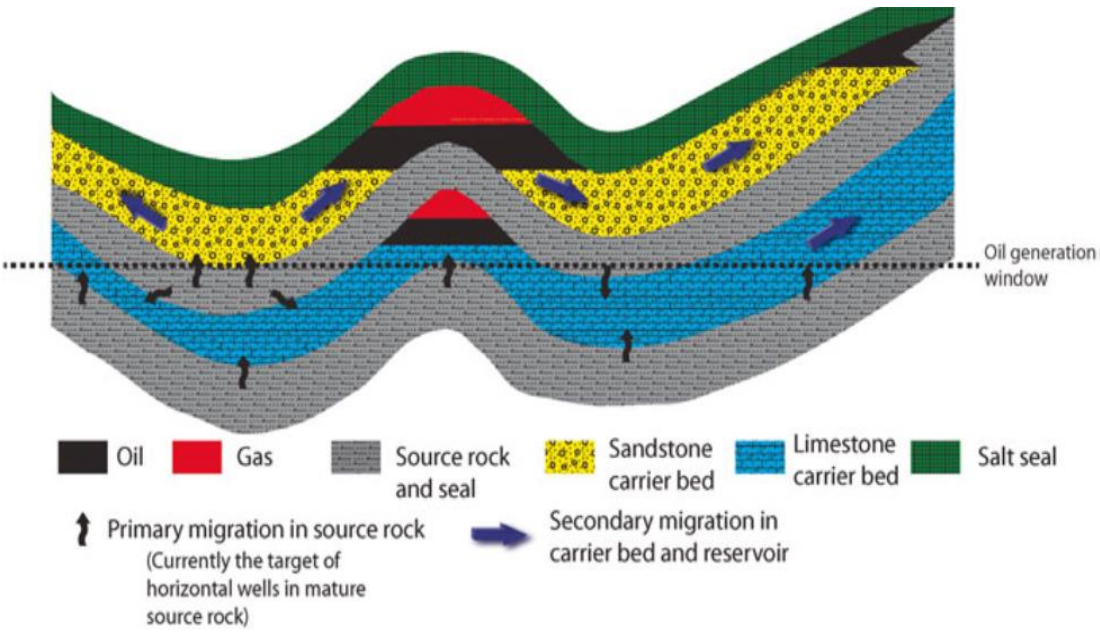

Figure 3.10. Migration pathways in a hydrocarbon system (Modified from England et al. 1991 as cited in Dolson, 2016).

3.4.2. Reservoir rock

Reservoir rocks are porous and permeable rocks that occur in many different shapes and sizes and allows hydrocarbons to accumulate (Broadhead, 2002; Doglioni, n.d.).

They are mostly clastics, carbonates, sandstones or carbonates, but they can also be fractured granites, volcanic rocks or even shale (Dolson, 2016). Depending on the type of rock, the quality of the reservoir can vary considerably and rapidly change laterally and vertically within the trap (Dolson, 2016). Some examples of volcanic rocks serving as reservoir rocks are from Greenland (Bojesen-Koefoed et al., 1999; Christiansen et al., 1998; Pedersen 1986; Pedersen et al., 2007) and in the Embla Field of North Sea. (Abay, 2017).

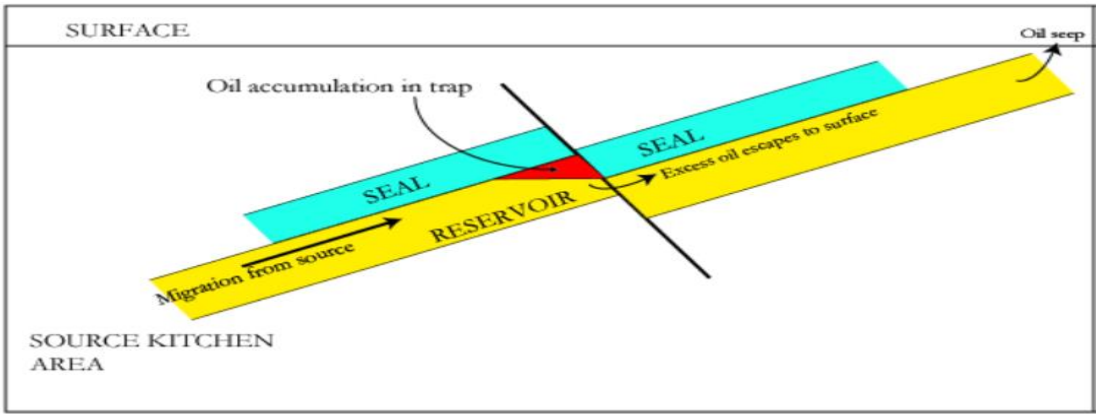

Figure 3.11. Reservoir rock (Isinugen, 2012).

3.4.3. Seal or cap rock

Seal or Cap rock is any rock which prevents the migration of hydrocarbons, promoting the formation of hydrocarbon accumulation (Downey, 1994; Huc, 2016; Abay, 2017). Seals are classified into regional and local where regional seals roof migrating hydrocarbons and local seals confine accumulated hydrocarbons (Ulmishek 1988; Downey 1994). The most effective seal rocks are evaporites, fine-grained clastic and organic rich rocks (Downey 1994). Seals generally have low porosity and permeability that migrating petroleum cannot penetrate through (Dolson, 2016). Depending on the type of lithology, seals may be formed from shales, siltstones, tight carbons, and salts (Nalivkin, 1983; Magoon, 1988).

3.4.4. Traps

Traps are any geometric arrangement of rocks that permits significant accumulation of hydrocarbons in the subsurface (Tissot and Welte, 1984). There are two types of hydrocarbon traps known as structural and stratigraphic traps. Stratigraphic traps are traps formed in a wide variety of depositional environments where the reservoir facies pinch out laterally up-dip into seals (Dolson et al., 1999; Dolson, 2016) and are the common trap type globally, occurring in all provinces where hydrocarbons are generated (Robb 1989; Dolson 2016). An example is the oil field in Prudhoe Bay, Alaska, where petroleum is trapped by a combination of folding and faulting of the reservoir sediments (Robb, 1989). Tectonic activities such as folding and faulting are the reason the formation of structural taps (Tissot and Welte, 1984). Sand lenses, pinnacle reefs and pinch out zones are types of stratigraphic traps (Tissot and Welte 1984, Robb 1989), while anticlines, fault growth and salt structures are examples of structural maps (Abay, 2017) as shown in Figure 3.11.

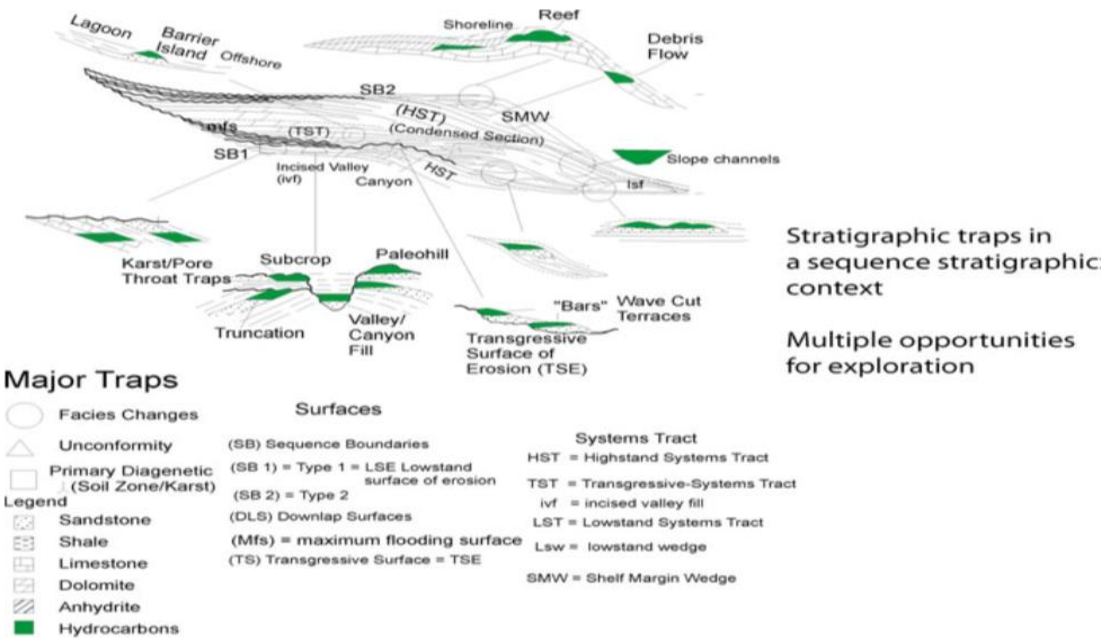

Figure 3.12. Common types of Stratigraphic traps found in various hydrocarbon systems (Modified from Dolson et al., 1999 in Dolson 2016).

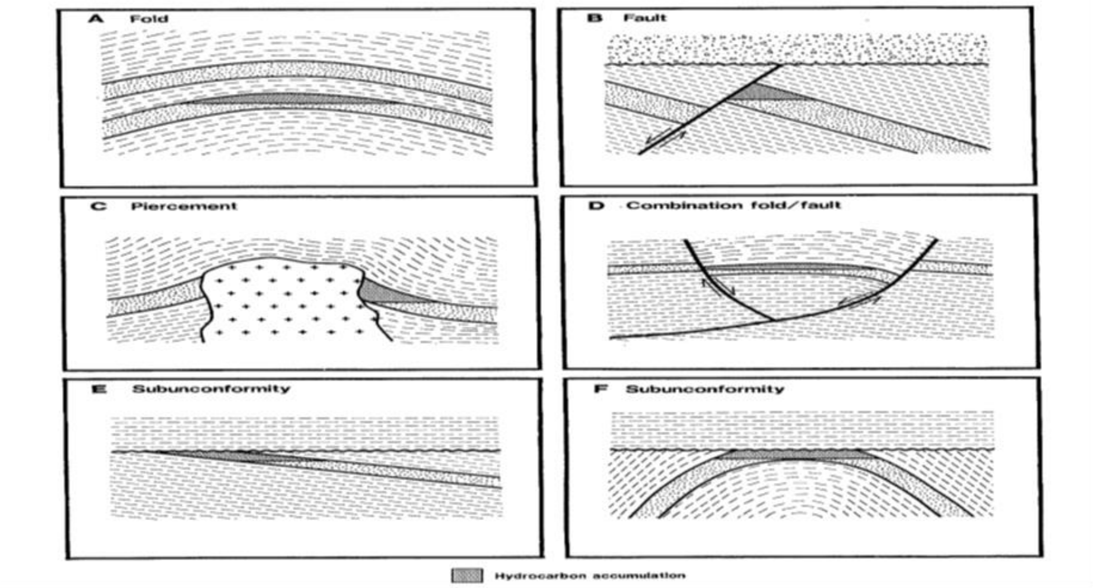

Figure 3.13. Common types of Structural traps in a hydrocarbon system (Magoon and Dow, 1994).

3.4.5. Depositional environment

There are different types of depositional environments that allows the preservation of organic rich matter in sediments allowing petroleum accumulation over long geologic periods of time. A geomorphic unit that allows sediments to be deposited within depressions over long periods of time can be termed as a depositional environment (Mahesha and Balasubramanian, 2013). Mahesha and Balasubramanian, 2013 classified depositional environments into sedimentary, continental (alluvial, fluvial and lacustrine), transitional (deltaic, lagoonal, tidal and beach), marine and other types (evaporative and glacial) of depositional environment. The deposition of sediments into sedimentary basins to form good source rocks to produce oil and natural gas depends on the type of depositional environment present.

According Leythaeseaur, 1983 indicated that marine or lake depositional environments usually produce high quality petroleum source rocks. In a study done in China’s eastern Junggar basin by Bai et al., 2017 it is found out that the potential source rocks within the Junggar basin were of terrestrial to coastal depositional environments under oxic to dysoxic, and fresh to brackish conditions possibly with intermittent seawater influence. Aliyuda et al., 2017 in a work done in the North Sea of Norway states that paralic/shallow marine, deep marine and continental depositional environments have good yields of petroleum production. Burton et al., 2019 states that both marine and reduced environments have the potentiality for petroleum source rocks but that of the reduced environment has a higher importance. A study carried out in the Abu Garadig basin of Egypt proved that the petroleum source rocks present were of marine and mixed marine and terrestrial of origin defining the source of sediment deposition (Ghassal et al., 2018). An Ogbunike quarry site in Nigeria the formations are shale coaly rocks with features of lagoonal and swampy depositional environment indicating that the shales had high organic matter content and could be characterized as good petroleum source rock (Olajubaje et al., 2018).

Petroleum formed from a marine source is influenced by the formation of a carbon rich organic matter and high H / C enriched host rock, which requires the high productivity of plankton in water on the surface. Sedimentary rocks that are deposited in water that contain enough organic matter end up becoming petroleum source rocks that can generate and expel commercial amounts of petroleum and natural gas when heated (Walter, 2006). Certain restricted conditions within the depositional environment allow the formation of organic rich sediments mostly deposited in an aqueous environment. Organic matter rich mud at the bottom waters become oxygen deficient in a marine or lake environment leading to the formation of good quality petroleum rocks (Leythaeuser, 1983), as shown in Figure 3.14. The Black Sea, in deep shelf areas offshore Namibia, offshore Perù, Gulf of Maracaibo and offshore the Arabian Peninsula and the deepest parts of the East African lakes are some example of places that anaerobic or dysaerobic depositional environments have occurred.

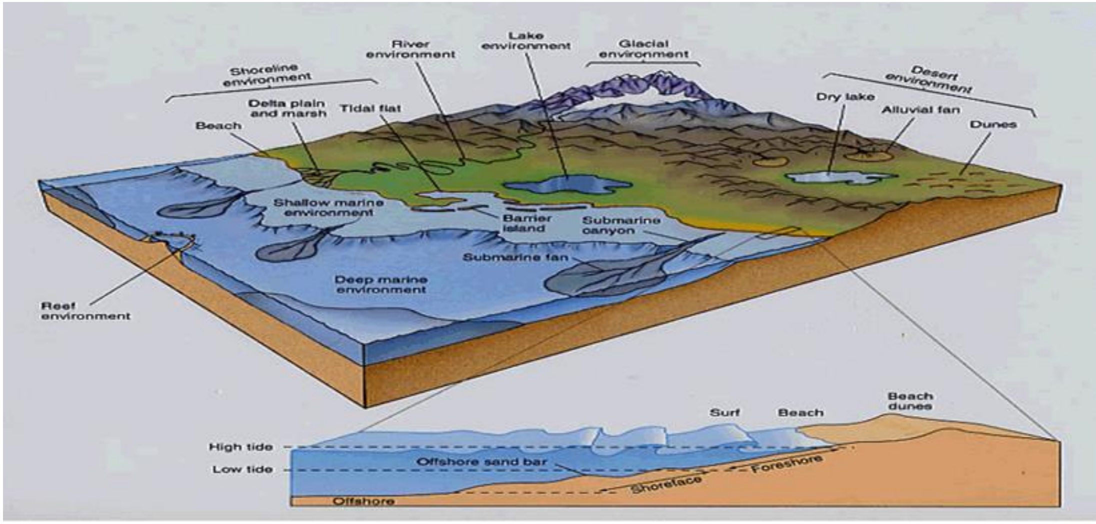

Figure 3.14. Different sedimentary depositional environment for possible petroleum accumulation (Brooklyn College Geology Department, n.d).

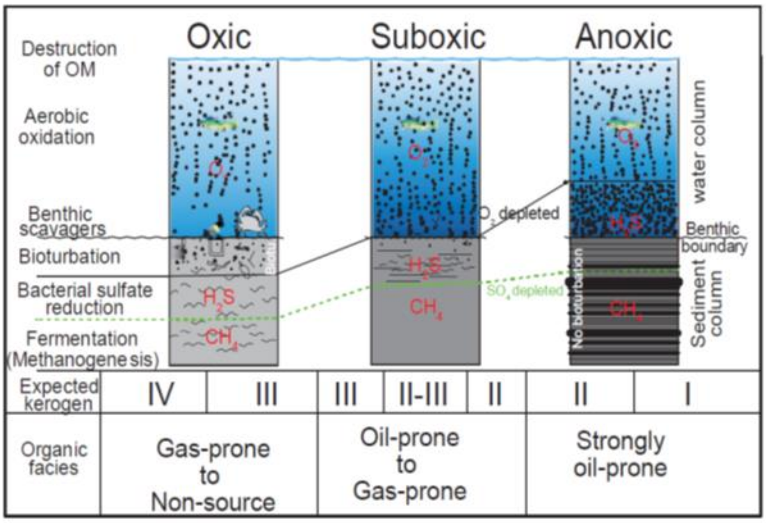

Figure 3.15. Depositional conditions (oxic and anoxic) (Abay, 2017).

3.4.6. Hydrocarbon formation

Petroleum known as black gold is composed of a complex, naturally occurring liquid mixture mainly hydrocarbons, sometimes with other compounds like oxygen, nitrogen and sulfur. Biomarkers which gives an understanding of the origin of the composition of petroleum is of great importance in the formation of petroleum (Leythaeuser, 1983). The origin of the petroleum and its accumulations can be determined from the results of the geological features of the source rock, the reservoir, the seals or the plugs and the traps. These features play an important role in the formation and accumulation of petroleum (Broadhead, 2002). Petroleum is formed when sediments are eroded from inland and deposited into depressions (sedimentary basins). These sediments, rich in organic matter is preserved over long periods of time. In most marine and lake environments where most of the marine life is originated, as these microorganisms die and settle down to the bottom of the sea or ocean, under oxygen deficient conditions and restricted water circulation allows the microorganisms to be well preserved at the bottom (Bjørlykke, 2010). Over long periods of continuous sediment deposition allows for them to become organic rich matter within the sediments later converting to source rocks over time (Walter, 2006).

As the preserved organic matter keeps getting buried deeper into the crust, with increasing temperatures, they tend to turn into kerogens and then start going through thermal maturation for oil and gas production and migration. Next process is the formation of kerogen and the subsequent conversion of kerogen into petroleum (Dembicki, 2016 as cited by Abay, 2017). The most important factors for petroleum formation are temperature and deep burial (Tissot et al., 1987 as cited in Höök et al., 2010). The deeper the preserved organic matter is buried, the higher the increase in temperatures and the more likelihood of formation of petroleum. As the petroleum forms from the source rock, there are pathways it needs to move from the source rock into an area of accumulation. The movement of generated petroleum from the low permeable source rock into the reservoir rock by the effect of buoyancy (area of accumulation) is known as migration (Bjørlykke ,2010). There are two types of migration process known as primary and secondary migration.

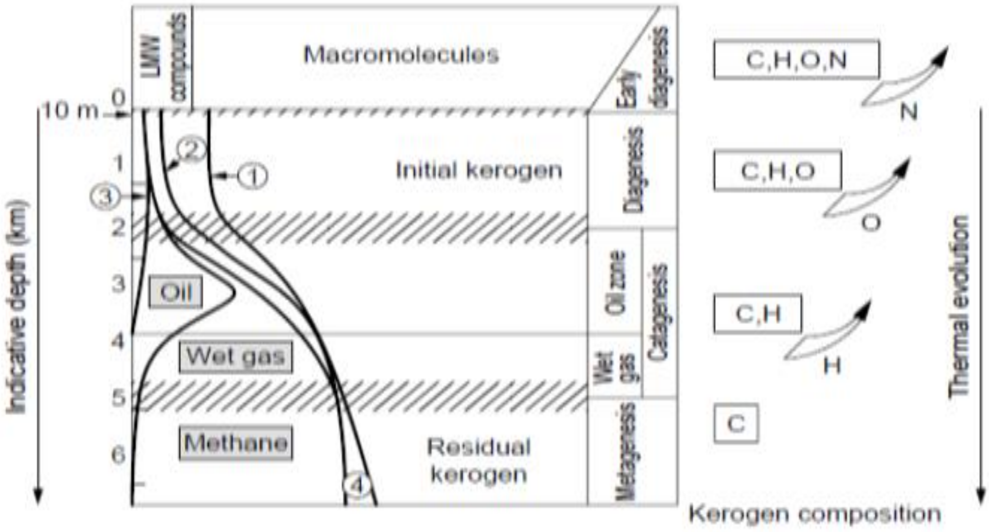

Figure 3.16. Hydrocarbon formation in stages from the breakdown of kerogens (Durand, 2003).

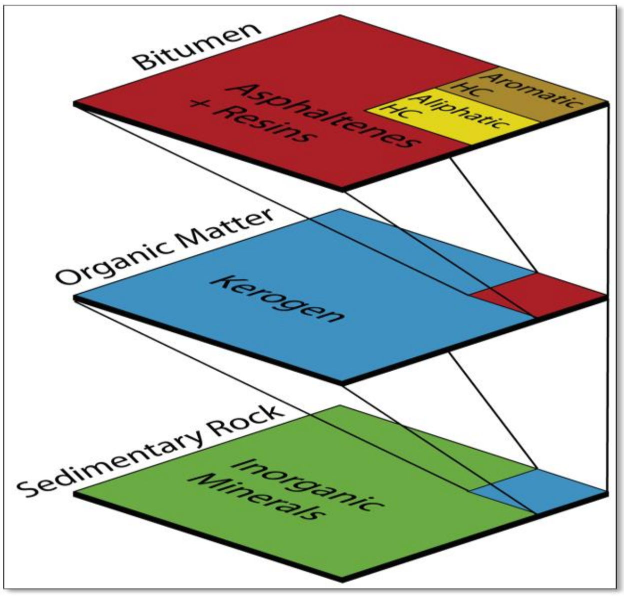

Figure 3.17. Stages of organic matter preservation in the source rock until the maturation stage where hydrocarbons are expelled (Abay, 2017).

3.4.7. Kerogen

A kerogen is a solid organic matter in petroleum source rocks, which are formed by the accumulation of biologically resistant macromolecular substances such as membranes, cell lipids, cuticles cell walls of algae, spores and pollen and are generally insoluble in low boiling solvents (Leythaeuser, 1983). Kerogens are made up of organic carbon which are bonded to a condensed and insoluble macromolecular material (geopolymer), which are formed into distinct monomers in a certain structural order depending on the origin of the organic matter (Walter, 2006; Bjørlykke ,2010). Killops and Killops, 1993, indicate that the major components of kerogens are systems of poly-condensed aromatic rings with attached aliphatic side chains of different lengths joined by different functional groups such as the ester, ketone, and sulfur bridges. The progressive burial of phytoplankton causes the early release of CO_2 and H_2O and the formation of kerogen (Bjorlykke, 1989 as cited in Robb, 2005). The kerogen matures with long-chain covalent bonds that characterize the organic molecules and degrade to low molecular weight compounds. At temperatures between 100 and 120 °C and at a depth of 3 to 4 km (depending on geothermal gradient) creates a proportion of hydrocarbons that can migrate from the source rock. This interval is called the oil window. By burying and breaking up molecular bonds, large quantities of gas, mainly methane, can form and migrate. The solid residue remaining in the sediment, called kerogen, desolates as burial progresses, and has a composition close to that of pure carbon (graphite) (Robb, 2005). See Figure 3 for summary.

Preservation of organic substances in sediments determines the potential of rich hydrogen with high H / C ratios> 1.2 (oil prone) or H / C ratios of 0.5 to 0.8 (gas prone) (Walters, 2006). Oxic and anoxic conditions are the favorable conditions for organic matter preservation where the oxic conditions favors rapid and complete heterotopic consumption of primary organic substances, while in anoxic conditions the initial H / C ratio of the primary material is conserved through selective preservation/or contributions from secondary biota. Other conditions, such as euxinic conditions, favor the incorporation of sulfur with consequent high S/C ratios (Walters, 2006).

Tissot et al., 1974 as cited by Abay, 2017 in his work indicated the types of the kerogen can be defined and interpreted mainly as a composition based on elements (H/C and O/C ratios) that are followed by the Van Krevelen plot. as shown in Fig. 8. Tissot, 1979; Tissot and Welte, 1984; Peters, 1986 and Durand, 2003 classified the kerogens into four broad categories based on their H/C ratios. These are referred to as type I, II, III, and IV. Kerogens are assigned designations as being Type I, II, III, or IV depending where they fall on the plot. Type I and II are oil-prone, Type III is gas-prone, and Type IV is inert carbon (Walters, 2006).

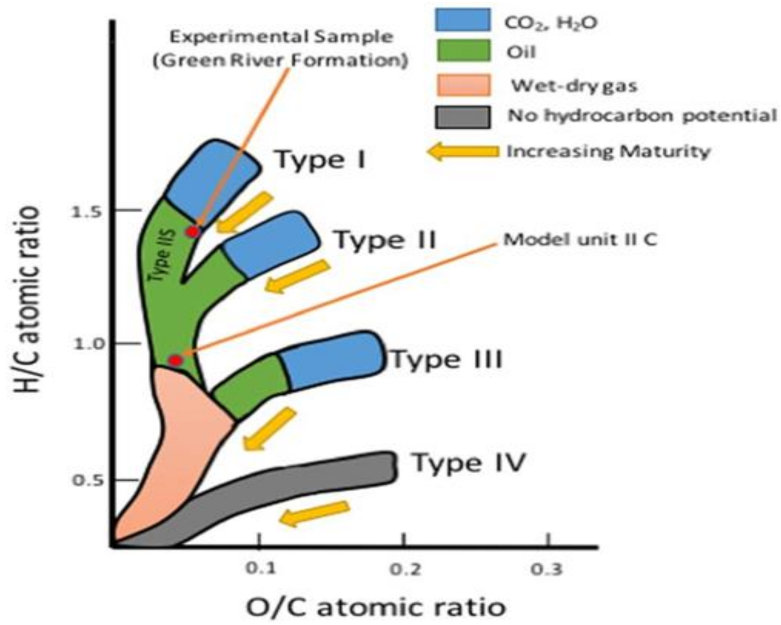

Figure 3.18. The four types of kerogens illustrated by Van Krevelen diagram (Type I, II, III and IV) with the associated products given off from kerogen (Pathak et al., 2017).

3.4.7.1. Kerogen Types

Walters, 2006 indicates that Type I kerogens have high H/C ratio, resulting from a high input of algae and bacterial biomass, formed chemically by a high percentage of long aliphatic chains but Killops and Killops, 2005 as cited by Abay, 2017 states that some may be derived from materials that have been reworked by bacteria. Most of the type I kerogen also known as sapropelic kerogen originate mainly from algae and spores which are products from the breakdown of fatty lipid organic material (Tissot & Welte 1978; Selley 1985; Hunt 1995 as cited in Al-Mashramah, 2011) while Hughes INTEQ, 1999 states they are of aliphatic origin with high hydrogen index(<300) and low oxygen index (>50) . Waples and Dougle 1985, Robinson 1969, Engel Macko et al., 1993 as cited in Faraj 2017 postulates that type I have higher rates of generating liquid hydrocarbons. From a theoretical point of view, Type I kerogen oil shales have the highest oil yield and are the most promising deposits for conventional oil retorting. (Altun et al., 2006). An example of type I kerogen petroleum source rock is that of Green River Formation of Western USA (McCarthy et al., 2011; Doglioni, n.d). The

Type II kerogen are mostly of lipidic origin mostly form algal (phytoplankton and zooplankton) detritus with high H/C ratio (1.28) and low O/C ratio (0.1) (Selley 1985; Al-Mashramah, 2011; McCarthy et al., 2011).

Both type I and II kerogens are mostly oil generating kerogens with type II sometimes generating gas due to the source of materials they are derived from. The formation of type I and II kerogens requires sediments that are deposited in anaerobic environments. One type of kerogen, known as type II-S (sulfur rich kerogens) derived from types I and II, is generally derived from carbonate depositional environments. As a result, petroleum produced from carbonate sources tend to be sulfur-rich (over 1.5% sulfur) which can be witnessed in the Monterey Formation of California, or the La Luna Formation of Venezuela (Walter, 2006; Altun et al., 2006; McCarthy et al., 2011). An example is of type II kerogen source rocks discovered are Kimmeridge Clay of the North Sea and the Bazhenov Formation of Siberia (McCarthy et al., 2011, Doglioni, n.d). Type III kerogens mostly originate from swamps and coastal plains (Walters, 2006) or continent and marine detrital environments (Doglioni, n.d) made of terrestrial higher plants (humic) with higher oxygen and lower hydrogen content rich in lignin and cellulosic tissues which mostly generates gas (Robb, 1989; Hughes INTEQ, 1999; McCarthy et al., 2011, Doglioni, n.d). Hughes INTEQ, 1999 states type IV are inertinite and Robb,1989 indicates are mostly woody of origin and do not produce any hydrocarbons. MacCarthy et al., 2011 puts it that type IV are usually derived from residual old sediments through erosion with high carbon and low hydrogen content.

3.4.8. Maturation

The process of kerogen transformation in petroleum with increasing temperature and finally to graphite is called maturation of organic matter (Tissot and Welte, 1984). The degree of thermal maturation is determined by various geochemical parameters. These geochemical parameters are production index (PI)), pyrolysis parameters (e.g. Tmax, hydrogen index (HI), reflectivity of vitrinite (% Ro) and light hydrocarbons, aromatic parameters and biomarkers (Hunt, 1996; Peters et al., 2012; Tissot and Welte, 1984, as cited by Abay, 2017). Gas chromatography-mass spectrometry, gas chromatography, incident light microscopy and rock-Eval pyrolysis, can be used to evaluate the thermal maturation and hydrocarbon generation potential (Obermajer, 1997). The vitrinite reflectivity, measured on rock or kerogen, is the most common indicator of maturation and possibly the most reliable for organic matter in source rocks (Hunt, 1996 as cited by Abay, 2017).

The kerogens go through processes such as thermal maturation, secondary alteration processes, biodegradation and water washing and deasphalting. Thermal maturation of the oil or the cracking of the oil is a process that occurs due to a temperature rise in the trap. The petroleum or trapped oil tends to be buried deeper (Blanc and Connan, 1994). The Rainbow Reef in Canada is an example of this process (Blanc and Connan 1994). Tissot and Welte, 1984 indicates that migrated petroleum from the source rock into the reservoir can undergo chemical and physical changes and these changes are as the result of secondary alteration processes. Biodegradation is the process by which meteoric waters containing bacteria and microorganisms enter the petroleum systems and alter the hydrocarbons accumulated in shallow reservoirs at temperatures below 80 °C (Leythaeuser, 1983; Tissot and Welte 1984; Blanc and Connan, 1994; Walters, 2006) and on the other hand, water washing occurs at low boiling range levels of hydrocarbons, resulting in a decrease in API gravity (Blanc and Connan, 1994). Deasphalting is another process of alteration that occurs when the natural gas produced is migrated from greater depths as mature host rocks after secondary migration. This causes the precipitation of asphaltenes from medium crude oil by dissolving oil with large amounts of gas and / or light hydrocarbons in the range of C1 to C6. (Tissot and Welte 1984, Leythaeuser 1983, Blanc and Connan 1994.

3.4.9. Hydrocarbon maturation processes

Another aspect of hydrocarbon formation is diagenesis, catagenesis and metagenesis of organic matter (see Figs. 5 and 6). These are commonly referred to as the maturation process, which are the phases of alteration stages with the carbon cycle that progressively alter the composition of the sedimentary organic matter. Kerogens go through some transformation processes which can be categorized into Diagenesis, Catagenesis and Metagenesis. Diagenesis is the first and initial breakdown of kerogens which usually happens at shallow depths (up to 1,5 km.) below the subsurface at mild temperatures (50oC) after the deposition of the organic matter (Tissot and Welte 1984; Selley, 1985; Horsefield and Rullkötter 1994). During diagenesis, the kerogens tend to lose oxygen as well as CO2 and H2O (Vandenbroucke,2003) by the process of biogenic and abiogenic reactions (Selley, 1985; Al-Mashramah, 2011). Kerogen accounts for 80-90% of the total organic matter content in sediments and is known to be the largest form of organic matter as compared to coal, asphalt, gas, and oil and as well the end product of diagenesis (Durand, 1980; Vandenbroucke and Largear, 2007; Huc, 2013 as cited by Abay, 2017). At the end of diagenesis, the organic matter then become more of kerogens and bitumen (MacCarthy et al., 2011).

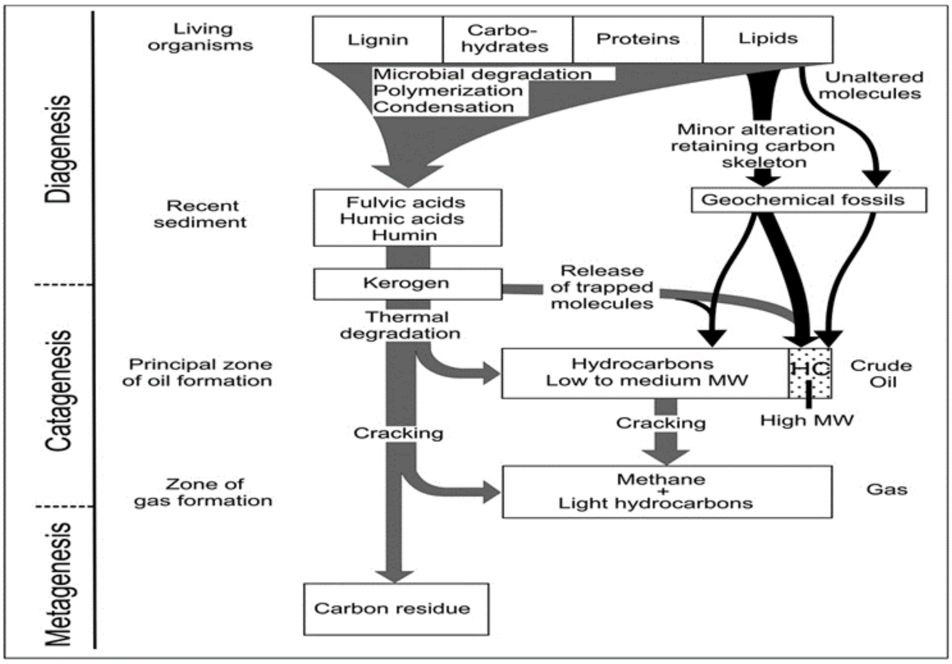

Figure 3.19Petroleum formation in organic rich sediments (Tissot and Welte, 1984 as cited by Abay, 2017).

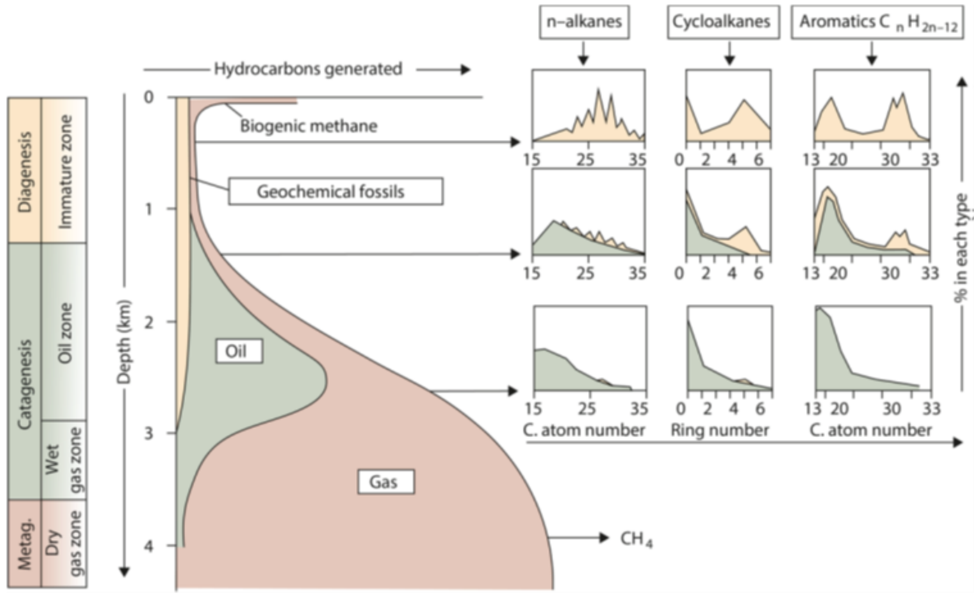

Figure 3.20. The stages of diagenesis, catagenesis and metagenesis (Abay, 2017).

After the process of diagenesis, due to increasing burial and increasing temperatures and pressure, the phase of catagenesis begins. Catagenesis is the phase where major liquid oil and wet gas are generated as the sedimentary rock is buried deeper with increasing temperatures (50-150 ^{o}C) and pressures (Hughes INTEQ, 1999). The most important factor here is the influence of temperature which allows the kerogens in the compacted rock to breakdown through thermal cracking where chemical bonds are broken further and some groups within the chemical chain is lost. At this phase, the broken bonds (C-C and C-O) then can generate the liquid oil and wet gas as indicated in Fig. 6 (Raluchukwu, 2011). It is in the phase of catagenesis where the oil window is found and type I and II kerogens produce oil and gas and type III kerogens produce gas (MacCarthy et al., 2011). Catagenesis comes to a complete end when the kerogens are exhausted from expelling the oil and gas at a vitrinite reflectance levels of 2% and T(max) values ranging from 480^{o}C and 490^{o}C and temperatures ranging from 50-175^{o}C (Hughes INTEQ, 1999; Walters, 2006).

Metagenesis is the final phase of further thermal cracking of the remaining kerogens at around 4,000 meters deep into the earth where temperatures are very high (150-200 ^{0}C) with greater buried rates. At this phase, the remaining hydrocarbons are able to produce only dry gas mostly methane. Metagenesis is termed as the gas window zone since no liquid oil is generated at that phase (Hughes INTEQ, 1999; Walters, 2006; MacCarthy et al., 2011; Raluchukwu, 2011;).

3.5. Petroleum Systems in the Gulf of Guinea and Ghana

The geological settings and the tectonics of Gulf of Guinea and Ghana will be discussed in Chapter 4. In this section attention will be given to the petroleum system of Gulf of Guinea and Ghana although detail information of the petroleum system of Ghana will be discussed in Chapter 4.

Most occurrences of petroleum and natural gas in the Gulf of Guinea are mainly concentrated within the Cretaceous reservoirs (Brownfield, 2016). The main source rocks of the Cote d'Ivoire- Ghana Tano Cape Three Points are within the Cretaceous Albian and Cenomanian-Turonian black shale with Kerogen type II and III (Jianping et al., 2010). Along the Ghanaian shelf from the Tano to Accra-Keta segment have lacustrine source rocks. The Saltpond basin has the Devonian shale as the main source rock and that of the Accra-Keta and Benin basin are of upper Cretaceous- Paleogene shale with a high TOC value (Jianping et al., 2010). The Keta Basin is postulated to have similar source rocks like that of the Tano basin (Tucker, 1992 as cited by Brownfield and Charpentier, 2006). The main source rocks of the Benin Basin are the Maastrichtian Araromi, Coniacian Awgu Formation, and Paleocene to Eocene Imo shales which contains type II and II-III kerogens with TOC of 2 to more than 5 weight percent. Apart from the Eocene shale, the others are observed in the offshore part of the Keta basin (Brownfield and Charpentier, 2006).

Hydrocarbon Generation**:** Hydrocarbon generation within the GOG Province is mostly within the Albian and Cenomanian source rocks of Cretaceous petroleum system (Brownfield, 2016; Brownfield and Charpentier, 2006). The deep-water areas of the offshore Cote d'Ivoire and Tano Basins, offshore Keta-Benin basins and Dahomey Embayment eastward the Niger Delta are hydrocarbon generative areas (oil kitchens) (Brownfield, 2016; Brownfield and Charpentier, 2006). Generation of hydrocarbons within the Cote d'Ivoire-Tano section started in the late Cretaceous to present and that of Keta-Benin and Dahomey Embayment started in the late Miocene to present. The Saltpond basin having Lower Paleozoic source rocks, generation of hydrocarbons are speculated to have started in the late Carboniferous into the early Tertiary (Brownfield, 2016; Brownfield and Charpentier, 2006). As compared to the Niger Delta which has the Agbada and Akata marine shale formation and Cretaceous shale with paralic and prodeltic Type II and Type III kerogen with TOC values ranging from 1.4 weight percent to 5.2 weight percent which seems similar to that of the source rocks found within the GOG Province with the rifting events and mode of sediment deposition in the delta quite similar. Hydrocarbon generation started from Eocene to Present (Ekweozor and Okoye, 1980; Lambert-Aikhionbare and Ibe, 1984; Doust and Omatsola, 1990; Stacher, 1995; Tuttle, Brownfield, and Charpentier, 1999; Haack et al., 2000 as cited by Brownfield, 2016).

Reservoir, Traps and Seals: The main reservoir rocks across the GOG region are the late syn-transform Albian sandstones and Cenomanian to Maastrichtian post-transform marine and turbidite clastic rocks (Brownfield and Charpentier, 2006). The reservoir system is mainly Albian- Cenomanian sandstones within the Cote d’Ivoire-Tano section. Along the Ghanaian shelf, Saltpond basin has Albian sandstone and Devonian sandstones. The Accra-Keta and Benin segment have Albian and Cenomanian sandstones as reservoir rocks (Jianping et al., 2010; Brownfield, 2016). As compared to the Niger Delta which is at the eastern segment of the GOG Province and known for its huge oil and gas reserves has Eocene to Pliocene aged rocks serving as reservoir rocks (Evamy et al., 1978 as cited by Brownfield, 2016). Pre-transform traps (fault blocks), syn-transform structural and stratigraphic traps are the trapping mechanisms in the GOG province (Brownfield, 2016) and that of the Niger Delta of Nigeria mainly has structural trapping mechanisms (Doust and Omatsola, 1990 as cited by Brownfield, 2016). The sealing system of the GOG province are the shale and faults (syn-transform reservoirs) and shale (post-transform reservoirs) (Brownfield, 2016) and that of the Niger Delta has shales as the sealing rocks (Brownfield, 2016).

CHAPTER 4. LITERATURE RESEARCH AND THE STUDY AREA

4.1. Chapter Introduction

This chapter aims at the looking at the previous work done about the sedimentary basins of Ghana, the background information, the general geology, and basins of the study area. The previous work focuses mainly about when petroleum exploration started in Ghana and the background information talks about the location, climate, and other vital information about Ghana. The general geology mentions about the rock formations found in Ghana as well as the sedimentary basins in Ghana.

4.2. Literature Research

While conducting literature research, some previously published works related to this research have been collected and investigated. Some of them are summarized and presented in the remainder of this section.

From a global perspective, many others have emphasized about the importance of plate tectonics for understanding the oil and gas potential of a basin or region. The work includes Bryant et al., 2012. Plate tectonics plays an important role in oil and gas discoveries in recent years. Characteristics of hydrocarbon play at one end of a continent is used to discover another using the plate tectonics principles. An example is the use of the discoveries of the Tano basin of Ghana (West Africa) to discover oil and gas in French Guiana and Brazil (Bryant et al., 2012).

Another good example of the role of plate tectonics in petroleum exploration is the paper by Bai et al., 2016. According to the findings of the researchers, the Melut basin (South Sudan) and Bongo Basin (Chad) have similar lithology and difference in tectonic evolution. Hydrocarbon accumulation in both basins are within the primitive Cretaceous based on the investigation into the formation history of hydrocarbon. This difference in development has led to different storage conditions for the basement reservoirs in relation to caprocks, hydrocarbons charge and preservation, and accumulation. The important lesson from this article is that although two or more basins may have the same basement lithology, if they undergo a different tectonic evolution, they would represent different accumulation conditions for the basement reservoirs with respect to the caprocks, and hydrocarbons charge and preservation, and accumulation.

The role of tectonics in hydrocarbon accumulation of the Albertine Graben was studied by Abeinomugisha and Kasande in 2009. From these studies, it was revealed that, there was plate tectonically movements that led to the deposition of thick sediments in lacustrine and fluvio-delta environments. They then explained that rapid tectonic subsidence associated with the input of sediment led to the formation of stratified lakes, accompanied by the deposition of source rocks. The hydrocarbon exploration in the basin has proven the deposition of rocks, reservoirs and caprocks. In summary, they claimed that tectonics played a crucial role not only in the deposition of source rocks, reservoirs and cap rocks, but also in the formation of structural traps. However, hydrocarbon routes were also provided. From this work, understanding the accumulation of hydrocarbons in a basin or in a region requires understanding the tectonics of the basin or region.

Ulmishek 2001 investigated the oil potential of the Caspian Sea by subdividing the subjects into petroleum occurrences, stratigraphic sections, source rocks, reservoir rocks, seal rocks, traps and assessment units. It clearly explained each of the above arguments in the case of the Caspian Sea and explained that, consequently, the hydrocarbon potential of the basin is well understood.

Ghana is located on the Gulf of Guinea and three of the four Ghanaian basins are in this Gulf. The Gulf of Guinea has an area of approximately 236,670 Km^2 and covers the coastal and offshore areas of some West African countries which includes Ghana, Benin, Ivory Coast, Western part of Nigeria and Togo. The basins within this province includes, the Dahomey Embayment, Keta, Benin basins, Tano, Ivory Coast and Saltpond (Brownfield 2016).

Numerous geophysical and geological data on the Gulf of Guinea have been integrated from the Niger Delta / Douala Basin to the Cotonou Basin (Benin or Dahomey). The integration of regional geophysical, seismic, geological and well-log data reveals discordant fracture zones beneath the Niger delta, suggesting that the coastal West African basins are a series of wrenched basins, that favorable for the accumulation of hydrocarbons in several parts of the basin. In addition to the well-known indicators of hydrocarbon maturity, such as oil shows, production fields and tar sands, large sediment thickness column are indicated to be matured in several wells, according to the TTI (Time-Temperature Index) estimates obtained from quantitative basin modeling (Babalola, 1990).

In 1998, Benkhelil et al., published a study that showed that, the edge of Benue and the Cote d' Ivoire - Ghana Margin had displayed several similar tectonic and sedimentary features. The authors explained that; in both regions, the initial stages of rifting (Early Cretaceous) are comparable, with the grabens filled by continental deposits being formed under extension, followed by trans-tensional movements due to intra-continental wrenching. Marine sediments were deposited in an unstable tectonic environment during Albanian epoch, causing many deformations of the soft sediments associated with the activity of the fault zones. In addition, a phase of tectonic compression was recorded in both basins at different times; the late of the Albanian-Cenomanian along the Ivory Coast - Ghana Marginal Ridge (CIGMR) and the Santonian in the Lower Benoue Trough. In both cases, the fracturing, cleavage, and folding occurred, with the shearing related to transpression along the major zones of transcurrent fault zones.

The thermal regime, including low-grade metamorphic recrystallization and hydrothermal activity, was quite similar and occurred both before and during the tectonic compression phase. The similarities between these areas can be explained by the prevailing geological conditions in the early stages of formation of these intra-continental wrench-controlled basins (Benkhelil et al., 1998).

According to Benkhelil et al., 1998, In the Late Cretaceous, significant differences occurred in the newly created Ivory Coast - Ghana Margin, which is prominent in the Ivory Coast - Ghana Marginal Ridge adjacent to the oceanic lithosphere, began to subside as a consequence of progressive cooling, whereas the Benue domain was submitted to restricted marine to continental sedimentary conditions, ending in the Maastrichtian by a general emergence of the domain.

Brownfield and Charpentier 2006 reported that there were up to five oil systems in the Gulf of Guinea, but Cretaceous system consist of total petroleum system in the region. It is stated that the assessment of this unit had enough data for evaluation. The authors also explained that there are two important differences within the province and the passive margin basin (Niger Delta). These are the influence of transform tectonics and the absence of evaporative and salt deformation. There are no large and long-lived delta systems in the province, which typically involve rapid burial of source rocks and large deposits of high-grade hydrocarbons.

The USGS evaluated the potential of unconventional conventional petroleum resources in the Gulf of Guinea. The valuation revealed that there is an average of 1,004 mB of unexplored conventional oil and 10.071 billion ft3 of gas and 282 mB of natural gas liquids. It is believed that most of the petroleum potential is found in the deep waters off the coast of the province. In areas where hydrocarbon generation is relatively shallow, gas resources can be large and accessible (Brownfield and Charpentier 2006).

In 2016, a study published by Brownfield revealed that the Gulf of Guinea differs in two key aspects from the passive marginal basin (South Niger Delta): The tectonics of the transform-fault tectonics strongly influenced it, and evaporites and associated salt deformation are absent. The Gulf lacks deltaic systems that result in rapid source-rock burial and abundant hydrocarbon reservoir systems.

In addition, Brownfield stated in 2016 that hydrocarbons in the province were generated from Early to Late Cretaceous marine source rocks. The primary source rocks are Turonian in age and contain a Type II kerogen. The generation could have started at the beginning of the Tertiary and continued to present day. Hydrocarbons migrated from adjacent source rocks or updip along faults from deeper sources. The trapping mechanisms are pre-transform trapping associated with fault blocks, syn-transform structural, and post-transform stratigraphic traps. Reservoir seals are mainly marine shale, minor fault-related seals and shale-filled channels.

Finally, Brownfield reported in 2016 that the US Geological Survey estimated the potential of unexploited conventional petroleum resources in the Gulf of Guinea region, averaging 4,071 million barrels of unexploited conventional oil (34.461 billion cubic meters) and 1.145 million barrels of natural gas liquids. It is believed that most of the petroleum potential is found in the deep waters off the coast of the region. Gas resources may be large in areas where hydrocarbon accumulation is relatively shallow.

One of the few studies previously published on the Ghanaian basin is a work by Boamah 2017. The author reported on a systematic reconstruction of the complex geological history of the Voltaian basin. Five phases of the tectonic-geological development of the Voltaian basin have been identified. Various minerals from the study were reviewed and discussed. Although the author is concerned about metallic and non-metallic minerals within the basin, I expected him to touch something small on the hydrocarbon in the basin, but unfortunately, he never mentioned it.

Finally, a book by Aryeetey, 2014, stated that the Devonian sandstone within the Saltpond basin preceded the opening and expansion of the Atlantic Ocean and the separation of the African and South American plates. Hydrocarbons in this place are trapped in Devonian structural heights and the stratigraphies ranges between Palaeozoic pre-rift sediments and Lower Cretaceous rift sequence. The key information in this document is that the Takoradi Formation is the only proven petroleum reservoir in the Saltpond basin.

4.3. Study Area

4.3.1. Ghana

Republic of Ghana is located on latitudes 4O 45 1N and 11O N and longitudes 1o 15I E and 3O 15 W. The capital city of Ghana is Accra (Accraexpat, n.d.). Ghana gained its independence from England on 6th March 1957 and its Republic on 1st July 1960. The first Prime Minister and President of Ghana was Dr. Kwame Nkrumah. Ghana has three neighbouring countries, and these are Burkina Faso, Togo and Cote d'Ivoire. The landmass area of Ghana is 238,500 Km2 and the current population of Ghana is 29,675,818 (29.46 million).

Formerly, Ghana had 10 administrative regions, but the current government headed by Nana Akufo-Addo, further divided the regions in 16 administrative regions (Figure 4.1).

Figure 4.1. Map of Ghana with its administrative regions (Ghana Map, 2019).

4.3.2. Regional geology of West Africa

Ghana is situated at the Gulf of Guinea (GOG) in West Africa on the West African Craton (known as Pre-Cambrian Guinea) which was preserved during the Protozoic (2000 Ma) and Eburnean Orogeny cycle (Mensah, 2015). The Eburnean Orogenic cycle consisted of Archean and Paleoprotozoic crystalline rocks overlain by Neoproterozoic and younger sedimentary succession (Figure 3.5, David et al., 1994; Ennih and Liegeois, 2008; Feybesse et al, 2006 as cited by Abitty et al., 2016). The West African Craton is surrounded by both the Pan African and Hercynian Orogenic belts (Trompette, 1994; Ennih and Liegeois, 2008; Feybesse et al, 2006 as cited by Abitty et al., 2016). According to Attoh and Ekwene, 1997, the Eburnean Orogeny of Ghana occurred when the Birimian Supergroup was accreted onto the Man Shield during the Late Paleoproterozoic.

The West African Craton is the second largest region in Africa which is predominated by well-preserved lower Proterozoic rocks. It encompasses broad belts of metamorphosed volcanic and sedimentary rocks that can be located in Ghana, Niger, Burkina Faso and Cote d'Ivoire. The Craton is bordered to the east and west by the late Protozoic mobile belts (700 to 500 Ma) also called Pan African mobile belts (Figure 3.5, Kesse, 1985; Wright, 1985; Leube et al., 1990 as cited by Mensah, 2015), Archean and Paleoproterozoic aged rocks (Reguibet Rise) in the north and the Leo Rise (Guinea) in the south. These domains are separated by the Proterozoic to Paleozoic sedimentary basins of Taodeni and entirely surrounded by Pan African belts (Trans- Saharan mauritides and rockillides). The western portion of the Leo Rise is encompassed by the Archean and the eastern portion by the Birimian separated by Sassandra fault and shear zone and by Archean-Paleoproterozoic transitional domain (Feybesse and Milesi, 1994; Caby et al., 2000; Klein and Moura, 2008 as cited by Bimpong, 2014).

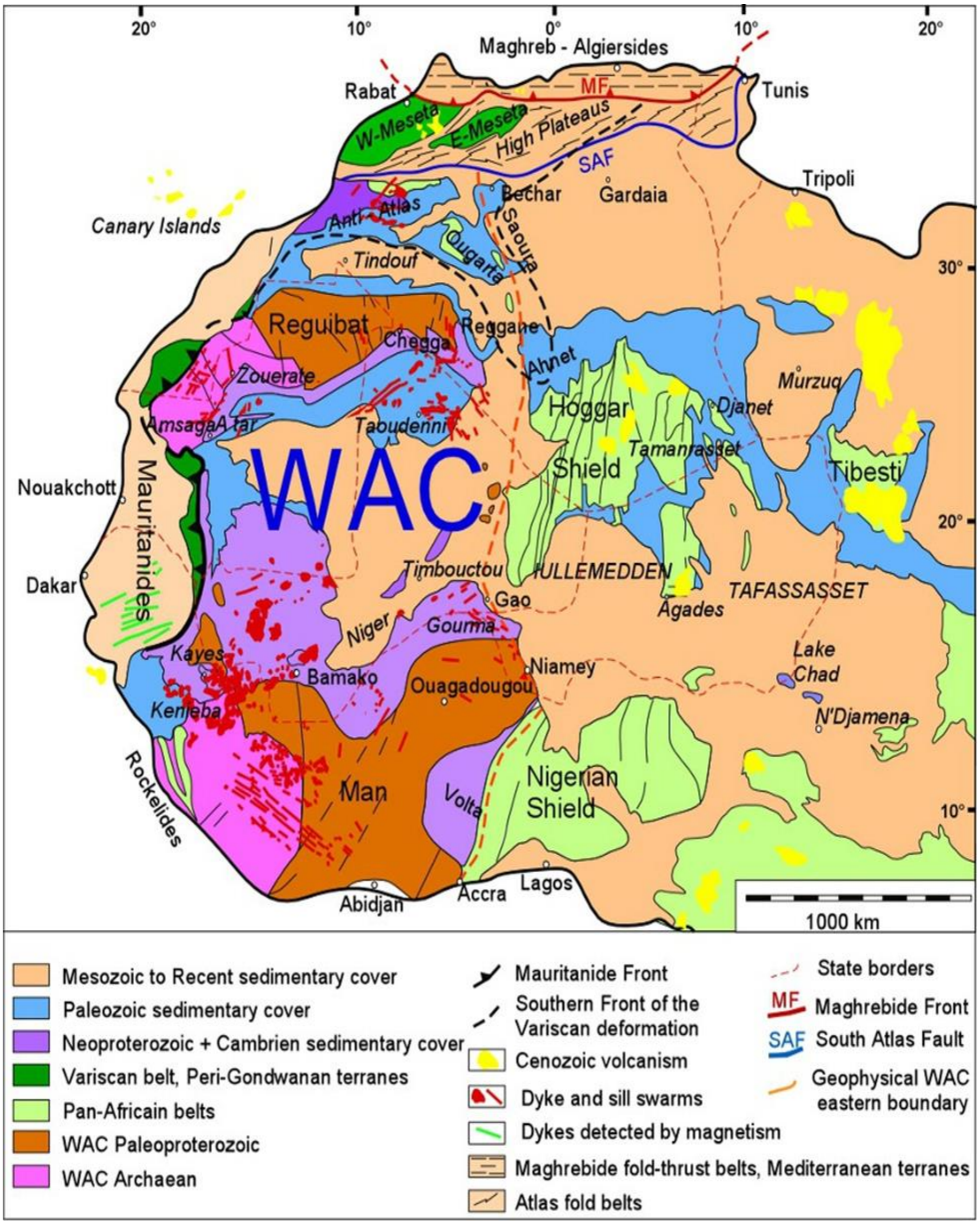

Figure 4.2. Regional Geology of the West Africa (Fabre, 2005; Liegeois et al., 2005; Ennih and Liegeois,2008 as cited in Youbi, 2011).

4.3.3. General geology of Ghana

The main rock units underlying Ghana are the Birimian, Tarkwaian, Dahomeyan systems, Togo series and Buem formations. The Birimians are intruded by Basin-type, Belt-type and Bongo granitoids. The Precambrian rocks are overlain by the Voltaian System (late Protozoic to Paleozoic) (Wright, 1985 as cited by Graham, 2013).

From Table 4.1 and Figure 4.3, the geological provinces of Ghana are explained. The Birimian System (Proterozoic terrane) occupies northwest and western part of Ghana. The Tarkwaian System is made up of the Ashanti, Bui, and Bole-Navrongo Belts. These are clastic sediments. The Voltaian Basin is a late Precambrian to Paleozoic sediments. The Dahomeyan System occupies the eastern part of Ghana; the Togo and Buem Formations; A Pan-African mobile belt. The Dahomeyan is separated from the Birimian by the Akwapim - Togo range.

Table 4.1. Generalized Geological provinces of Ghana (Eocene, 1997).

Reference	Formation/ Series/ System	Description
Kesse (1985)	Appolonian Formation	Alternating sands, clay and limestone
Kesse (1985)	Amisian Formation	Interbedded soft pebbly grits, conglomerate, arkose and clay
Kesse (1985)	Sekondi Series	Sandstone, shales, conglomerate, pebble beds, grits, mudstones
Kesse (1985)	Accraian Series	Alternating shales, sandstone, mudstone, pebble grits
Kesse (1985)	Voltaian system	Quartzite, shale, mudstone, conglomerate, limestone, arkose
Kesse (1985)	Buem Formation, Togo Series, Dahomeyan	Shale, sandstone, arkose, lava
BHP Minerals (Ghana) (1992)		Undeformed mafic dykes
Oberthur et al., 1988; Pigois, op. cit.	Post peak metamorphism gold mineralization	Shear zone and quartz vein-hosted mineralizatiuon
Kesse (1985)	Tarkwaian deposition	Quartzite, grit , conglomerate,phyllite
Eisenlohr and Hirdes (1992)	Cape Coast Granitoids	potash- rich, muscovit- biotite granite
Hirdes and Davis (1998)	Formation of Tarkwaian depositories and infill	Quartzite, grit , conglomerate,phyllite
Hirdes and Davis (1998)	Birimian tholeiites	
Eisenlohr and Hirdes (1992)	Dixcove granitoids	Soda- rich hornblende biotite granite. Early phase of thrusting?
Hirdes et al., 1992	Synvolcanic tonalitic granodioritic belt granitoids and volcanics	
Hirdes and Davis (1998)	Extrusive volcanism in Birimian	
Hirdes and Davis (1998)	Felsic volcanics	
Eisenlohr and Hirdes (1992)	Deposition of Birimian metasedimentary rocks and metavolcanics	Meta lava and pyroclastic rock, phyllite, schist, tuff, greywacke, chemical sediments, Mn- carbonate and chert
	Archean basement	

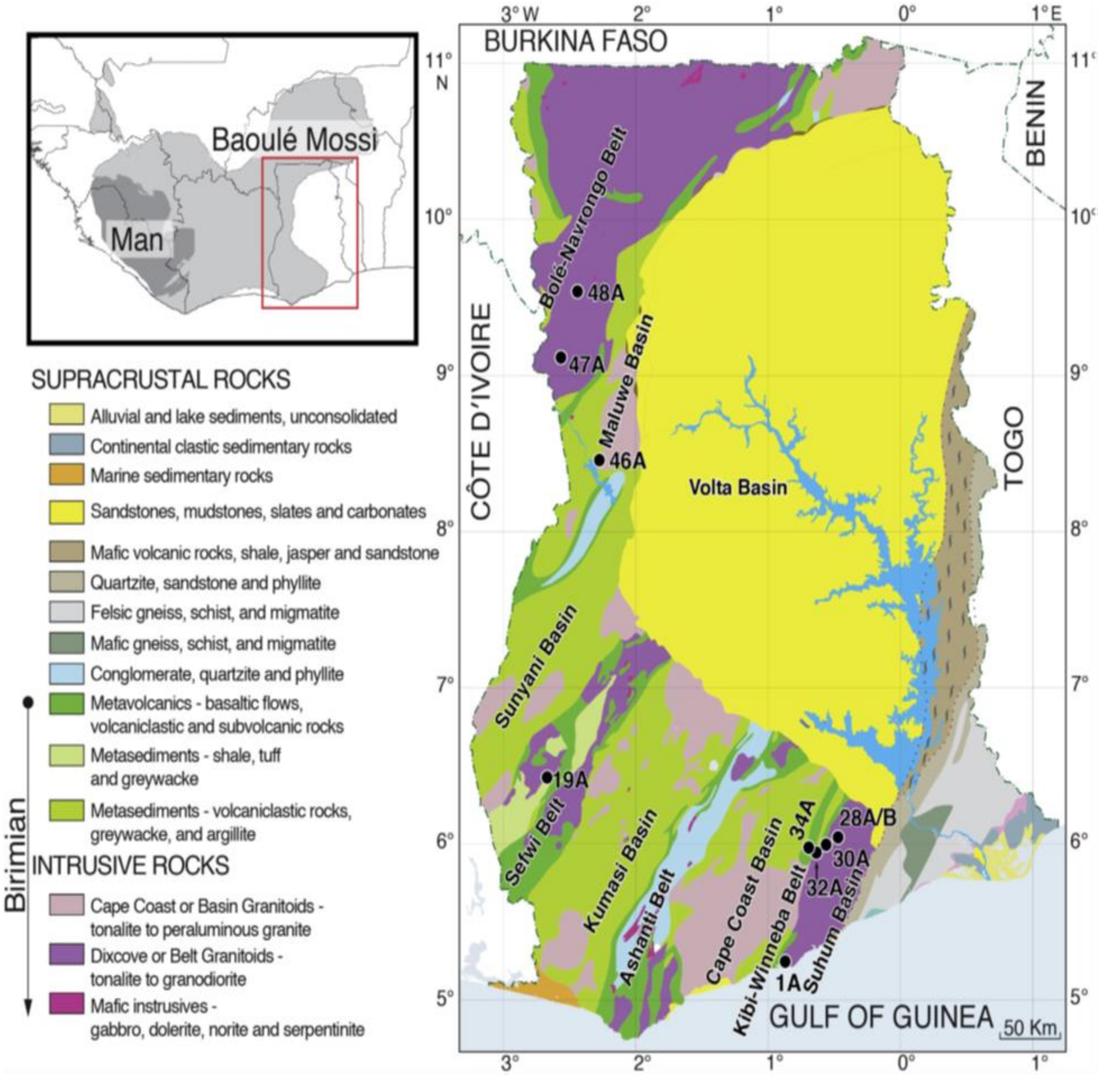

Figure 4.3. Geological provinces of Ghana (Peterson et al., 2008).

4.3.4. Sedimentary basins

The richness of a basin is defined by the ultimate hydrocarbon reserve per area or else volume of sediment per area (Bally and Snelson, 1980). It is easy to demonstrate that the richness of a given basin type ranges from very rich to very lean for individual basins within the same class. Some of the richest basins in the world such as the Los Angeles, the Ardmore, the Maracaibo and the Sumatra basins, present quite unique combinations of source, reservoir, seal and an overall basin evolution that cannot be satisfactorily replicated elsewhere. Hydrocarbon explorers continue to compare and analyze sedimentary basins to discover and /or understand hydrocarbon systems. In unexplored or underexplored basins, source beds and reservoirs are poorly known, but often analogues from similar basins elsewhere are useful to support an untested play. However, the use of such analogies remains very limited as suggested by the general observation that new plays, often initiated by the discovery of giant fields, are surprises that at first sight don’t fit easily with any analogues elsewhere. This is particularly true for subtle stratigraphic and combined stratigraphic/structural traps. On the other hand, following the discovery of a new play, it is of course sensible to use reservoir and hydrocarbon parameters from initial discoveries as analogues to reduce exploration risk.

In fact, worldwide, most of the onshore and near-offshore hydrocarbon reserves have been found in proximity (within a radius of about 200 km) of surface oil shows that were already known early in the last century (Höfer, 1909). Over the years increasingly more sophisticated technology improved the definition of primarily structural targets. Only in recent decades there has been an increased effort to understand the context of sedimentary basins in their totality (Mégnien, 1980; Mossop and Shetsen, 1994). For the hydrocarbon explorer basin analysis ultimately will always and primarily be based on the best possible seismic resolution, which will be particularly useful in definition of new types of stratigraphic traps.

According to the Encyclopedia of Hydrocarbons; The sedimentary basins in which organic substances that may generate hydrocarbons accumulate are a direct consequence of plate tectonics. These basins are formed both within plates and at their margins as a result of three main processes of subsidence: thinning of the lithosphere, in other words extensional or transtensional tectonics; thermal cooling of oceanic and continental lithosphere at passive margins; folding of the lithosphere at subduction zone hinges due to slab retreat, or to sinking generated by the load of a mountain belt or a delta on a continental margin. Therefore, from tectonics, basins are generally divided into three broad types of sedimentary basins. These include dominantly extensional basins on rigid lithosphere, perisutural basins and epi-sutural basins (basins located within orogenic belt).

The dominantly extensional basins on rigid lithosphere are further divided into four types. They are rift system basins, passive margins basins, ocean basin and cratonic basins. Rift system basins may have their own hydrocarbon reservoirs and source beds forming hydrocarbon systems that are limited to a single mega-sequence or else hydrocarbon systems that are shared with overlying and underlying mega sequence.
In recent years passive margins have been subdivided into: (1) Rifted margins, underlain by a highly extended crust and associated rift systems. The syn-rift fill may be continental and/or marine. (2) Volcanic margins, underlain by very thick wedges of volcanics that are characterized by Seaward Dipping Reflectors (SDR) on seismic profiles. Sometimes explorationists mistook SDR's for syn-rift sediments, leading to the drilling of some dry holes. (3) Transform margins, divided into: transtensional transform margins, characterized by transtensional half-grabens (e.g. the south coast of southern Africa); and transpressional transform margins, characterized by transpressional folds (e.g. offshore Ghana). The passive margins are classified as mixed carbonates /clastics or dominantly clastic margins. Production from structurally relatively undisturbed passive carbonate margins is rather limited, while dominantly clastic margins are major hydrocarbon producers. The end members of clastic margins are mega-deltas and their corresponding deep-sea fans. These contain some of the world's most prolific hydrocarbon provinces including the Gulf of Mexico, the Niger Delta and the Nile Delta. Other mega-deltas such as the Amazon, the Zambesi and the Bengal remain under explored. The oceanic basins are of little economic interest to hydrocarbon explorationists. The oceanic crust is typically overlain by a relatively thin cover of mudstones that may well include some, mostly immature, source beds and fewer significant reservoirs with increasing distance away from continental margins.

The perisutural basins are divided into six sub-types of basins. They are deep-sea trenches, foredeeps or forehand basins located on rigid lithosphere, remnant ocean basins, foredeeps or forehand basins disrupted by basement uplifts. Deep sea trenches are of no interest to hydrocarbon explorers; however, they have been considered as long-term repositories for radioactive waste. Remnant ocean basins are transitional basins mostly underlain by oceanic crust adjacent to folded belts. A good example is the onshore and offshore Ganges Delta, which is still underexplored and may have a very substantial hydrocarbon potential. The Black Sea may be another example. Foredeeps do include the most prolific hydrocarbon accumulations of the world, including many of the Middle East basins. Rich source beds occur both in the underlying platform mega-sequences and the overlying foredeep sequences. While in the Middle East hydrocarbon trap domains are dominated by Mesozoic and Cenozoic carbonates, huge reserves of Middle East size are also contained in the Tar Sands and Heavy Oil traps of the distal foredeeps of Venezuela and Canada. Hydrocarbon systems in foredeeps may be limited to specific mega-sequences of the platform and the foredeep but are often shared by both systems with hydrocarbons migrating from the underlying platform across the foredeep unconformity into the overlying clastics, as is the case for the above-mentioned Tar Sands. The hydrocarbon richness of foredeeps is easily explained by the asymmetry and size of these basins, which, given good source beds, provide large perennial fetch areas from mature source beds. In addition to these conventional hydrocarbons, foreland basins and their equivalents in foreland folded belts contain most of the world’s coal reserves and their associated potential for coal-generated natural gas.

The third group of Epi-sutural basins are divided into five sub- types and they are; basins associated with oceanic subduction and island arcs, forearc basins, circum pacific back arc basins, back arc basins associated with continental collision on post orogenic collapse basins and lastly basins associated with major strike-slip faults. Forearc basins contain several separate mega-sequences with the lower mega-sequence perhaps providing source beds and the upper one having the reservoirs. Commercial production from forearc basins is known from the Talara Basin (Peru) and the Cook Inlet (Alaska). A few forearc basins may be dominated by extensional structures, and others are affected by strike-slip faulting.

4.3.5. Sedimentary basins in Ghana

Ghana has four sedimentary basins namely Tano, Saltpond, Keta and Voltaian Basins (Figure 4.4). The Tano, Keta, Saltpond are located along the coastal shores of Ghana which resulted from the continental rifting during the Early Cretaceous epoch. The

Voltaian basin is an inland basin which is of Paleozoic age like the Saltpond basin. The Tano and Keta Basins are of Cretaceous ages. These basins make up nearly one-half of Ghana's total area and exploration of oil and natural gas is mainly focused on these areas. The Tano basin covers an area of 1165 sq. km, Keta basin is 2200 sq. km, Volta Basin is 103,600 s.q. km and that of the Continental shelf is of 27560 sq. km (Arku, 2012).

Due to continuous continental rifting about 125 Ma between Africa and South America leading to subsidence and sagging resulting in the formation of deep basins along the edges of the transform belt. This permitted the deposition and preservation of organic matter under anoxic conditions forming thick organic rich shale source rocks which was deposited during the Albian, Cenomanian and Turonian period (Brownfield and Charpentier, 2006; Adda, 2013; CGG, 2016). Figure 4.5 shows some of the basins in Ghana along the Gulf of Guinea.

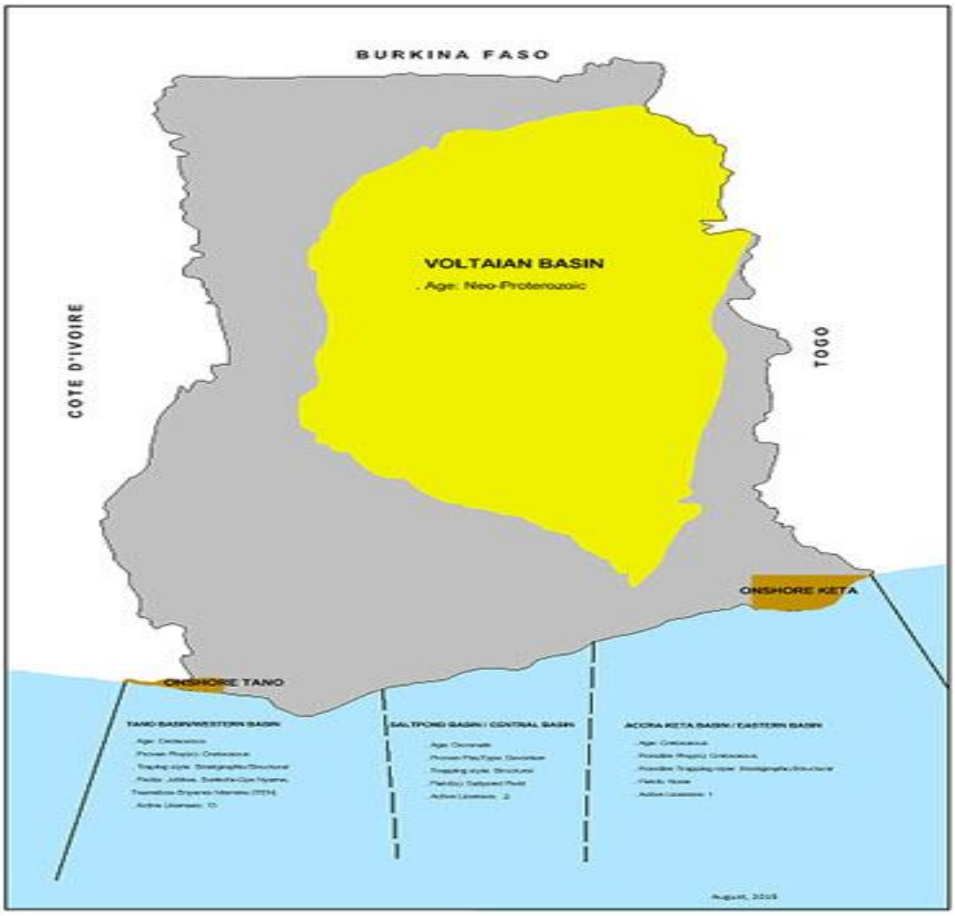

Figure 4.4. Sedimentary basins in Ghana (Petroleum Commission, 2019).

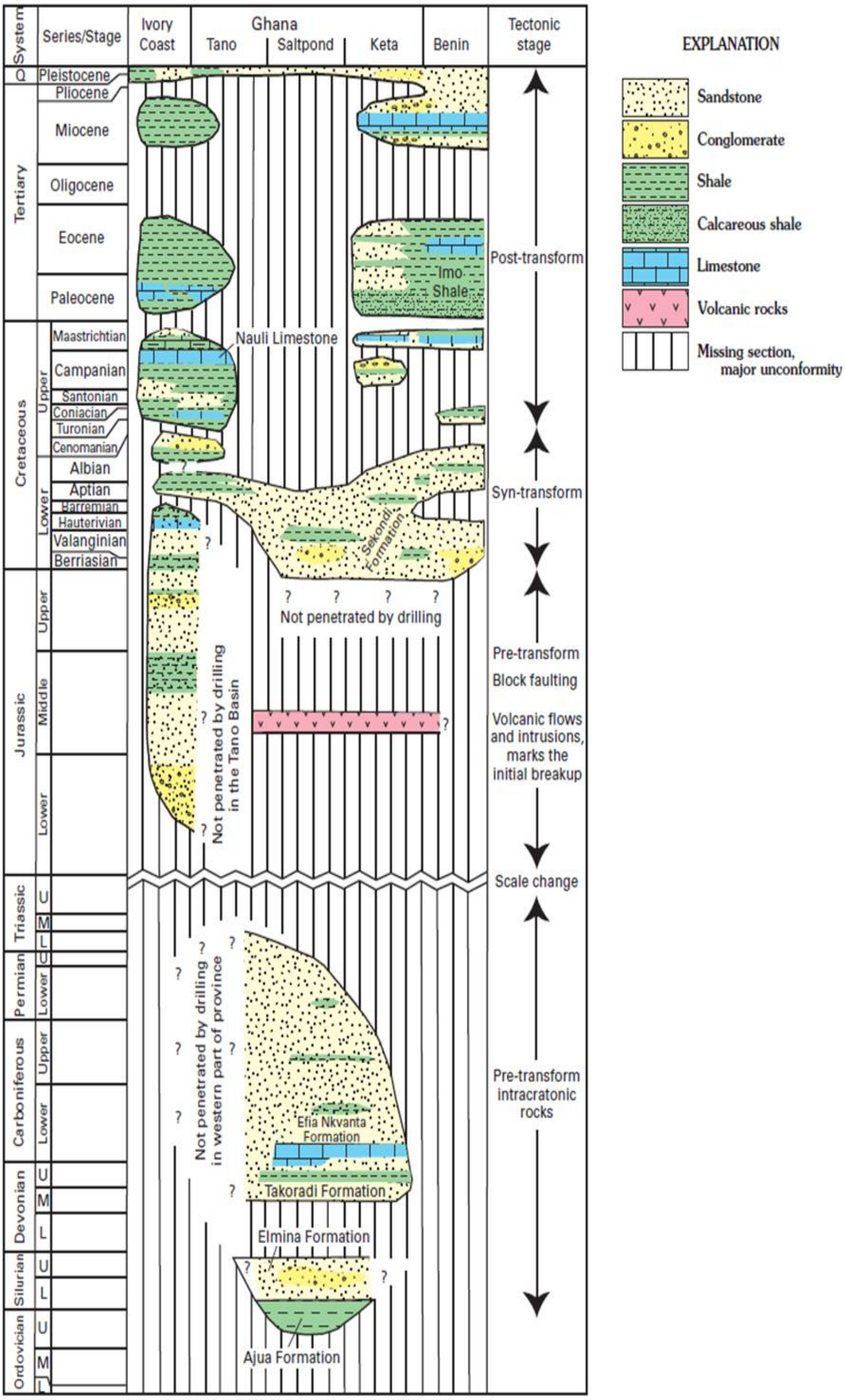

Figure 4.5. Stratigraphic section of the Basins in Ghana along the Gulf of Guinea (Brownfield, 2016).

4.3.5.1. Tano basin

The Tano basin is a deep infilled sedimentary basin found on the West African Transform Margin which seems to be like a wrench, pull-apart like with faults and anticlines and pinch out as the main trap system (Tetteh, 2016). The Basin is situated in the southwestern part of Ghana with a little portion of it inland and most of it offshore (Tetteh, 2016) and an extension of the Ghana-Ivory Coast Basin (Ablordeppey, 2016). The Tano basin is one of the sedimentary basins formed during the Late Jurassic period when the Atlantic rifting system began to break up the Paleo-continents of Africa and Southern America (CGG, 2013) and the separation of the of the African and South American plate during the Albian period (Ablordeppey, 2016). Large turbidite fan or channel complexes of thick clastic sequence in the basin from fluvial and lacustrine environments resulting from several lakes and river systems have played significant roles in the deposition of these clastic sequence in the early Cretaceous epoch (Adda, 2013). After the deposition of these clastic sequence within the basin, it resulted in three main play systems mainly Albian, Cenomanian and Turonian play. Figure 4.6 shows the cross section of offshore Tano basin.

The largest discoveries and productive fields are within the Turonian play and known as the Jubilee and TEN fields. Other substantial discoveries have also been made in the Cenomanian play like the Sankofa field (Tetteh, 2016). The main tectonic processes that influenced the formation of the Tano Basin during the rifting period are the Pre-rift phase during the Precambrian and late Jurassic, Syn-rift phase accompanied by sediments of early Cretaceous age and a Post-rift phase of marine Cenomanian up to date (Nana Gyamfua, 2015).

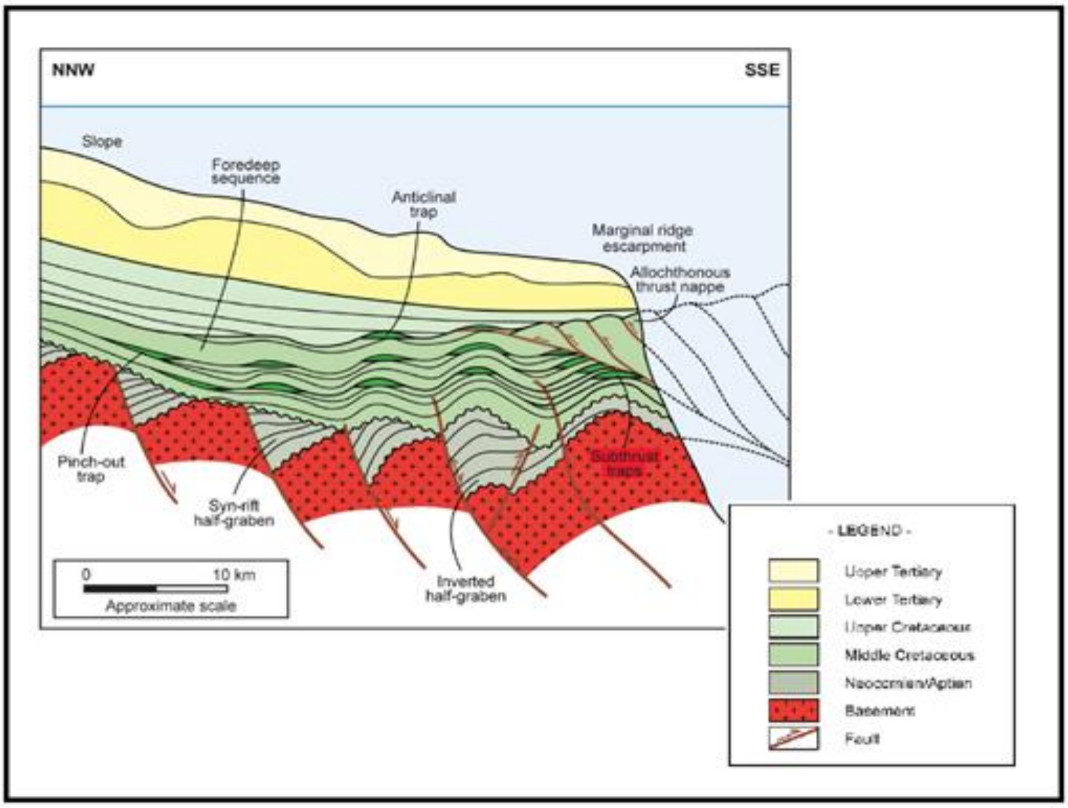

Figure 4.6. Cross section of offshore Tano basin showing the play types present (IHS Report, 2011 as cited by Tetteh, 2016).

The Tano basin has been stratigraphically divided from the base to the upper section (Figures 4.5,4.6 and 4.7) (Atta-Peters, 2013; Amoo Micheal, 2014; Tetteh, 2016). The Basin is about 7000 to 9000 feet deep with the basement rock of early Aptian age followed by the Bonyere shale formation which was deposited at the same time which is the source rock and the sandstones are which were deposited after serves as the reservoir rock. The presence of an unconformity in the basin is as a result of an uplift and erosional event during the Upper Albian age (Tetteh, 2016).

Aptian Series: The Aptian series is made up of the lower Aptian (Kwabenaswaso formation) and the upper Aptian. The lower Aptian sequence is observed in the north and south of the basin. It unconformably overlies the Carboniferous consisting of fine-grained sandstones with poor porosity formed in interbedded sandstones and characterized as well by dark shales (Davis, 1986 as cited by Ablordeppey, 2016). The upper Aptian sequence is made of thick shale interbedded with sandstone and siltstones

(Davies 1986; Ghana National Petroleum Cooperation, 1998 as cited in Ablordeppey, 2016).

Cenomanian Formation: The Cenomanian formation is made of mainly shale. It was deposited after the sandstones with huge deposits of limestones within the Cenomanian age (Tetteh, 2016). In the deeper area above the Cenomanian is the presence of an unconformity. From the bottom of the Cenomanian to the upper sequence are embedded sandstone and limestone overlie by a thin sequence of black shale. In the Cenomanian are limestone that overlies shoal limestone which are both late Cretaceous in age. The lower middle Cenomanian in the shallow area is defined by an embedded fine to coarse grained sand with sporadic calcite cement and grey, variably silty mudstone (RRI, 1998; Davis, 1986 and RRI 1998 as cited by Ablordeppey, 2016).

Turonian and Upper Santonian, Campanian and Maastrichtian: At about 920 feet, the presence of the Turonian and Upper Santonian portion is observed. It is made up of grey shales and claystones, occasionally having characteristics of dolomite or limestones (Tetteh, 2016).

Turonian: Claystones with thinly embedded siltstone and limestone can be observed in the Turonian (Ablordeppey, 2016). Features of dark grey, angular, calcareous and silty are imprints in the claystones and the siltstones have calcareous cement like features (Davies 1998 as cited by Ablordeppey, 2016). It is this portion which has the commercial accumulations of the Tano offshore plays (eg. Jubilee Field, Tweneboa Field) (Nana Gyamfua, 2015).

Santonian: Between the Turonian and the Campanian is the Santonian formation with a thickness of 412 meters with the sediments mostly dark grey shales with interbedded siltstones. The base of the formation is mostly dominated by unconsolidated sands. A marine deposition environment can be observed in the sequence during deposition (Davies, 1986 as cited by Ablordeppey, 2016).

Campanian: The Campanian section follows the Turonian and Upper Santonian which is composed of portion of shale rich with occasional stringers of dolomite and limestone where the Teak and Odum fields were discovered (Gyamfua, 2015; Tetteh, 2016).

Maastrichtian: The Maastrichtian portion indicates the later stages of the Upper Cretaceous dominated by claystone as well as sandstone and dolomite with a thickness of between 138 to 178 meters observed in the Tano. (Gyamfua, 2015; Tetteh, 2016). Davies, 1986 as cited in Ablordeppey, 2016 states that, the two sections (upper and lower) of the Maastrichtian is mainly made up of unconsolidated coarse-grained sandstones interbedded with fossiliferous and glauconitic mudstones.

Tertiary: The Tertiary section is mainly composed of the Paleocene, Eocene, Oligocene and Miocene ages (Gyamfua, 2015). Unconformity is observed in the Cretaceous due to the absence of the Lower Paleocene where the Poleocene overlies in the Tano basin (Ghana National Petroleum Cooperation, 1998 as cited by Ablordeppey, 2016). The middle and lower sections of the Eocene consist of finely laminated dark grey/ brown claystones with thin beds of fossiliferous dolomite and fine sandstone. The events of uplifting and erosion during the Alpine Orogeny caused huge deposition of thin bedded or completely absence of the the Paleocene, Upper Eocene and Oligocene portions. (Gyamfua, 2015; Tetteh, 2016).

Source Rock: The Tano basin is mainly composed of shale source rocks from the Upper Albian, Cenomanian and Turonian ages. These source rocks are interbedded with the reservoir rocks that are intimately connected (Tetteh, 2016). The Kerogen types with the Tano are type II and Type III with some source rock plays indicating type I and type IV. The Total Organic Content potential (TOC) ranges from 1-4 proving the source rocks are of good to very good TOC values. This has lead to huge hydrocarbon yield in the Tano Basin (Tetteh, 2016)

Reservoir: Large turbidite channel complexes in the deeper parts of the Tano basin were formed due to the deposition of clastic sediments from the Tano river drainage system from the western parts of Ghana and Ivory Coast (Adda, 2013). The plays of the reservoir system in the Tano basin are the Albian reservoir play, Maastrichtian sandstones, Cenomanian Series, Turonian Series, and Campanian sandstones. Among these plays, the most successful and important due to the accumulation of hydrocarbon in commercial quantities is the Turonian series play. The Jubilee field, Tweneboa, Enyera and Ntome (TEN) fields are indicators of huge discoveries of the basin (Adda, 2013; Ablordeppey, 2016). The reservoir plays have porosity values ranging from 17-23% with permeability of 100-3000 Md. The net gross ratio ranges from 30-80% and oil saturation also ranges from 60-90%. The API of the oil in the Turonian series is 32-38o. Tetteh (2016) also states that the Albian sandstone reservoir made only one oil and gas discovery. The accumulation of hydrocarbons within the Cenomanian sandstone reservoir has not been very productive and only one discovery has been made in this play.

Seals and Traps: The seals in the basin are marine shales composed of Turonian Shale series, Albian Shale series and Cenomanian Shale series (Tetteh, 2016). The Trapping system are both stratigraphic and structural traps (Adda, 2013). Structural and stratigraphic trap features such as normal faults, pinch out, clastic depos lens and anticlines exist in the Turonian play series.

The main trapping system in the Albian play is structural with anticlinal features as well as dome like structures and fault blocks. Both structural and stratigraphic traps exist in the Cenomanian play series. These were formed by normal faulting, Pinch outs, draping structure and clastic depos lens. (Tetteh, 2016).

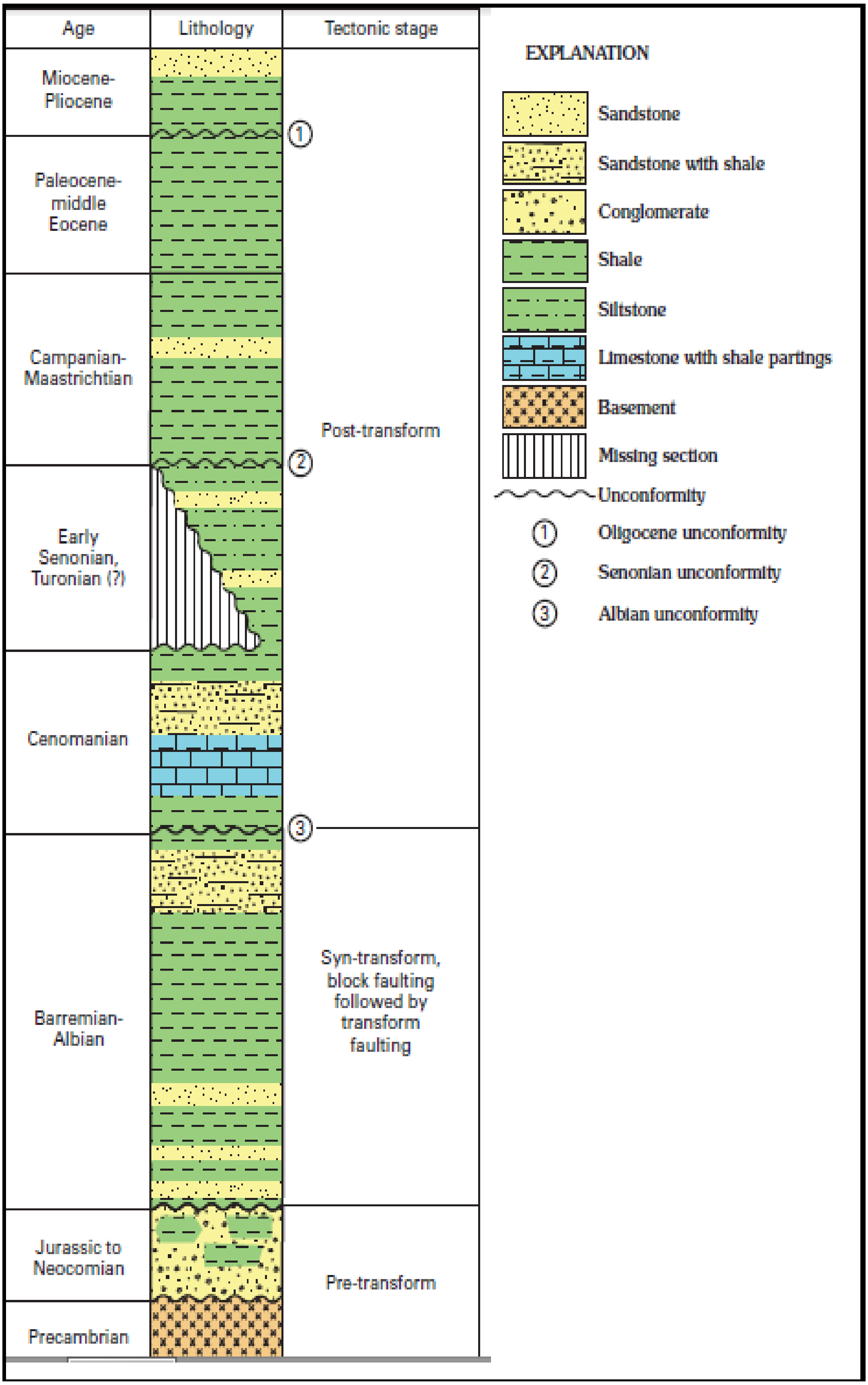

Figure 4.7. Stratigraphy of the Tano Cape Three Points Basin of Ghana (Doku, 2015).

4.3.5.2. Accra – Keta basin

The Accra- Keta basin (Figures 4.8 and 4.9) is one of the largest sedimentary basins located in the Gulf of Guinea occupying the extreme south eastern corner of Ghana covering a total area of 3,755.50 sq. km of which 2,201.50 sq. km is onshore and 1,554.00 sq. km is offshore (Kesse, 1978). The Basin extends westward from the Niger Delta consisting of creeks and lagoons (Keta lagoons) (Ajayi 1980; Kesse, 1985 as cited by Kumapley, 1988). According to Apaalse et al., 2013 states that the basin trends SW-NE. This Basin was created during the continental rifting of the African and South American plates along the edges of the continents leading to the creation of the Atlantic Ocean attributing to the formation of sedimentary basins which is evidence of the Late Precambrian Orogenic belt (Apaalse et al., 2013). These tectonic events took place during the Pan African Orogeny (500-600 Ma.), during the Late Jurassic to Early Cretaceous.

Stratigraphy: The Stratigraphy of the Keta basin is well explained in detail by authors like Khan, 1970, Apkati, 1970 and Kesse, 1985. Kesse, 1985 stated that Khan, 1970 proposed in a work done in the basin that the rocks are Cretaceous, Devonian and Quaternary Tertiary age with the bottom made of Dahomeyan quartz- biotite gneisses as well as Palaeocene, Eocene and Miocene to Recent ages.

Kesse, 1978 indicates the basin is made up of shales, siltstones, sandstones, clay-stones and limestone beds (mainly fossiliferous). The rocks are syn-transform rocks of Early Cretaceous age (Kjemperude at al., 1992 as cited by Brownfield, 2016). The structure and sedimentation of the Basin is due to the influence of tectonic events which are Pre-rift stage (Precambrian-Late Jurassic), Syn- rift stage (Late Jurassic-Early Cretaceous) and Post-rift stage (Late Cretaceous to Recent) (Brownfield and Charpentier, 2006; Abu et al., 2010 as cited by Atta- Peters et al., 2017).

Source Rock: The source rock in the basin are Early Cretaceous lacustrine shales (type II and III kerogens) and Turonian- Cenomanian organic shales (Abu et al., 2010 as cited by Adda, 2013).

Reservoir Rock: The reservoir system of the basin is made of rocks of Late Cretaceous, syn-rift Albian, and Tertiary ages (Abu et al., 2010 as cited by Adda, 2013).

TRAPS AND SEALS: Both structural and stratigraphic (more dormant in the basin) traps are associated with the Cretaceous-Tertiary shales as seals (Abu et al., 2010 as cited by Adda, 2013).

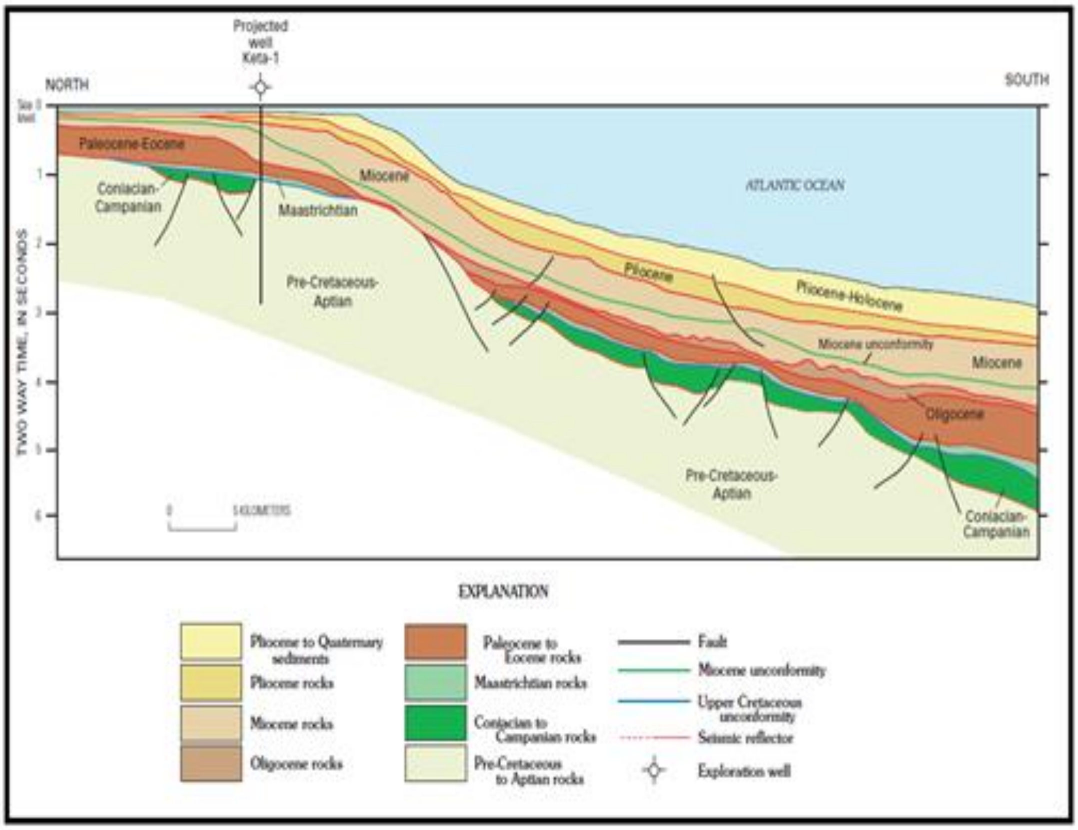

Figure 4.8. Cross-section of the Accra- Keta Basin in Ghana (Kjemperude at al., 1992 as cited by Brownfield, 2016).

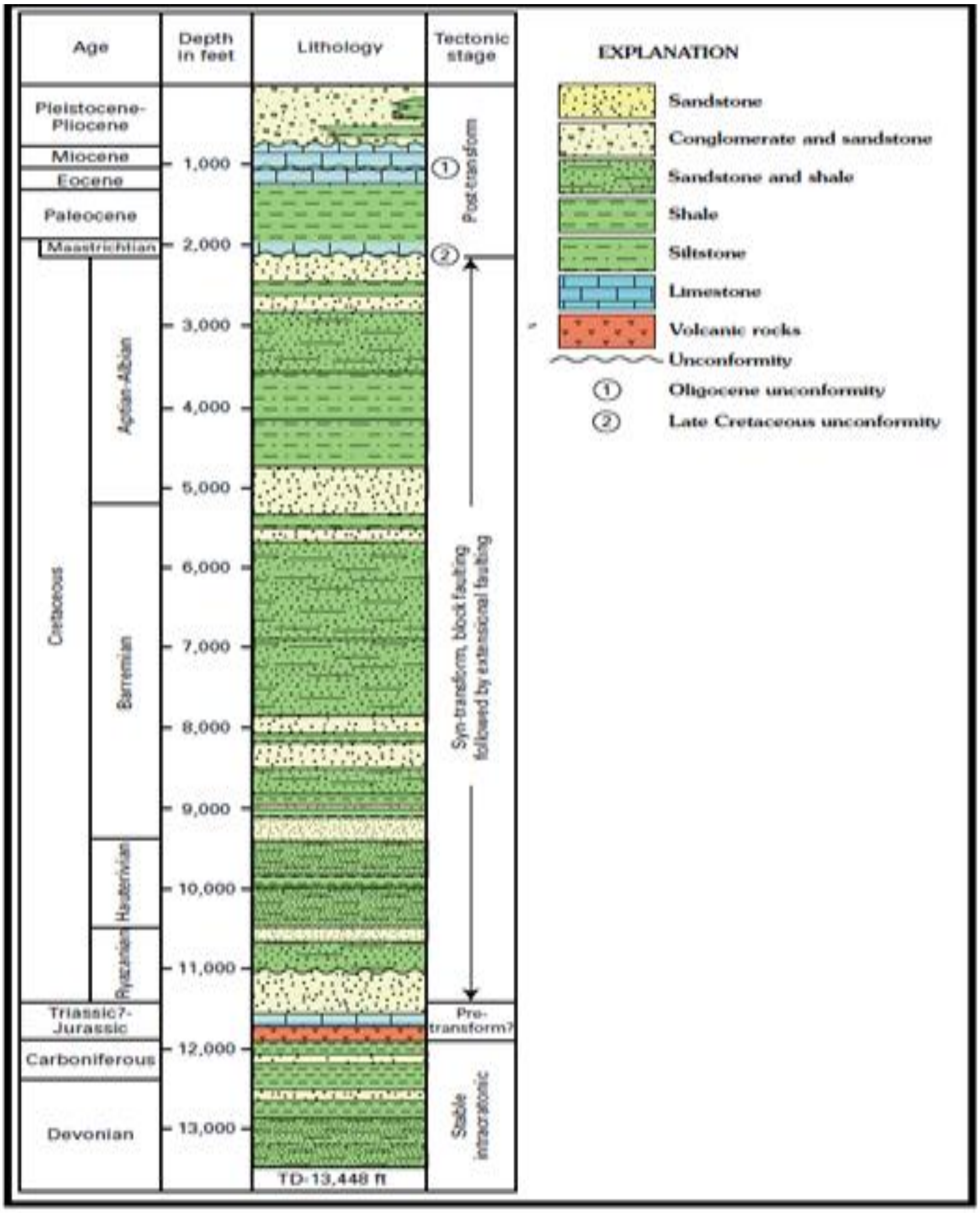

Figure 4.9. Stratigraphic section of the Keta Basin in Ghana (modified by Kjemperude at al., 1992 as cited by Brownfield, 2016).

4.3.5.3. Saltpond – Central basin

The Saltpond-Central Basin (Figures 4.10 and 4.11) is one of the Paleozoic basins in Ghana (Brownfield and Charpentier, 2006). Between the Tano-Cape Three Point basin and the Accra-Keta basin is the Saltpond basin covering an area of 12,294 sq. km (Aseidu et al., 2005 as cited by Adda 2013; Atta-Peters et al., 2015). Aryeetey, 2014 states that, the Romanche Fracture zone with the structural framework constituted with a complex set of fault bounded horst and grabens trending NW-SE direction dominate most parts of the Saltpond basin. The origin of the sediments within the basin are coastal marine to non-marine environments (Ordovician to Cretaceous age) (Adda 2013).

Stratigraphy: Form lithofacies and depositional environments in the Salpond basin, the formations are separated (Asiedu et al., 2005 as cited by Adda, 2013). The youngest in age in the stratigraphy of the basin is the Lower Cretaceous sediments. The Sekondi Sandstone (Triassic-Early Jurassic) is the next oldest rock followed Efia Nkwanta Beds (Late Carboniferous-Permian) then the Takoradi Shales (Middle Devonian-Early Carboniferous) then Takoradi Sandstone (Devonian) and finally the Elmina Sandstone (Late Ordovician-Early Silurian) as the oldest in the stratigraphy (Adda, 2013).

Figure 4.10. Map of the Saltpond- Central Basin of Ghana (Atta-Peters et al., 2015).

Source Rock: The Saltpond basin is assumed to have the oldest shale source rocks of Middle to Upper Devonian age (Takoradi Formation) (Kjemperud aat al., 1992 as cited by Brownfield, 2016). The origin of the sediments are from brackish marine environment (Brownfield, 2016). The Lower Paleozoic has proven to be the only Petroleum System in the Saltpond basin. The two main source rocks which are dark grey shales (Type II kerogen) of the Lower and Upper Takoradi Shales have good TOC (3.5-4.0 %) and HI values (Adda, 2013; Aryeetey, 2014). Maturation of the source rock was proven through the analyzing the burial history reconstruction and geochemical analysis (Adda, 2013).

Reservoir: This reservoir system is Devonian to Carboniferous reservoirs. The Takoradi Sandstone Formation serves as reservoirs in the basin (Adda, 2013) The reservoir rock has a porosity of 12-20% with permeability rate of 40-500 mD (Aryeetey, 2014).

Seals and Traps: fault-bounded blocks (structural features) and sandstones interfingering into shales (stratigraphic features) serves as the trapping mechanisms and the Takoradi Shale Formation serves as the sealing (Adda, 2013).

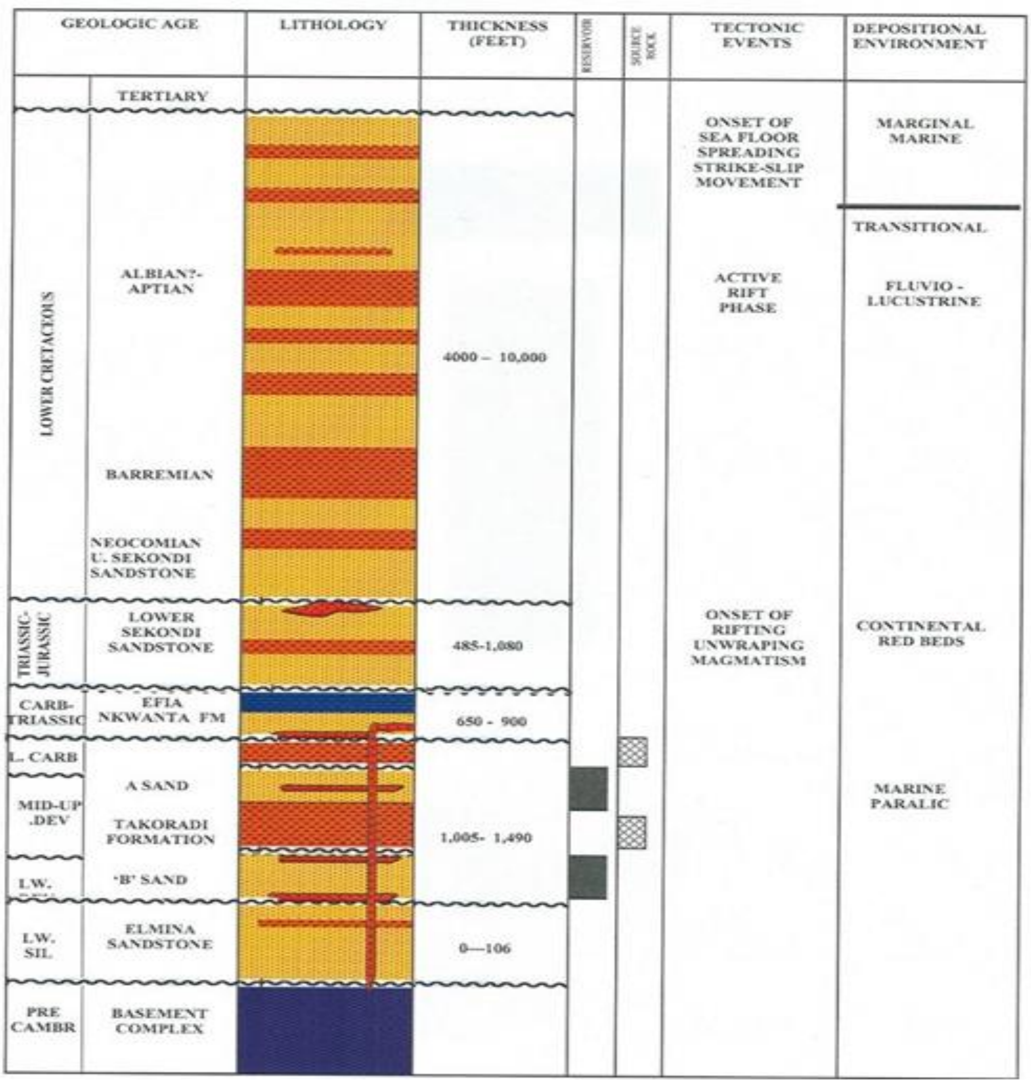

Figure 4.11. Stratigraphic section of the Saltpond- Central Basin in Ghana (Aryeetey, 2014).

4.3.5.4. Voltaian basin

A general information about the Voltaian Basin is given in the general geology of Ghana. The Voltaian basin takes about 40% of the landmass of Ghana, therefore makes it a giant geological province. In this section, a detailed description of the various lithological sequences will be given.

The Volta River Basin has an estimated area of 400,000 sq. km which stretches over six West African Countries as indicated in Table 4.2. These countries are Mali, Burkina Faso, Ghana, Togo, Benin and Cote d'Ivoire (Volta River Basin Report, 2002). The Voltaian basin is an intracontinental basin formed between the Neoproterozoic to Early Paleozoic. It is infilled with largely clastic sedimentary rocks (Fiako, 2008). The Voltaian basin is made up three mega sequences known as Bombouaka/ Gambaga, Pendjari/ Oti, and Tamale/ Obosum (Fiako, 2008) and lithologically divided into the Upper Voltaian, Middle Voltaian and Lower Voltaian (Yamoah, 2015).

Table 4.2. Countries through which the Volta basin extends through West Africa (Government of the Volta River Countries, 2002).

Country	Area of Volta River Basin (km2)	% of Basin	% of Country in Basin
Benin	17,098	4.1	15.2
Burkina Faso	178,000	42.65	63
Cote d'Ivoire	12,500	2.99	3.9
Mali	15,392	3.69	1.2
Togo	26,700	6.4	47.3
Ghana	167,692	40.18	70
Total	417,382	100%	

The Bombuoaka/ Gambaga/ Kwahu Mega-sequence (Lower Voltaian) is the lowest lithostratigraphic unit with detrital and epicontinental characteristics (Affaton, 1990 as cited by Kalsbeek, 2008). The Lower Voltaian is mainly composed of sandstones, siltstones, shales and mudstones as well as the presence of carbonates, cherts and conglomerates which were deposited between 650 Ma. - 1000 Ma. (Wright et al., 1985 as cited in Jager and Menge, 2012). The Voltaian System is made up of basal sandstone (galls, quartz-sandstone and pebbly grits and grits with ripple marks) which can be observed the western and northern part (Dapaah-Siakwan and Gyau-Boakye, 2000).

The Oti or Pendjari mega-sequence (Middle Voltaian) unconformably overlies the Bombouaka / Gambaga mega-sequence with a thickness of about 2500 m representing a duration of about 350 Ma. (Mensah, 2015). The Oti or Pendjari mega-sequence is made up of the Buipe and Porga group representing the middle Voltaian (Kalsbeek, 2008). The first group is the Buipe group which is known to have similar feature of the Triad of the Taoudeni Basin (Kodjari Group) are mostly facies of tillites or tilloids, barite-bearing dolomitic carbonates and argillaceous and/or calcareous thin-bedded cherts defined as silexites. (Leprun & Trompette 1969 as cited by Kalsbeek, 2008). The second group is the Porga group mainly made of shales and siltstones, limestones, greywackes and lenses of various facies of sandstones, as well as silexites and rare tuffs. 576 ± 13 Ma is the estimated age of the basal phosphorites through Lu-Hf dating analysis (Barfod et al. 2004 as cited in Kalsbeek, 2008). According to Rb- Sr isochron age dating has proven that the shales of the Porga to be 660 ± 9 Ma (Clauer & Deynoux 1987 as cited by Kalsbeek, 2008).

The Tamale/ Obosum Mega-sequence (Upper Voltaian) is the upper sequence of the Volta Basin and has the youngest group of sediments which is only observed in Ghana. It unconformably overlies the Oti or Pendjari Mega-sequence with thickness of about 500 m (Kalsbeek, 2008; Affaton et al. 1991 cited by Mensah, 2015). Due to its continental nature of origin, it comprises reddish coarse-grained to conglomeratic, polymictic and cross-bedded sandstones, including horizons, lenses or sequences of mudstones, shales, siltstones, and limestones (Kalsbeek, 2008). Pan African Dahomeyide orogeny is the cause of the nature of the pebbles and boulders present in the mega-sequence. Junner & Hirst 1946 as cited in Kalsbeek, 2008 disagrees the event of the uplifting of the Pan African orogeny led to the westward migration of its depocenter. (Kalsbeek, 2008).

Petroleum system of the Voltaian: The only potential source rock in the Voltaian is the shales in the Oti group with the sandstones and limestones of the lower Voltaian as reservoir rocks. The potential sealing of the basin is possibly the Middle Voltaian shales and the stratigraphic features and faults could serve as traps. (Kalsbeek, 2008).

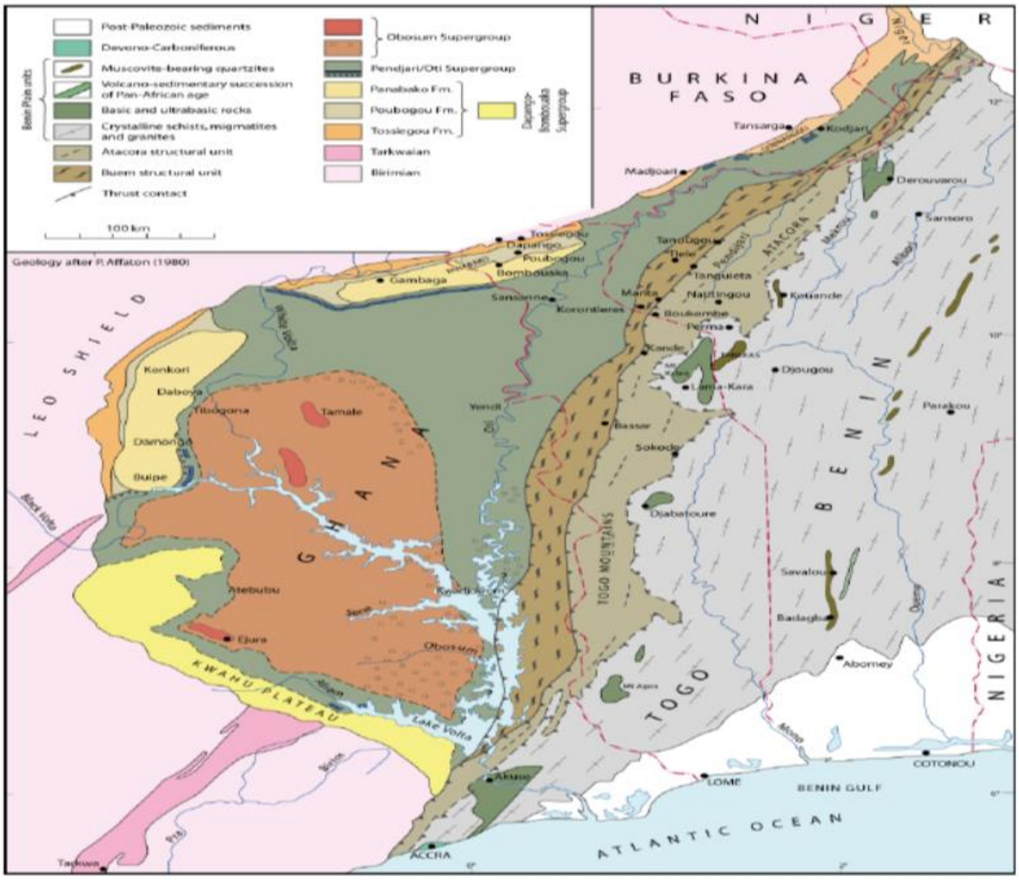

Figure 4.12. Map of the Voltaian Basin showing geological provinces in Ghana (Affaton, 1990 as edited by Kalsbeek, 2008).

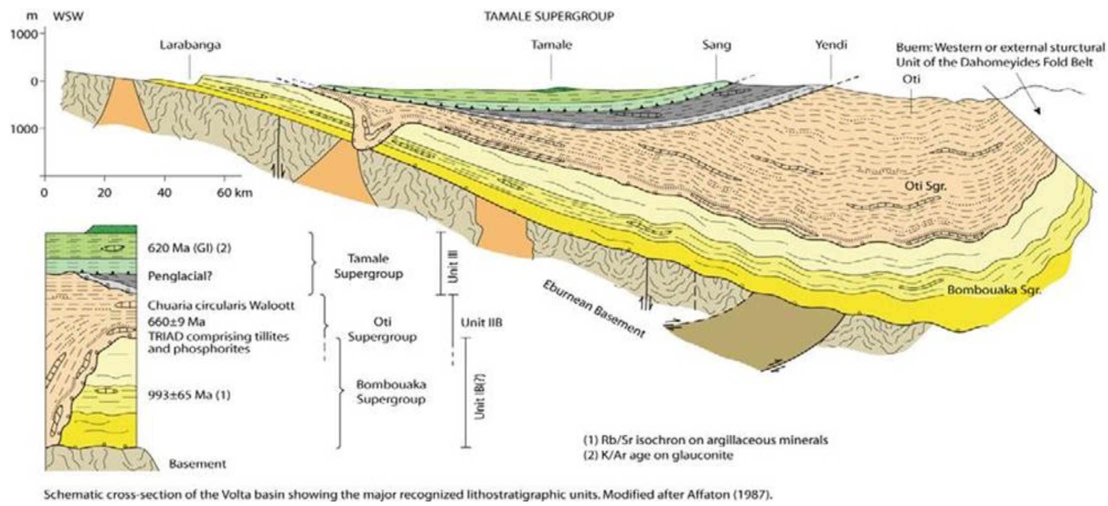

Figure 4.13. Cross-section of the Voltaian Basin in Ghana (modified by Affaton, 1990 as edited by Kalsbeek, 2008).

CHAPTER 5. RESULTS AND DISCUSSION

5.1. Chapter Introduction

This chapter aims at addressing the research questions raised in Chapter 2. The discussions of the answers to the research questions were organized according to themes. The themes covered in this chapter include; oil and gas discoveries in Africa, oil and gas exploration history of Ghana, geophysical explorations work related to oil and gas in Ghana and lastly Ghana's oil and gas potentials. The theme on Ghana's oil and gas potentials were grouped into four subsections namely; Tano Basin, Saltpond/Central Basin, Accra-Keta Basin and Voltaian Basin.

From literature survey, this work is the first comprehensive document containing information about all the major basins in Ghana, their geology, tectonics, and their oil and gas potentials. The available works before this thesis contain only some information on individual basins and some aspect of their oil and gas potentials.

5.2. Oil and Gas Discoveries in Africa

The events of plate tectonics have played a major role in petroleum and natural gas across the globe since the breakup of the Supercontinent Pangea. The African and South American Continents have experienced different forms of continental rifting stages and sheared margins that permitted the accumulation of important oil and gas resources all around the African continent. Some major oil and gas discoveries are also found onshore in sedimentary basins in countries like Uganda, Niger, Mali and other countries which have no coastal borders.

The northern part of Africa has the largest oil and gas reserves in Africa. This is followed by the western part of Africa (Heinrig, 2007). Africa holds one of the world's largest proven reserves and countries like Libya, Nigeria, Angola and Algeria host about 84.8% of Africa's total proven reserves (Beltrage, 2017). The oil potential of Libya is about 48.5 billion barrels, Nigeria has 37.1 billion barrels, Angola has 12.7 billion barrels and Algeria has 12.2 billion barrels of oil reserves. Countries like Egypt (3.9 billion barrels), South Sudan (3.5 billion barrels) and other countries like Gabon, Chad, Republic of Congo and Equatorial Guinea have also proven to have some notable reserves (Beltrage, 2017).

Recently in 2017, BP and Kosmos Energy made a major gas discovery of the coast of Senegal and Mauritania estimating a total of 15 trillion cubic feet of reserves in the Greater Tortue prospects (Petroleum Economist, 2018). In South Africa, Total stated that an offshore discovery was made in South Africa's Brulpadda prospect in the Outeniqua Basin with significant gas condensate with around 1 billion barrels of total resources of gas and condensate (Reuters, 2019). This was discovered in the lower Cretaceous reservoirs at about 187 meters feet (World oil, 2019).

The West African Margin (WAM) has experienced exploration activities for oil and natural gas for decades. Advanced technologies and instruments have allowed major discoveries along the WAM. The Gulf of Guinea (GOG) is located along the WAM which stretches from Cote d'Ivoire to the Northwestern part of Nigeria. Major oil and gas discoveries have been made along the GOG, because it was the last part of the opening of the South Atlantic Ocean providing favorable conditions along the transform faults and fracture zones leading to oil and gas accumulations. The Cote d'Ivoire-Ghana Transform Margins (CIGTM) is one of the margins where world class oil and gas discoveries have been made. A survey done by Equanuate Cruise in 1992 along the CIGTM delineated half grabens and asymmetric horsts in the deep Ivorian basin and reverse faulting and echelon gentle folds on the Ghanaian shelf (Sage, 1994; Basile et al. 1996; Mascle et al. 1997). The CIGMR contains the Espoire field of Cote d'Ivoire and Tano basin of Ghana which are both Cretaceous of age (Brownfield and Charpentier, 2006).

Exploration of oil and gas in Cote d'Ivoire began since 1980 (REEP, 2012; WEC, 2013 as cited by Ministry of Mines) and about 100 million barrels of reserves were estimated in 2005 (REEP, 2012 as cited by the Ministry of Mines; Menes Associates, 2017). The Espoire which was discovered in 1982 had an estimation of 93 million barrels of recoverable oil and 180 billion cubic feet of natural gas with CNR as the operator of the discovery. Later in 2001, the Baobab field of Cote d'Ivoire was discovered by the Canadian Natural Resources Ltd. (CNR) which it was estimated to have 700 million and about 200 million barrels of recoverable resources of oil. The quality of oil found in Acajou field is quite like that of the Espoire field with an average rate of oil known is 3500 bopd (OGJ editors, 2003). The Lion and Panthere fields have a capacity of about 1230 bopd which was discovered in 1980's. The Foxtrot field is the largest natural gas field of Cote d'Ivoire which was discovered by Foxtrot International LCD in the Turonian formations which contains the Mahi, Marlin and Manta gas fields. The Mahi field produces on average 32 million cubic feet of natural gas per day and some 250 barrels condensate per day, and that of the Marlin and Manta produces about 3000 bpd of oil and condensate currently (offshore technology, 2016). Most of the oil and gas discoveries made in the Cote d'Ivoire basin is within the Albian, Cenomanian, Senonian, Turonian and Maastricht sequences (Petrol, 2019).

Benin has an offshore basin namely Aje field located in the western end of Nigeria. Within this basin is the Ise formation which is mostly focused on because the rock is of upper Jurassic to lower Cretaceous ages containing conglomerate, sandstones and shales (Brownfield and Charpentier, 2006).

The Gambia is a neighboring country of Senegal (which has seen significant discoveries of oil and gas). An Australian oil company FAR stated that The Gambian blocks (A2 and A5) could hold about 1.2 billion barrels of oil due the significant discoveries made by The Gambia's neighboring countries (Mauritania-Senegal-Gambia- Bissau- Conakry) (Offshore Energy Today, 2019). So far, no information indicates the production of oil and gas in the Gambia.

Sierra Leone is not one of the oil producers just like The Gambia, because it hasn't discovered any commercial quantity of oil and gas. According to Repsol oil company (Afrol News, n.d.), exploration for oil and gas has started since 2003, offshore the coast of Sierra Leone drilling the Venus B-1 well and Mercury-1. The data collected indicates a high potential of possible oil and gas discoveries. African Petroleum in 2017 said offshore the Sierra Leonean coast had an estimate of at least 2 billion barrels of oil could be recovered with extensive explorational work done.

Liberia as one of West African's countries is believed to be rich in oil and gas resources. Exploration work done in about 10 wells drilled were dry indicating the geological complexity in their basin making it quite difficult to find oil and gas. These surveys were carried out by oil companies such as ExxonMobil, Anadarko, Repsol, Tullow and African Petroleum (FPA, 2017). More exploration and drilling works need to be carried out to be able to attain possible commercial quantities of oil and gas.

Togo is a neighboring country to Ghana and Benin. Togo has an offshore basin called the Dahomey basin, but so far major oil and gas oil discoveries haven't been made despite its location. Extensive exploration is ongoing to come up with significant oil and gas discoveries.

Nigeria, which is one of the Africa's oil and gas producing and exporting countries, has the Niger delta where significant oil and gas fields have been discovered. Nigeria was estimated to have 37 billion barrels of proved oil reserves by the Oil & Gas Journal (OGJ) in 2015 (eia, 2016) and it is the second largest after Libya. It has the largest natural gas reserves in the whole of Africa (eia, 2016). Nigeria started producing oil and gas since the 1980's. They used to have about 481 million barrels of oil, but have seen a drop over the years as it dropped to 37.448 in 2014, 37.062 in 2015, 37.453 in 2016 and 2017, 36.972 in 2018 according to OPEC's (Organization of Petroleum Exporting Countries) 2019 Annual Statistical Bulletin.(Punch, 2019). The significant discoveries made in Nigeria made other West African countries like Ghana considered to be important potential fields for oil and gas discovery since the geological structures along the Gulf of Guinea are similar.

5.3. Oil and Gas Exploration History of Ghana

According to the Ghana Geological Survey Bulletin No. 40, oil and gas exploration began in Ghana in 1896 in the Tano basin in what is now the western administrative region. This was due to the presence of oil and gas seepages that was found along the coast and it was discovered by the first explorers in the area.

There are big differences between the type of exploration during the first discovery of oil in Ghana and that of today. At the beginning of the discovery, it can be said that the discovery was by chance and that the wells were drilled without geological and geophysical understanding of the oil production. Those first wells had little documentation. Companies such as the West Africa Oil and Fuel Company (WAOFCO), the French Petroleum Company, the African and Oriental Petroleum Corporation (UAC) and the Gulf Oil Company drilled for oil in the onshore Tano basin between 1896 to 1986. In addition to this observation, these companies have encountered heavy oil, light oil and gas at various depths.

After Ghana's independence in 1957, responsibility for oil and gas exploration fell to the First Republic of Ghana from 1957 to 1966. At that time, the Gulf Oil Company continued to commence exploration exercises that had already commenced before the independence of Ghana. Soviet and Romanian geoscientists have also studied oil and gas in the Basin of Accra / Keta and Volta. At that time, relations between Ghana and the Soviet Union were very good. The drilling exercise was performed without geophysical exploration (especially seismic exploration). The results of the Volta team's exploration by the Soviet team showed traces of oil and gas in parts of north and northeastern Ghana.

During the period of the National Liberation Council and the Second Republic, i.e. between 1966 and 1972, oil and gas exploration continued. At that time, interest shifted from onshore exploration to offshore exploration. The extraordinary discovery of that time was the Seago 10-1 well by Amaco Petroleum (Saltpond Oil Field) and the discovery of the Tano Well by the Volta Petroleum Company (Tano Basin). Between 1972 and 1979, 17 wells were drilled. At this point three major developments in oil and gas exploration had occurred. According to Anon, an important gas discovery was made in 1973 offshore Cape Three Points. The Saltpond field started oil exploration at that time and was operated by AgriPetco. Finally, the South Tano oil and gas field was discovered in 1978 by Phillips Petroleum. At that time, 2D seismic data was used to map offshore and onshore prospects. The gravity method was used to map the onshore Keta basin.

Between 1979 and 2000, much work was done on oil and gas exploration in Ghana and many discoveries were made. In 1981, Phillips Petroleum went ahead to appraise the South Tano field by drilling further wells and they declared the South Tano discovery sub-commercial relinquished the block. They also appraised the North Tano which was discovered by Volta Petroleum but later declared the field non-commercial and relinquished the field.

Ghana National Petroleum Corporation (GNPC) was founded in 1985 to provide the requisite institutional framework to handle the country's exploration and production activities. In 1984, the Petro Canada International Assistance Corporation (PCIAC) and GNPC recorded approximately 20 seismic data in the Tano / Cape Three Points offshore basin. During the same period, Atlantic Richfield Company Limited (ARCO) discovered gas in Central Tano and in 1989, Hunt Oil Company discovered oil in deep water, but declared the discovery non-commercial. The last period to consider is from 2001 to 2007. Major reputable oil companies such as Kosmos Energy, Hess Corporation, Tullow Oil, Norsk Hydro Oil and Gas, etc. have further exploited the potential prospectivity of Ghana as a destination for investment. Some of the major discoveries of that time were; the discovery of oil by Dana Petroleum Plc. This discovery provided a solid technical foundation for determining the future direction of oil exploration in Ghana. According to anon, n.d. the most significant discovery that has crowned years of shared effort by all involved parties was the discovery of high-grade oil fields in the Mahogany prospect in the West Cape Three Points by block operation Kosmos Energy, technical operation by Anadarko, Tullow Oil and E. O. Group.

Ghana Petroleum Corporation (GNPC) is currently issuing licenses to various international oil and gas companies. These companies are well-equipped with exploration equipment, advanced technologies and highly qualified geologists, geophysicists and other highly specialized experts in the oil and gas industry. These companies use geophysical, geological and plate tectonics knowledge in oil and gas exploration. Due to this, companies can maximize their financial benefits and reduce losses.

5.4. Geophysical Explorations Related to Oil and Gas in Ghana

Geophysical methods are used in most geoscience exploration work for the search of groundwater, petroleum and natural gas, minerals, archeological work and a lot more. The use of geophysics in the petroleum industry is a well-known knowledge globally. Seismic, gravity, magnetic, magnetotelluric, resistivity methods and wireline well logs (gamma, sonic, resistivity etc.) are the geophysical methods adopted by the oil and gas companies in the search of oil and gas. In every exploration work, geological and geophysical data and other vital data as well as well logs and core samples to determine the position of the explored entity. In every exploration work like in petroleum exploration, some of the geophysical methods mentioned above are applied to determine the possible plays for commercial production.

In the case of the Ghana some of the geophysical methods were used to find commercial oil and gas in the prolific Tano basin and the Saltpond basins. To get geophysical data from these oil companies for a research is quite difficult, therefore geophysical information from published articles and unpublished work are mentioned in this chapter. These geophysical information about the sedimentary basins of Ghana give a better outlook in the possible petroleum and natural gas potential of Ghana.

The Tano basin being the most prolific of all the sedimentary basins has proven to have significant discoveries within it. Some of the geophysical work done in the basin can only be acquired from published articles. These articles give some vital information about the possible source rocks, reservoir rocks, traps and seals as well as the hydrocarbon plays in the basin.

Dailly et al., 2019 interpreted, that the seismic section of the Tano basin as shown in Figure 5.1 shows some features such as the deformation of the Romanche fault and Dixcove transpressional anticlines, the Late Cretaceous fan systems in the Dixcove ridge which represents a reservoir bearing rock of a possible mature source kitchen and the regional migration path in the Late Cretaceous play of the Oligocene- Miocene formations. Figure 5.2 shows the detailed geometry of the Late Cretaceous slope fan which gives information about the reservoir source.

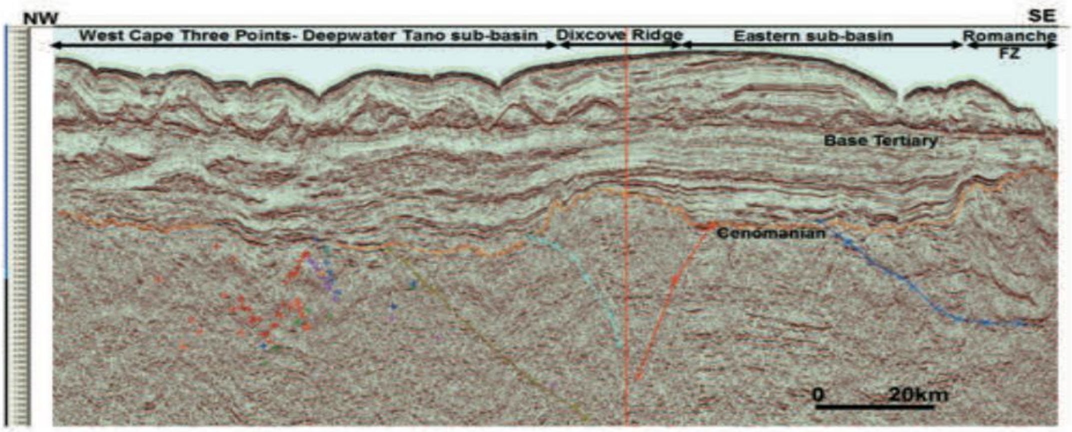

Figure 5.1. Seismic section of the Tano basin displaying some structural features and some fault zones. Obtained from Dailly et al., 2019.

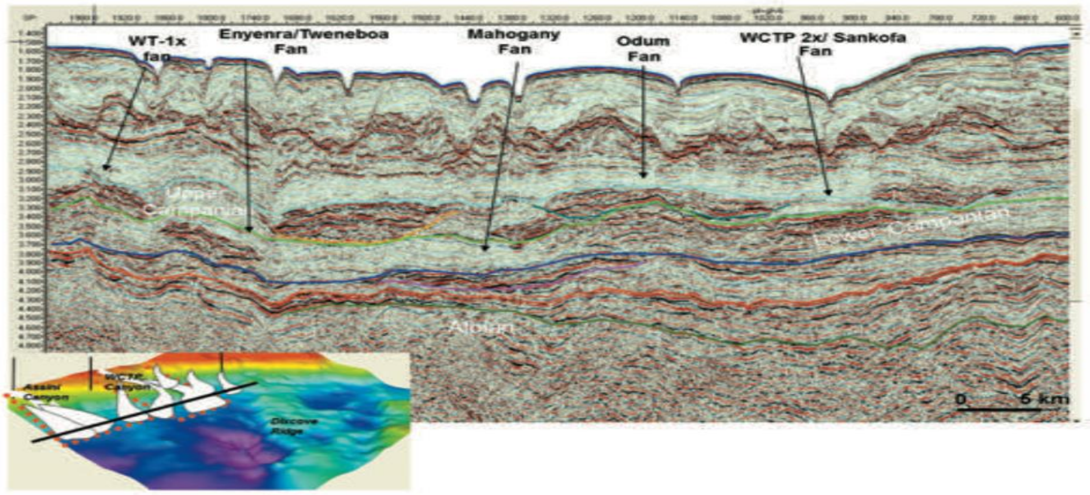

Figure 5.2 Seismic section containing some detailed geometry of the late Cretaceous slope fan of the Tano basin, obtained from Dailly et al., 2017.

The Mahogany-1 discovery (Jubilee field) is one of the most successful fields discovered in the Tano basin. Figure 5.3 - 5.5 shows some seismic sections obtained from the Mahogany discovery of the Jubilee field. Figure 5.3 explains a N-S seismic line and RMS far amplitude map of the Mahogany formation prospect showing the combined trapping mechanism (structural and stratigraphic) of the Mahogany-1 well. Figure 5.4 is a well log summary of both Gamma ray and Resistivity of the Mohogany-1 in the Turonian section elaborating the reservoir age, type of rocks present, formation thickness, porosity, permeability and fluid type. The Turonian section are mostly sandstones of high-quality oil-bearing fluids. Figure 5.5 shows a seismic 2D dip line NE-SW through the Jubilee field (Dailly et al., 2017; Dailly et al., 2019). Figure 5.6 is a NE–SW 2D dip line through Jubilee/Mahogany showing the up-dip trapping elements; yellow horizon is top Turonian fan. Figure 5.7 is a North–south line showing Mahogany 1 location and pinch out of Mahogany fan to the north.

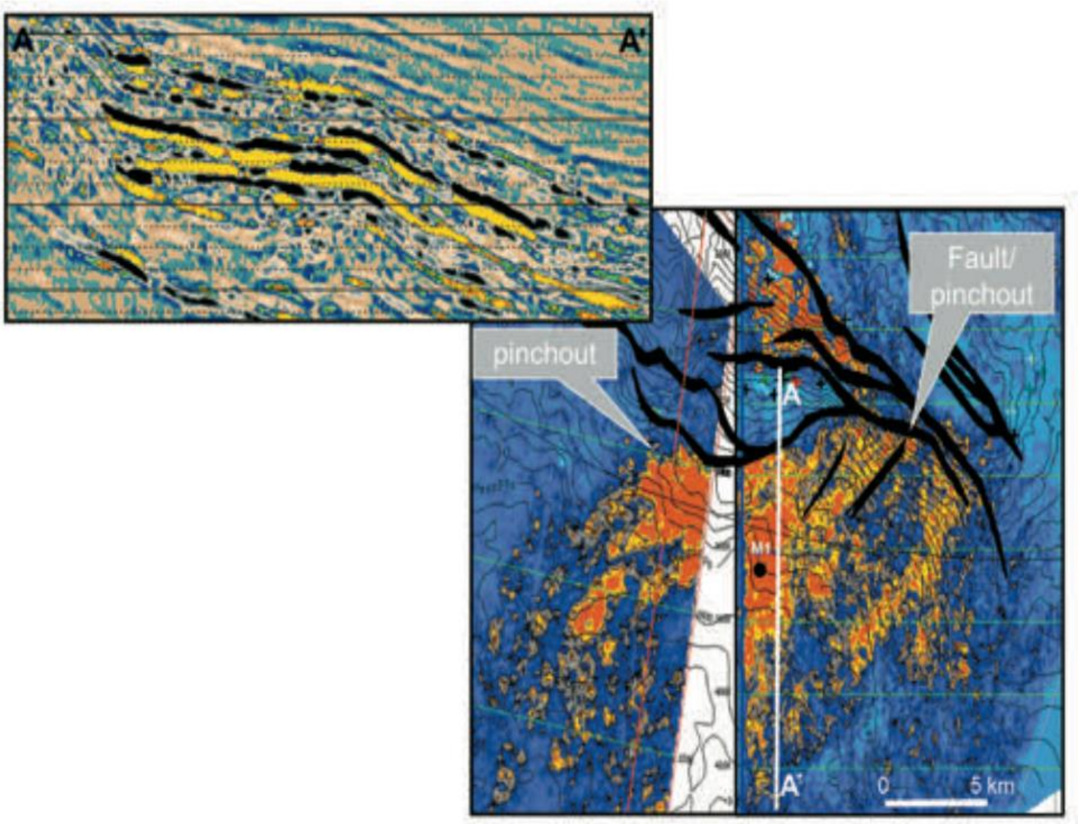

Figure 5.3. Mahogany-1 well in Jubilee field of the Tano basin (N-S seismic line and RMS far amplitude map), # obtained from Dailly et al., 2017.

Jubilee Field statistics

Discovery well	Mahogany 1
Water depth	900–1700 m
Reservoir age	Turonian
Field unit area	110 km^2
Depth to top reservoir	2100 m *bml*
Contact depths	3531/ 3755 m *bml*
Gross thickness	250 m
Net thickness	40–90 m
Porosity	20%
Permeability	100–1000 mD
Fluid Type	37*API*

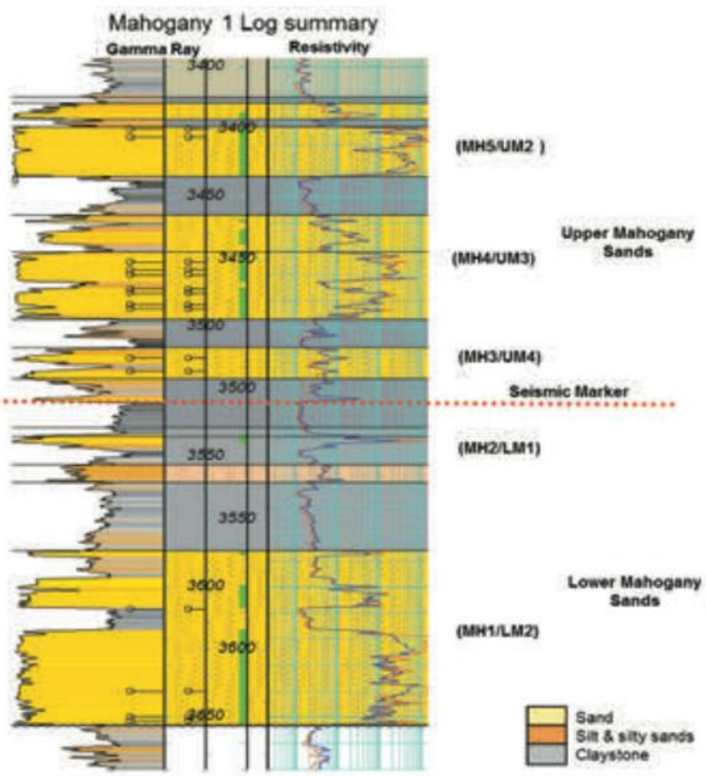

Figure 5.4. Well log summary of the Turonian section of the Mahogany-1 well, obtained from Dially et al., 2017.

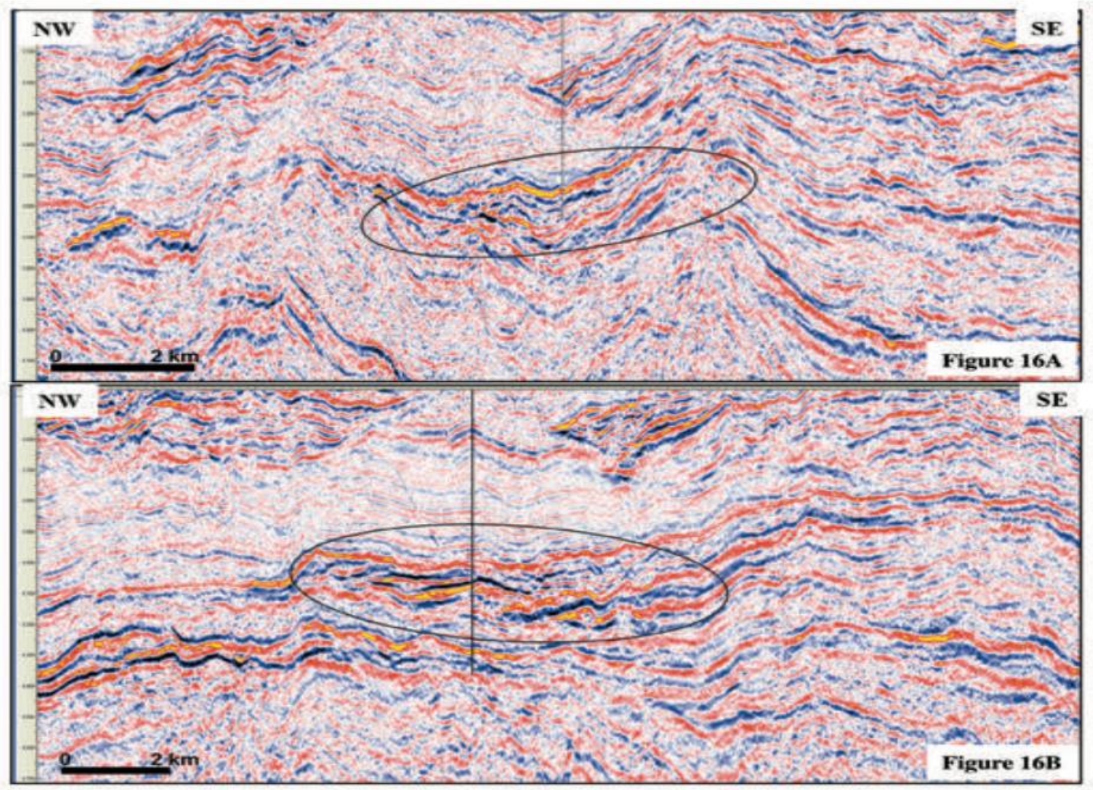

Figure 5.5. NW-SW 2D strike lines of the Jubilee and Mahogany fan indicated in the circles obtained from Dailly et al., 2017).

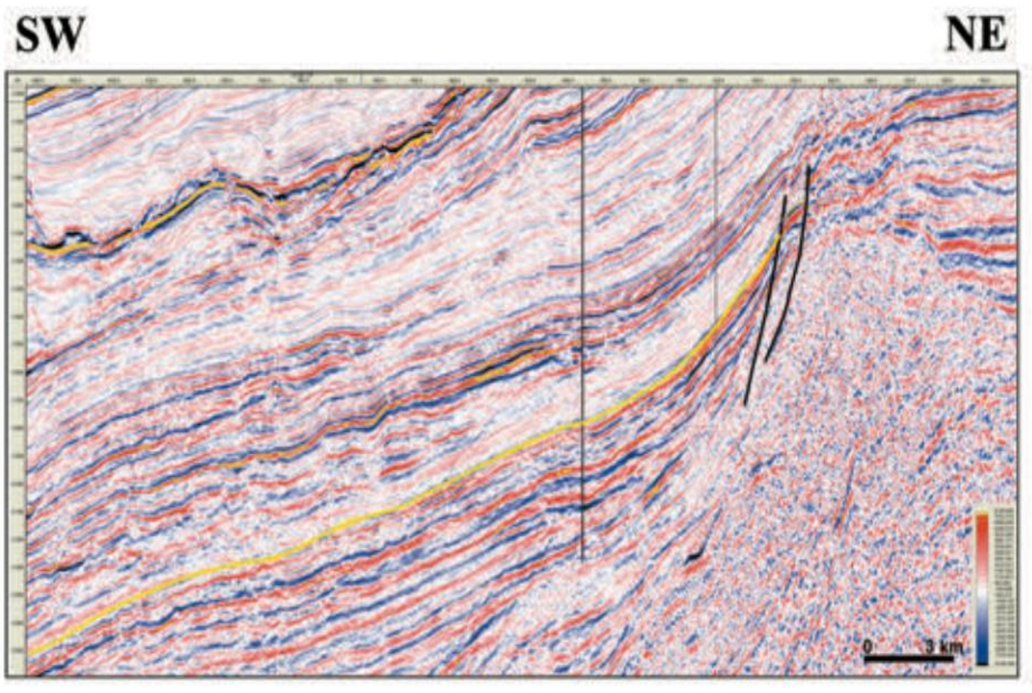

Figure 5.6. NE–SW 2D dip line through Mahogany showing the up-dip trapping, obtained from Dailly et al., 2017).

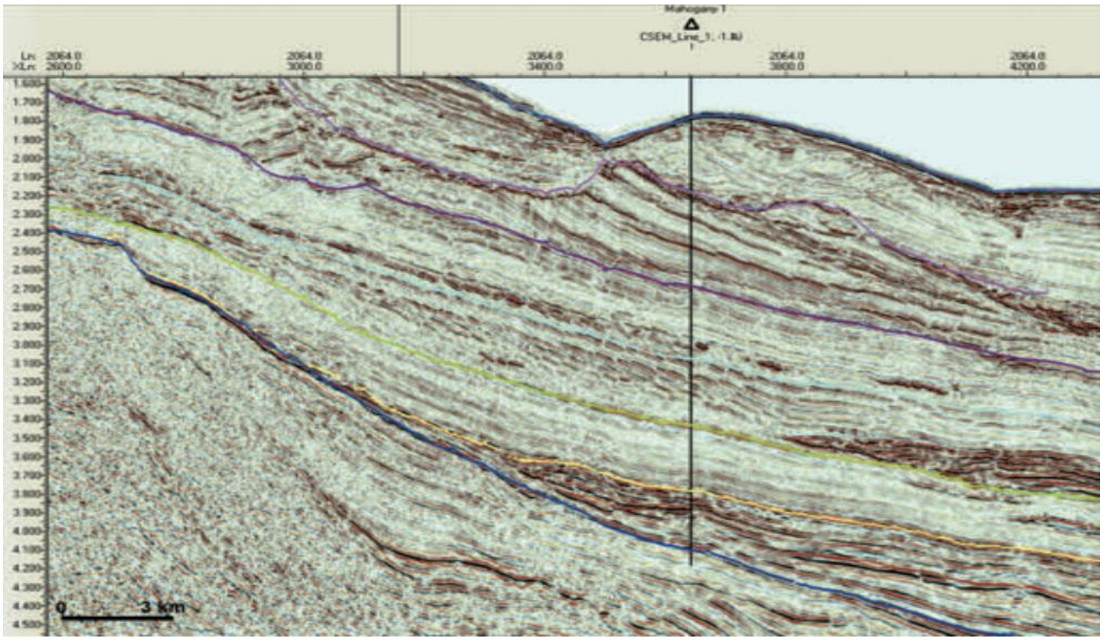

Figure 5.7. North–South line showing Mahogany 1 location and pinch out of Mahogany fan to the north, obtained from Dailly et al., 2017.

The Tweneboa, Enyenra and Ntomme (TEN) field was also discovered close to the Jubilee field has also seen massive explorational work. Seismic sections were acquired from the TEN field was carried out in the Turonian and Santonian formations to characterize the reservoir properties. Figures 5.8 – 5.14 are the seismic sections, maps and well logs obtained from the TEN field. Figure 5.8 is a seismic section of the mapped horizons of the TEN field of the Turonian and Santonian formations. Figure 5.9 shows the lower section of the section of the Turonian. The seismic section also explains the type of faults in the Turonian formation which can be seen to be normal faults with their orientation a bit of faults throws. It can be concluded that stratigraphic traps (interfingering of sand and shale) are more evident in the Turonian than structural traps (anticlines and faults). Gamma ray logs in Figure 5.10 and 5.11 were also acquired from the TEN fields from which it is interpreted that the grey color indicating a high gamma ray value indicating shale and the yellow color shows low gamma ray value indicating sand units. From the logs, Figure 5.11 shows a three-reservoir system and that of Figure 5.12 shows two reservoir systems (Ablordeppey, 2016). Figures 5.13 and 5.14 are well to seismic ties within the sand units in the wells (Sovereign-1 and Sovereign-2 wells). Figure 5.13 is the seismic section showing the ISO-proportional interval falls in the sand units indicating the reservoirs present. The yellow color indicates sand units which was correlated with the sand units of the gamma ray log as well as determine lateral extent of the reservoir units. This was done by correlating high negative amplitude with the sands. Figure 5.14 is a well logs tie to seismic data. It explains the characteristics of the sand shale units in the gamma ray logs with ISO-proportional interval which falls at depth range of each reservoir unit (N01, N03). The yellow colour indicates low gamma values which confirms the clean sands in the trough (red) on the seismic section. The W3 gamma ray log indicates good correlation with the sands. Figures 5.15 and 5.16 are structural maps of the upper and lower Santonian of the TEN field. Figure 5.15 indicates the upper Santonian dips from NE to SW interpreting a sloppy subsurface. Figure 5.16 indicates the lower Santonian which dips from north towards south showing in the red circulated portions showing anticlinal features from both figures explaining sediments were deposited in a sloppy subsurface topography (Ablordeppey, 2016).

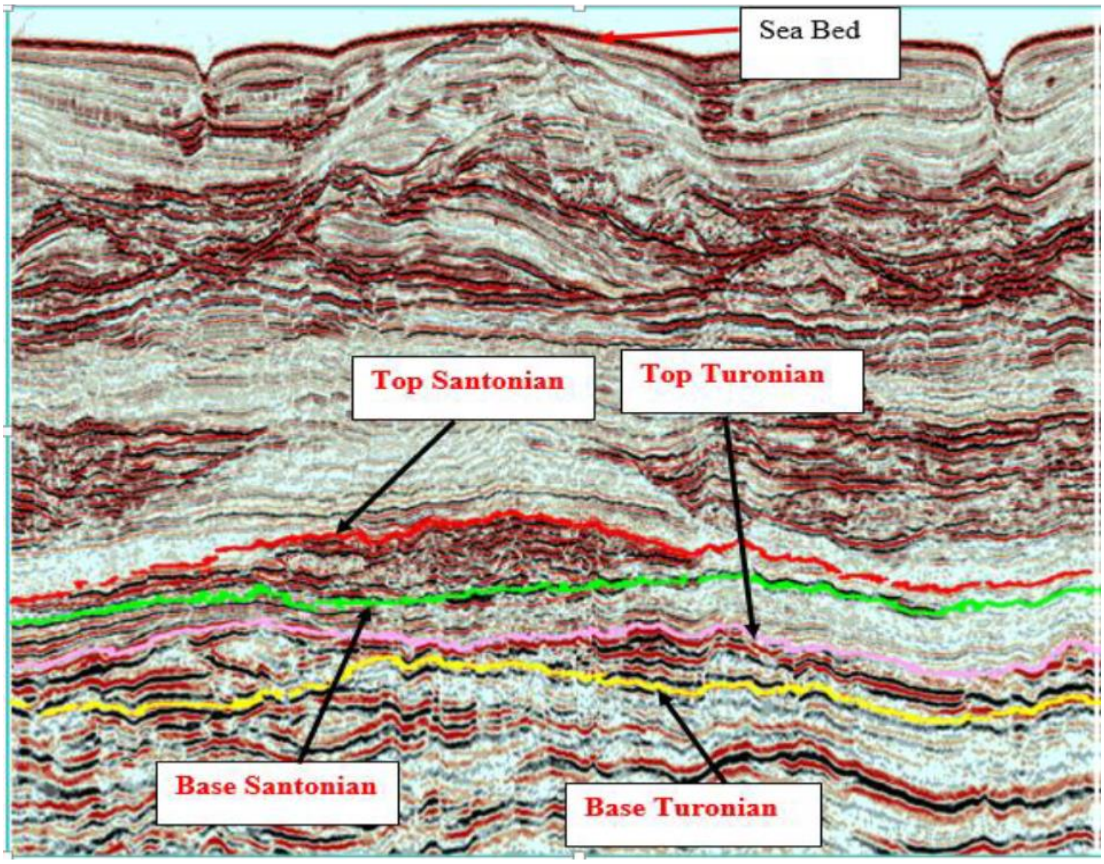

Figure 5.8. Mapped horizons of TEN field of the Santonian and Turonian, obtained from Ablordeppey, 2016.

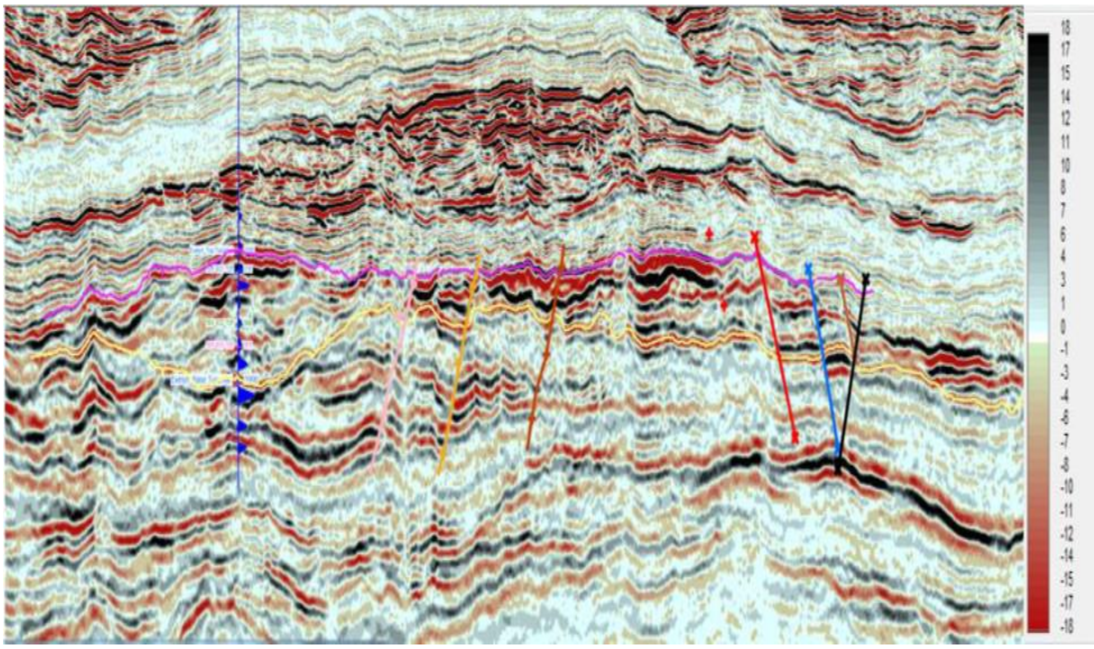

Figure 5.9. Illustration of the various faults from a seismic section in the Turonian formation, obtained from Ablordeppey, 2016.

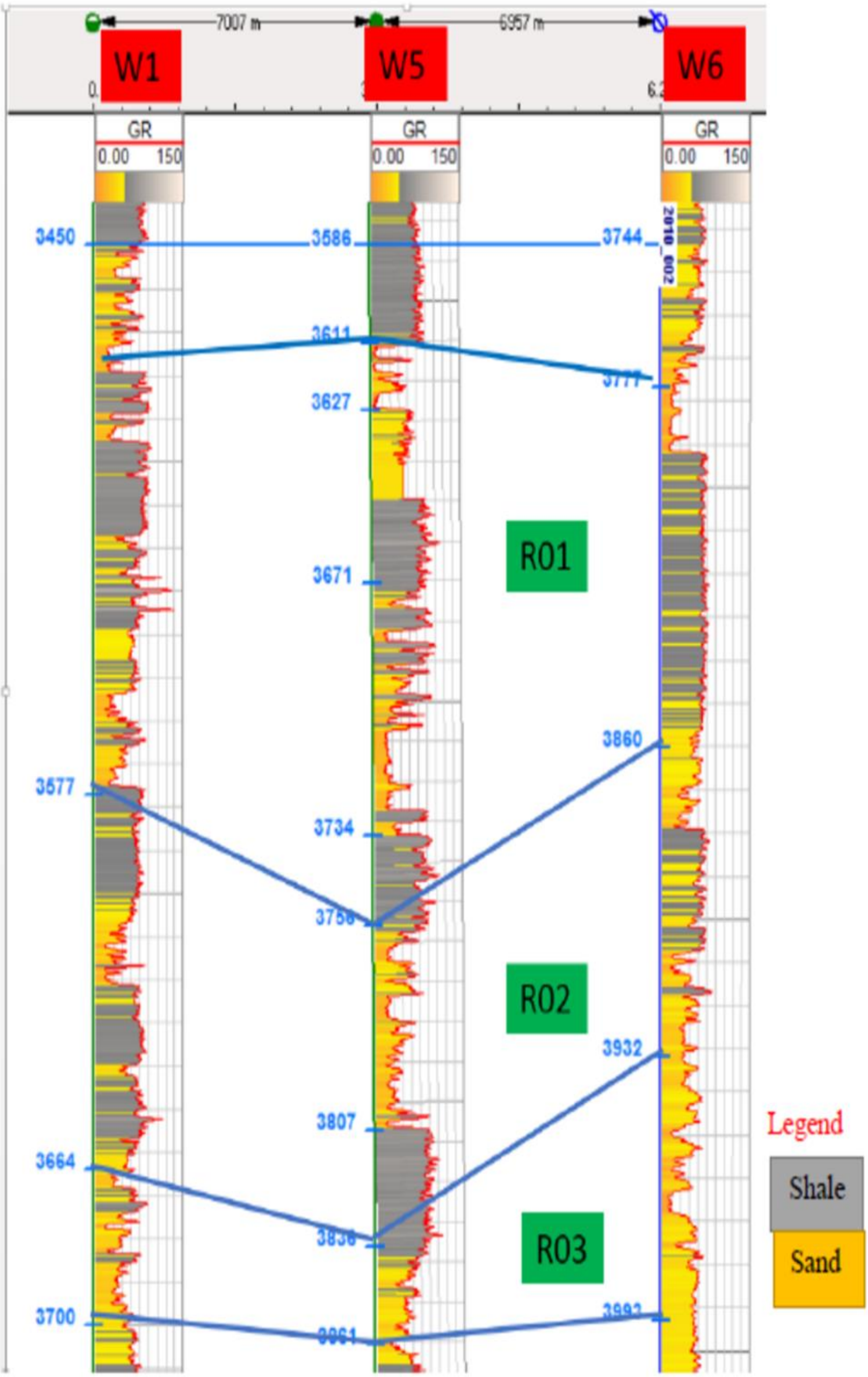

Figure 5.10. Well correlation within the Sovereign 1, obtained from Ablordeppey, 2016.

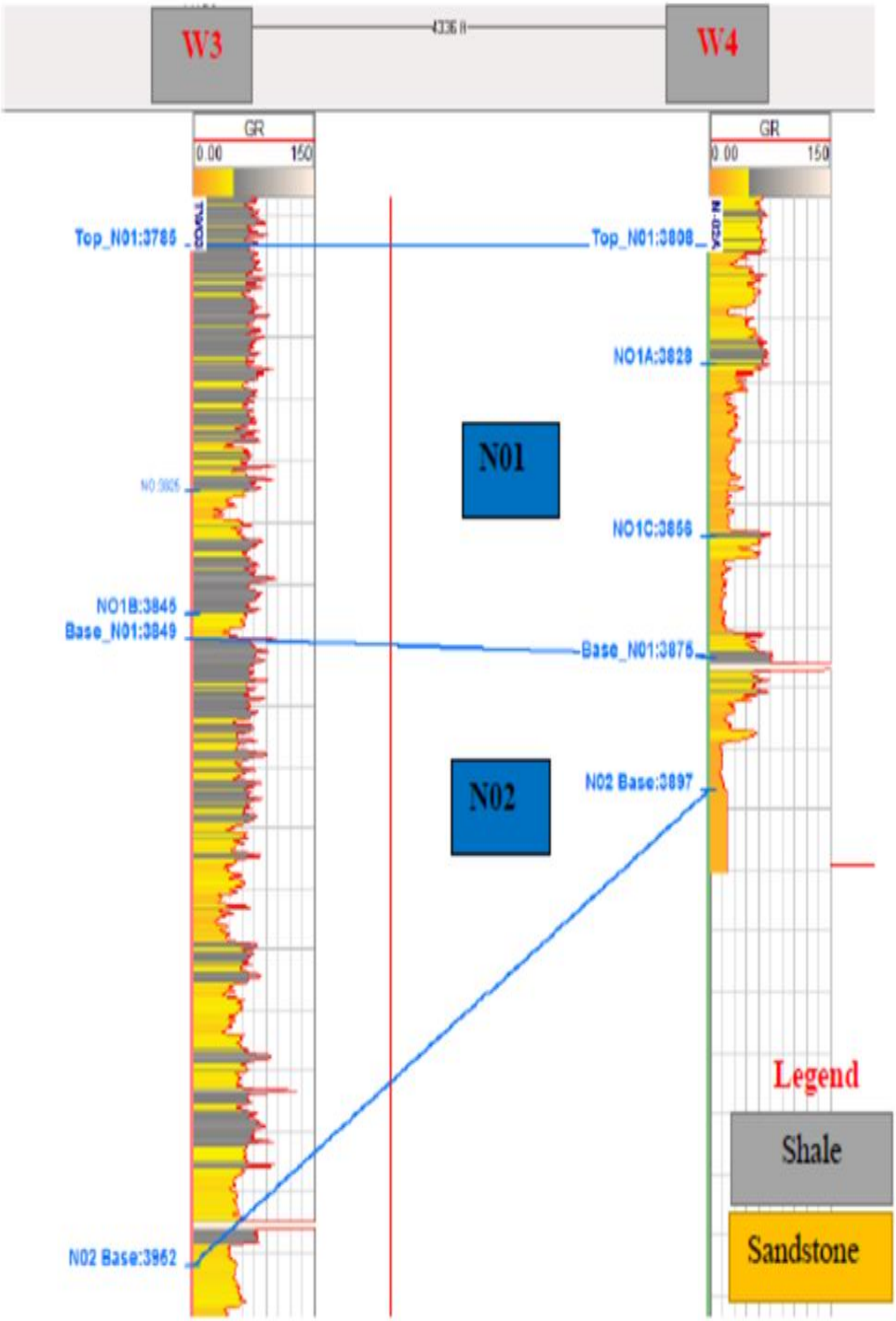

Figure 5.11. Well correlation within the Sovereign 2, obtained from Ablordeppey, 2016.

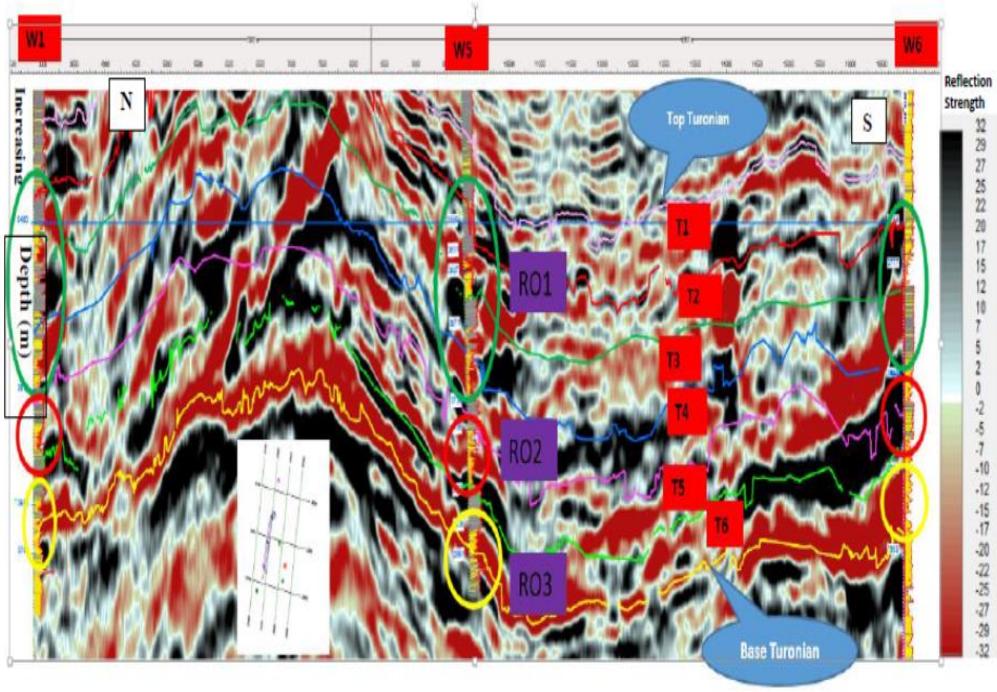

Figure 5.12. The behaviour of sands and shales units from Well to Seismic (EEI Data) tie and ISO-Proportional Intervals - A, obtained from Ablordeppey, 2016.

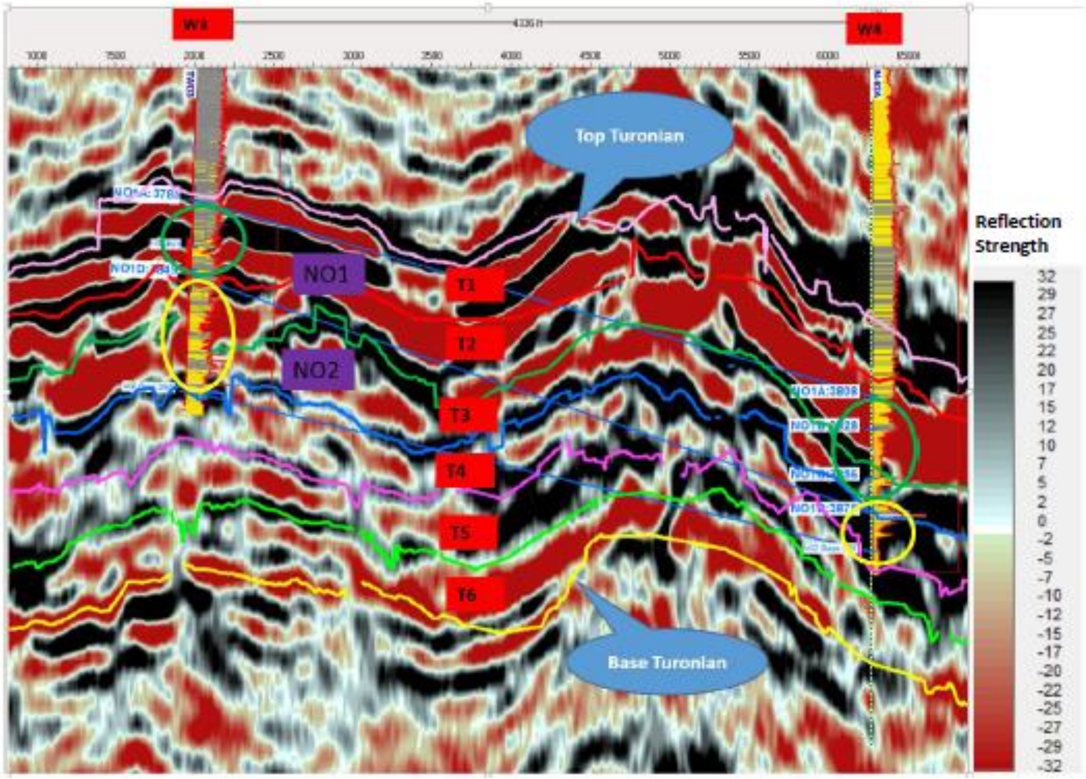

Figure 5.13. The behaviour of sands and shales units from Well to Seismic (EEI Data) tie and ISO-Proportional Intervals - B, obtained from Ablordeppey, 2016.

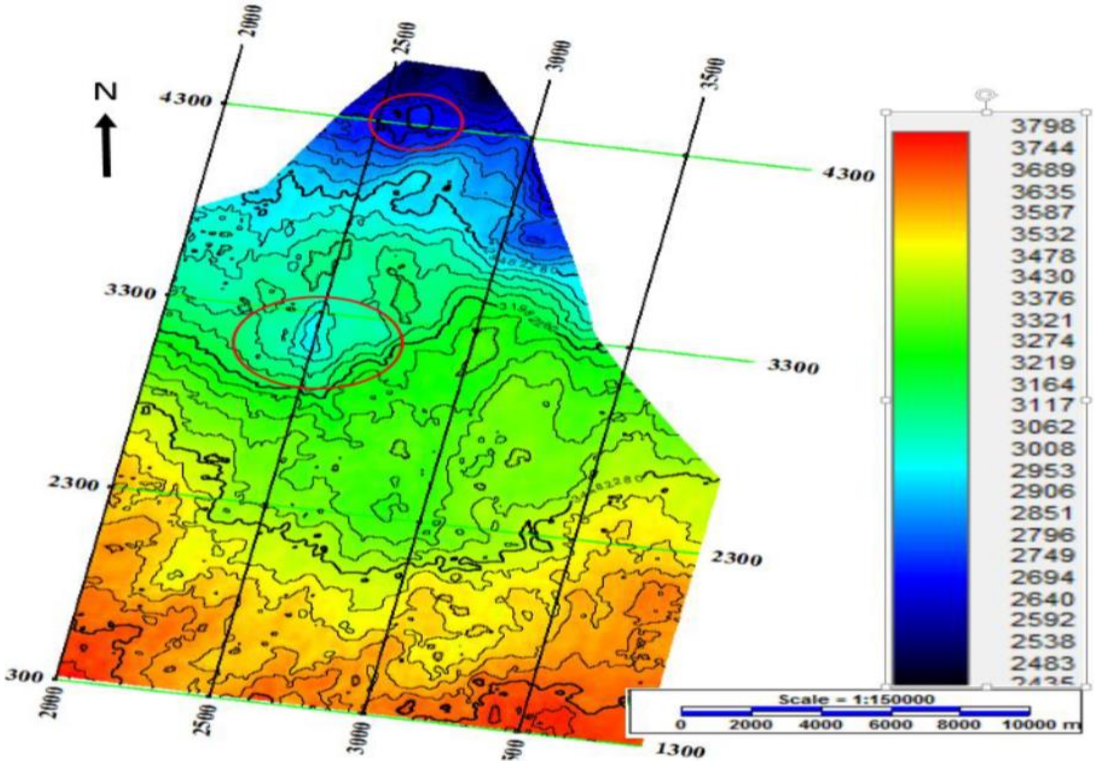

Figure 5.14. Structural map of the upper Santonian, obtained from Ablordeppey, 2016.

Geophysical works were conducted in the South Tano between the mid Turonian and intra upper Albian formation of the Tano basin to evaluate the hydrocarbon potential of these formations (Fontem, 2019). From the work, seismic and wireline log data were used for the evaluation and a well section window was created to elaborate the depth of the wells drilled as shown in Figure 5.15. The seismic-to-well tie, gamma ray logs and resistivity logs were used to create a horizontal map shown in Figure 5.16. Figure 5.17 was used to locate the fault zones along the reservoir section. The breaks (yellow lines) in the seismic section were interpreted as fault zones. Figure 5.18 of seismic-to-well tie was used to interpret the horizontal section of the formations present. Figure 5.19 illustrates the well section windows from top to bottom of the wells investigated. Figure 5.20 illustrates the well logs showing the reservoir zones within the mid Turonian-upper Albian (96.5Ma), Upper Albian (96Ma) to intra upper Albian (98Ma) and intra upper Albian (98Ma). Figure 5.20 also elaborates the facies log, resistivity log and neutron-density log of the reservoir zone. The facies log explains the presence of sand and shale facies present in the formations. The reservoir zones indicating the presence of petroleum and natural gas were determined using the density and neutron logs. These data collectively imply the presence of four major faults trending NW-SE, the well logs indicate good geophysical results of the proliferous reservoir zones which are the mid Turonian to intra upper Albian and upper Albian to Albian sections.

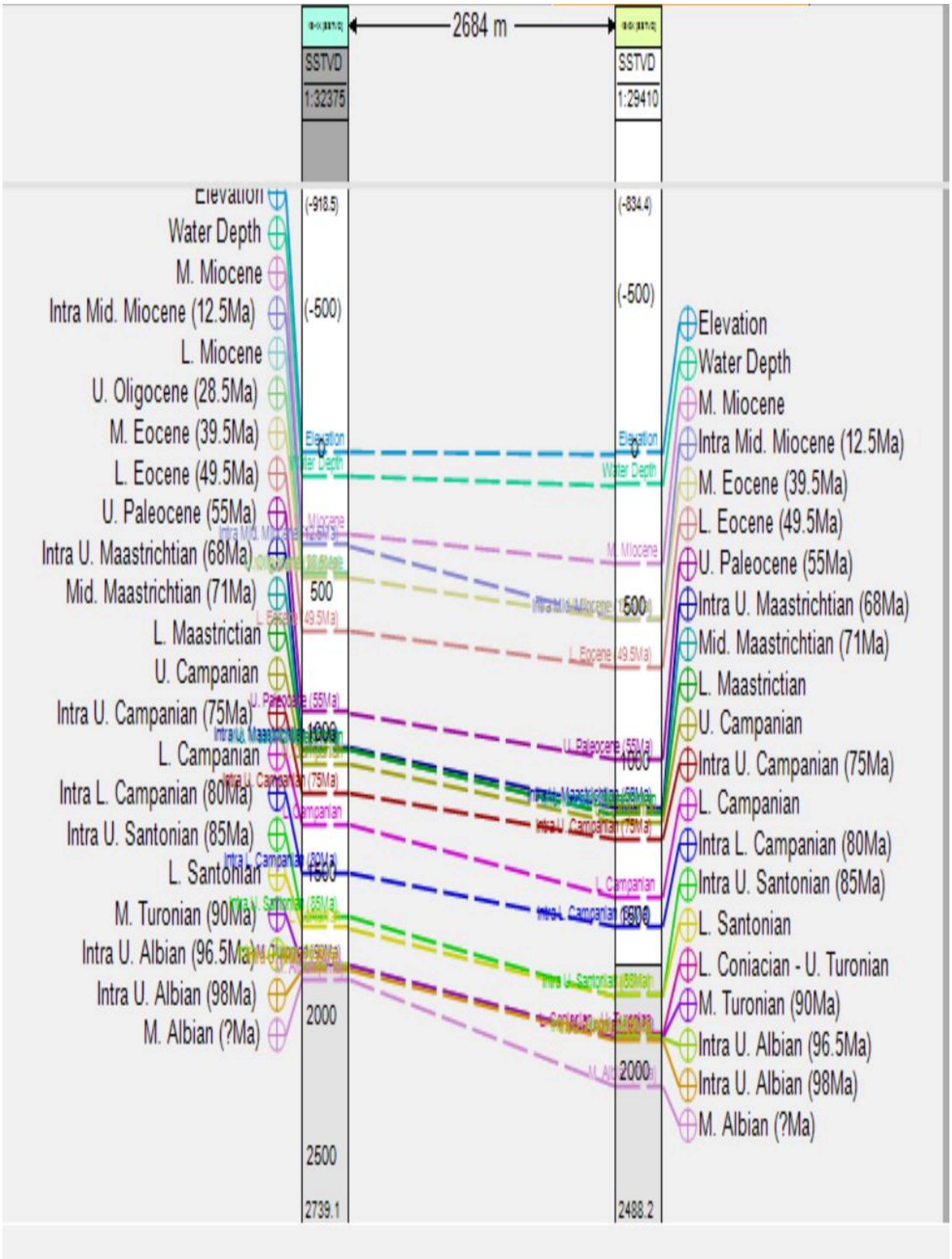

Figure 5.15. Well section window showing the depth of the wells from top to both (obtained from Fontem, 2019).

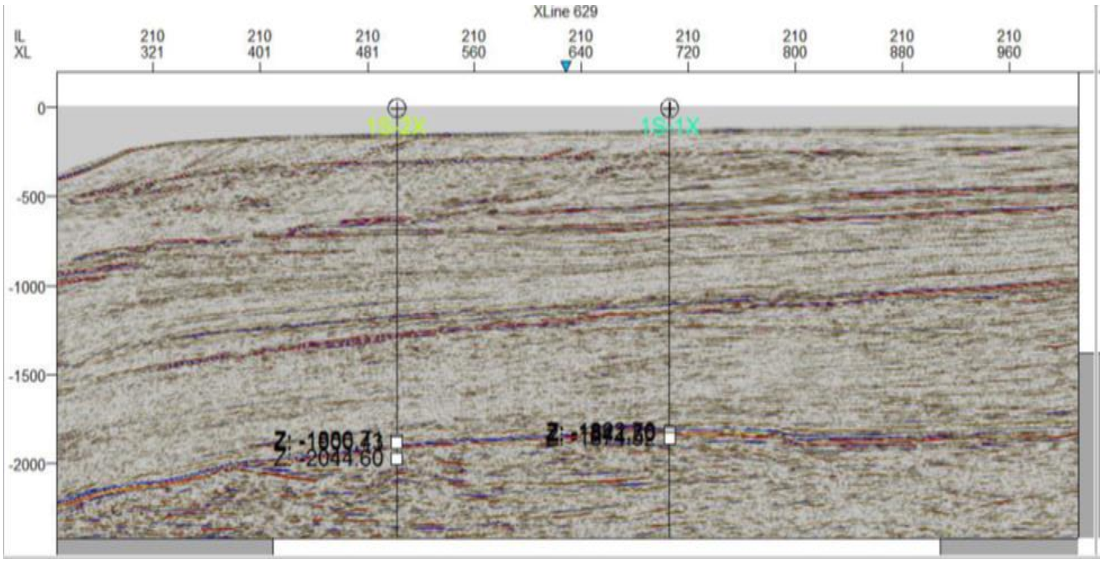

Figure 5.16. Seismic well tie section and horizontal map section of the surveyed section of the South Tano obtained from Fontem, 2019.

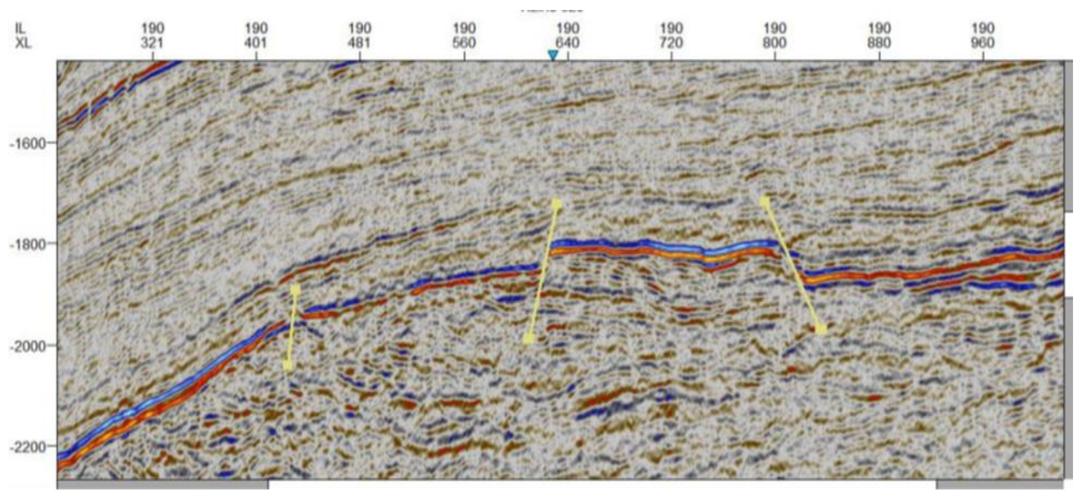

Figure 5.17. Seismic section delineating the major fault zones observed in the horizons (Fontem, 2019).

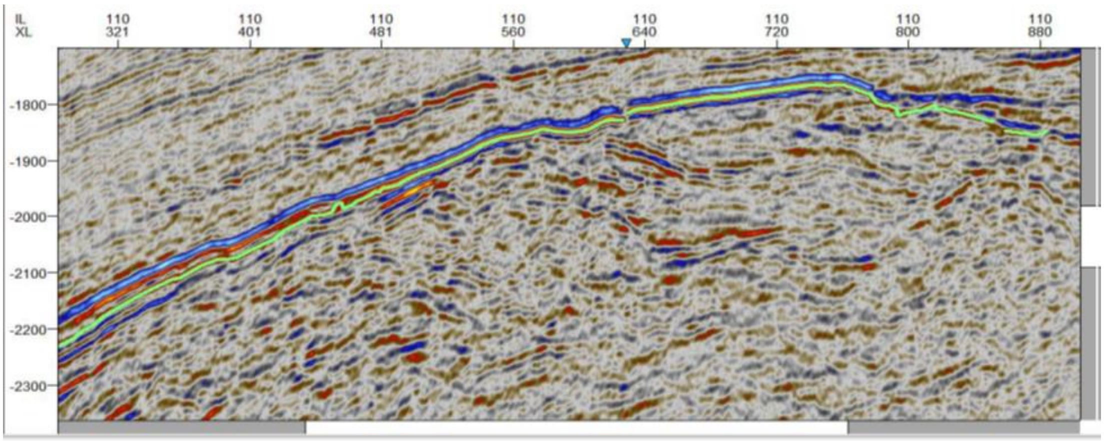

Figure 5.18. Horizontal interpretation made from the seismic section attained (Obtained from Fontem, 2019).

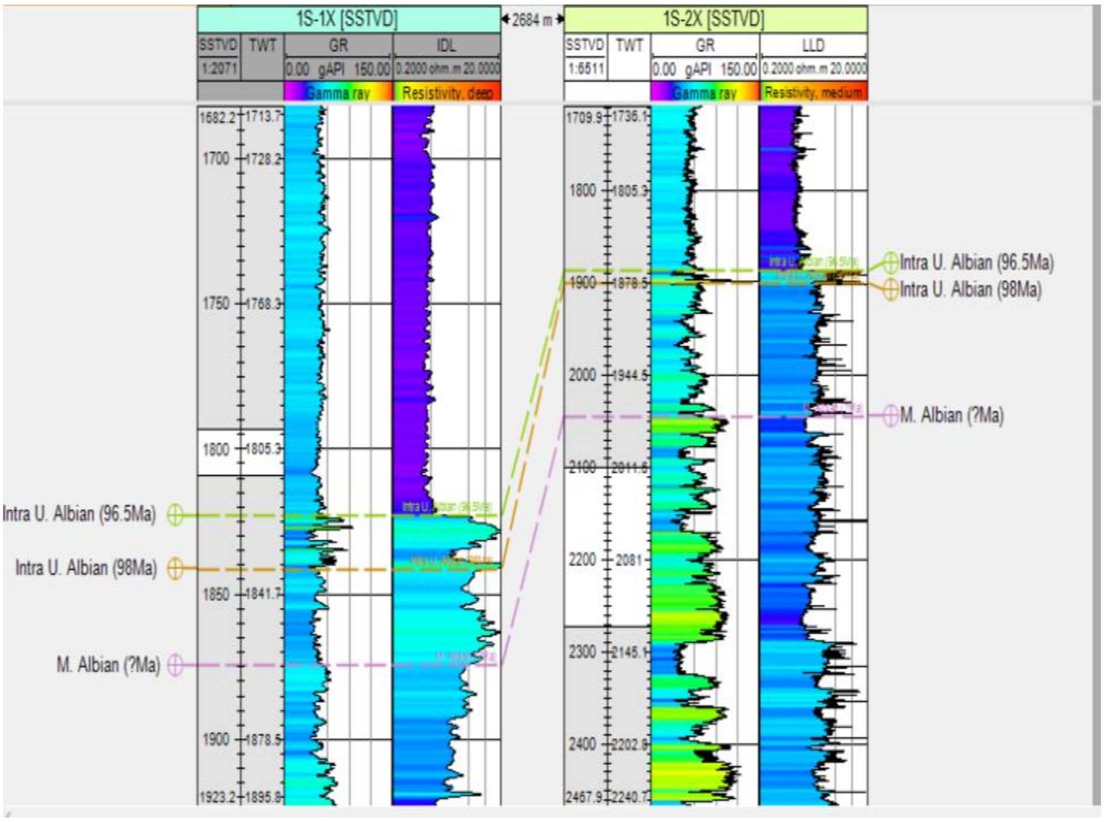

Figure 5.19. Reservoir zones delineated from correlation between the wells (Obtained from Fontem, 2019).

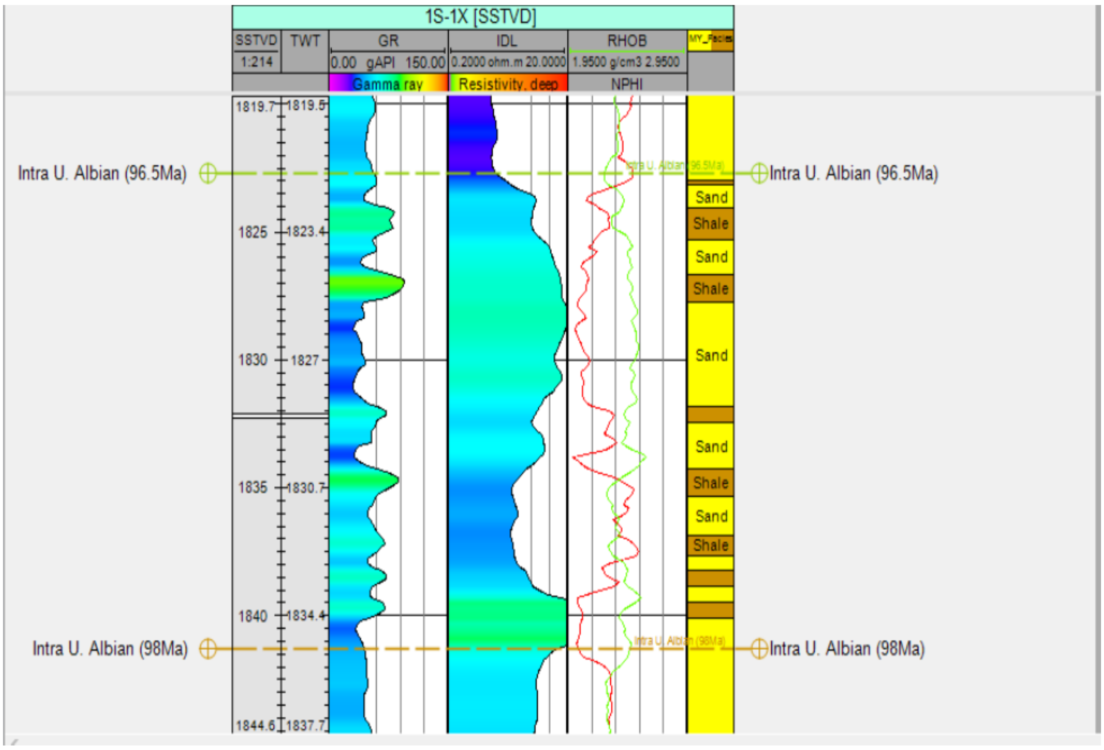

Figure 5.20. Combination of facies log, resistivity log and neutron density log to delineate reservoir zone (Obtained from Fontem, 2019).

The Saltpond is the second sedimentary basin that has undergone more exploration work after the Tano basin. Much geophysical work hasn’t been published about the Saltpond basin. According to Aryeetey, 2014, some geophysical work carried out between 2004-2009 in the Saltpond basin covering an area of 15,355 km. the results from the data acquired indicated a two-reservoir system in the basin. these reservoirs are both located in the Takoradi sands. The fist reservoir in the upper Takoradi sand had oil-water contact (OWC) at 7,665 feet subsea and a gas-oil contact (GOC) at 7,530 feet subsea. The second reservoir in the lower Takoradi sands also had GOC and OWC at 8,300 and 8,480 feet subsea respectively as shown in Figures 5.21 - 5.23. Figure 5.21 is a seismic map data coverage of the Saltpond basin carried out shown in the red circle. Figures 5.22 and 5.23 show a seismic section of the Saltpond basin elaborating various formations and faults.

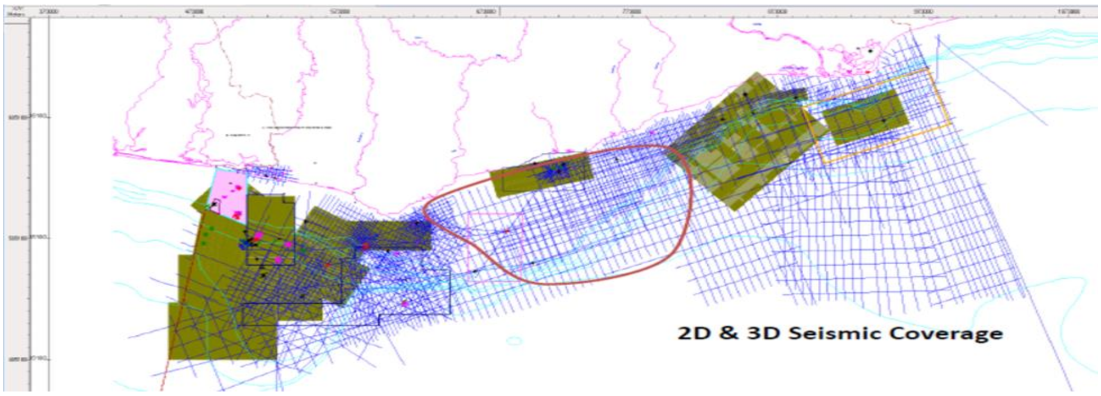

Figure 5.21. A 2D and 3D seismic survey data coverage of the Saltpond basin (Aryeetey, 2014).

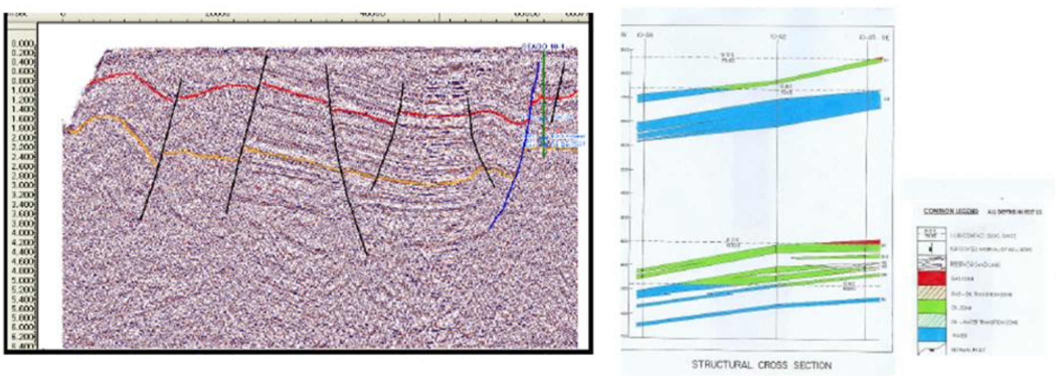

Figure 5.22. Seismic section of the Saltpond basin (Aryeetey, 2014).

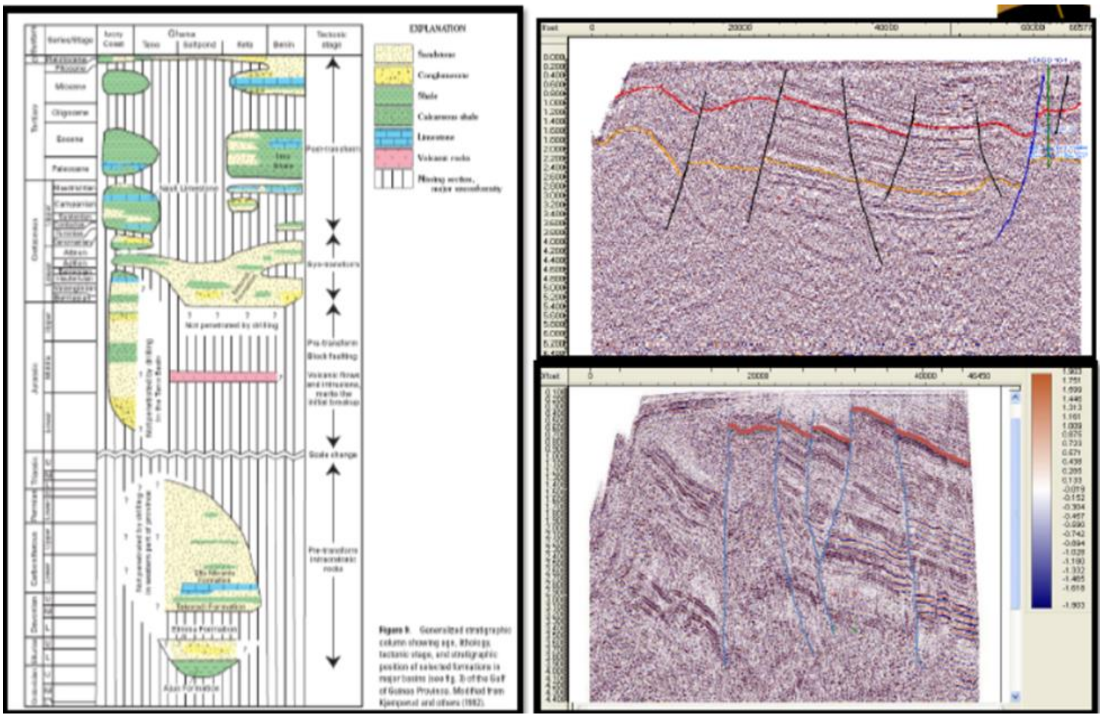

Figure 5.23. Seismic section showing the faults and structural styles in the Saltpond basin (Aryeetey, 2014).

The Keta and Voltaian basin have seen less exploration especially by geophysical work over the years. From literature, some geophysical data may be available, but for the petroleum and natural gas potential to be evaluated from geophysical results, there are not much published works to be considered. Recently a thesis work by Arku, 2012 who was able to attain some 2D seismic data from the GNPC about the Accra-Keta basin. The data were seismic and well logs and it was used to determine the hydrocarbon potential of the Accra-Keta basin. Figure 5.24 is a 2D seismic line survey sections carried out in the basin.

Figure 5.25 is a combination of the facies, SP and gamma ray logs of the well. The facies were created from the gamma ray logs to delineate the reservoirs zones corresponding it with the SP logs which were observed to have reflected to the zones of sand units (by using the API unit of 60 for areas within the Gulf of Guinea). To evaluate the formation in order to characterize the reservoir rock the gamma ray log and SP log were used to determine the total reservoir thickness of 744.33 m from a depth of 2385.77 m to 3130 m and a net of 541.73 m. It was observed that within the late Carboniferous to Triassic formation were preserved Paleozoic series overlain by marine carboniferous (sandstones shales, carboniferous shales and limestones) at thickness of 1000 to 1200 m.

Figure 5.26 is a gamma ray log, density and resistivity log used to determine the hydrocarbon saturation zones. This was done by creating an induction log to measure the resistivity of the formations and to delineate the hydrocarbon zones.

Figure 5.27 is a seismic section of the horizons and amplitude reflection events were the high where high amplitude and continuous reflections were found to correspond with the sand units, whereas low amplitude reflections were found to correspond to shale units.

Figure 5.28 is a seismic section of the horizons showing the various displacements and types of faults present. Areas where there were any breaks and displacements were noted to be fault zones as seen in the green, blue and yellow lines. There are three horizons present were the stratigraphic features are notices in horizon A of the early Cretaceous and horizons C in the Jurassic (light blue line). This also means that there is change in facies, because the reflectance from top through to the Neocomian has high amplitudes than from the Neocomian down to the late Jurassic. The structural features observed were normal faults cutting across from east and west. The central portion were observed to have dome shape structures indicating salt diapirism. Gas chimneys and channel system were as well observed indicating they migrated vertically from a deeper source (maybe Jurassic or Permian) into the Cretaceous in the seismic section shown in Figure 5.29. All these features present shows possible petroleum play types are present within the Accra-Keta basin.

The proven reserves estimated from the survey indicated about 148 million barrels of oil and 303.9 million cubic feet of gas. The probable reserves estimated was 334 million barrels of oil and 695 million cubic feet of gas and finally the possible reserves estimated were 495 million barrels of oil and 1.08 billion cubic feet of gas (Arku, 2012).

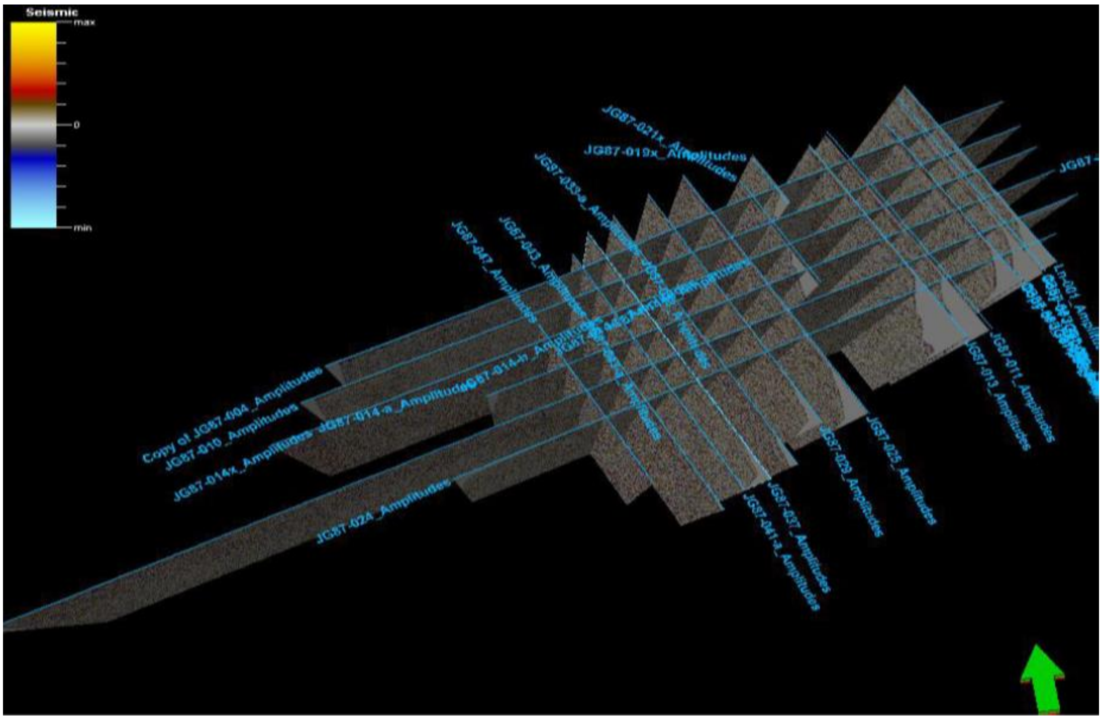

Figure 5.24. 2D seismic line of the surveyed area of the Accra-Keta basin (Arku, 2012).

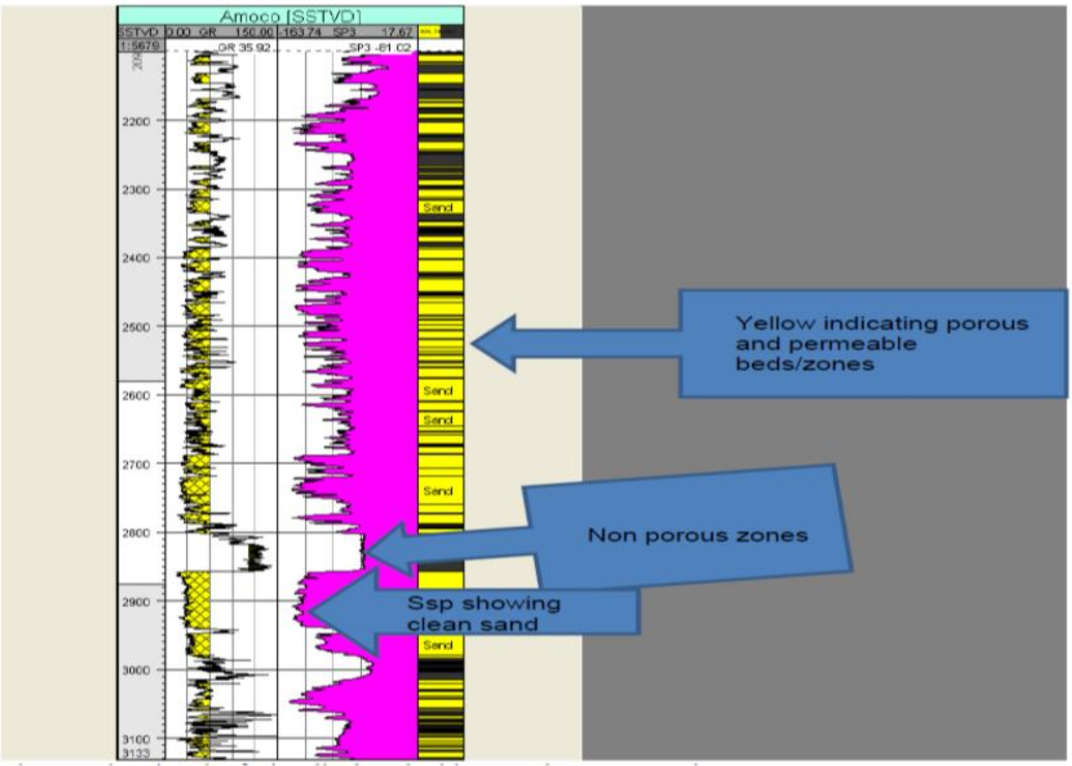

Figure 5.25. Well log of facies (Arku, 2012).

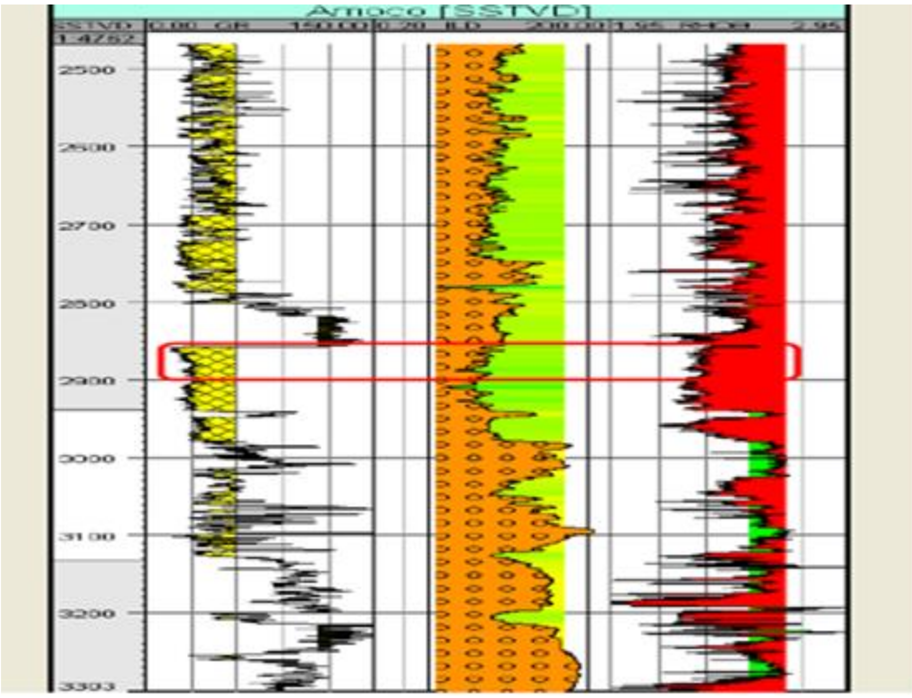

Figure 5.26. Gamma ray log, density and resistivity log used to determine the hydrocarbon saturation zones (Arku,2012).

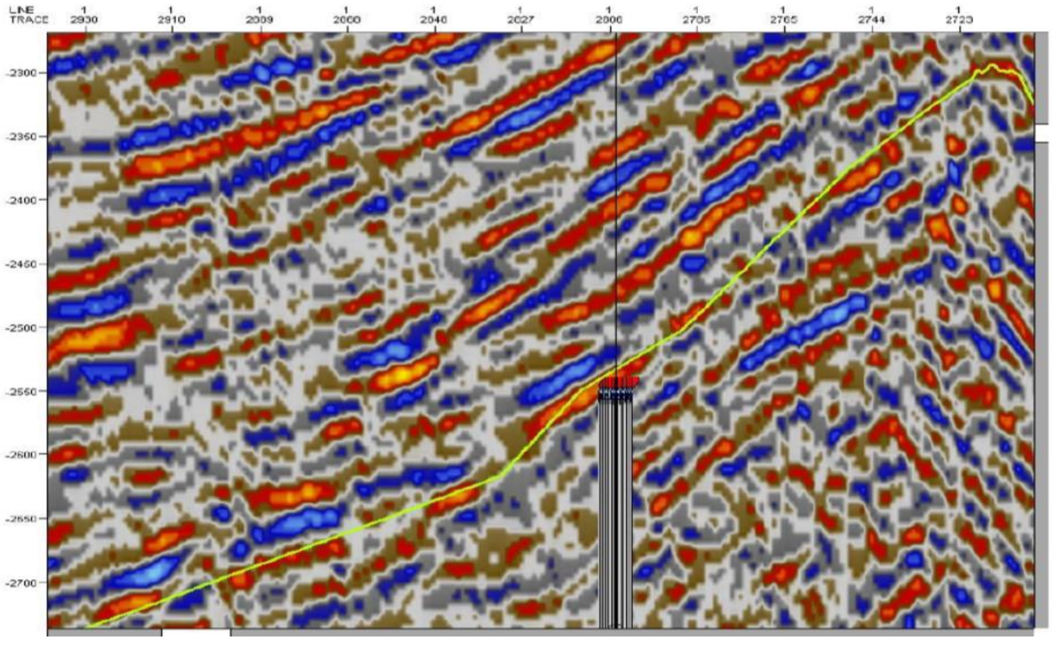

Figure 5.27. Seismic section of synthetic ties with horizon H1 picked (Arku, 2012).

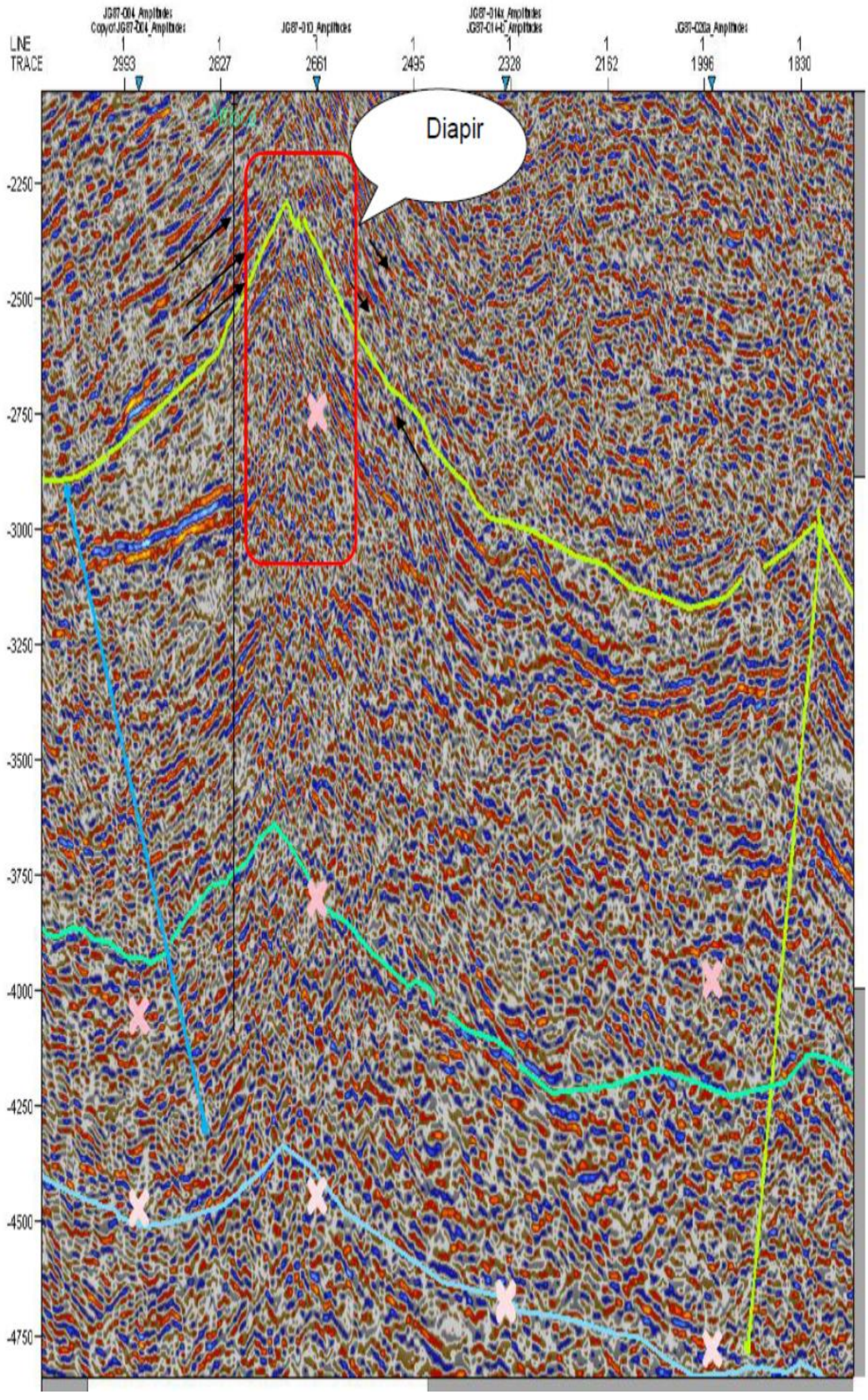

Figure 5.28. Seismic section of the horizons showing the various displacements and types of faults present (Arku, 2012).

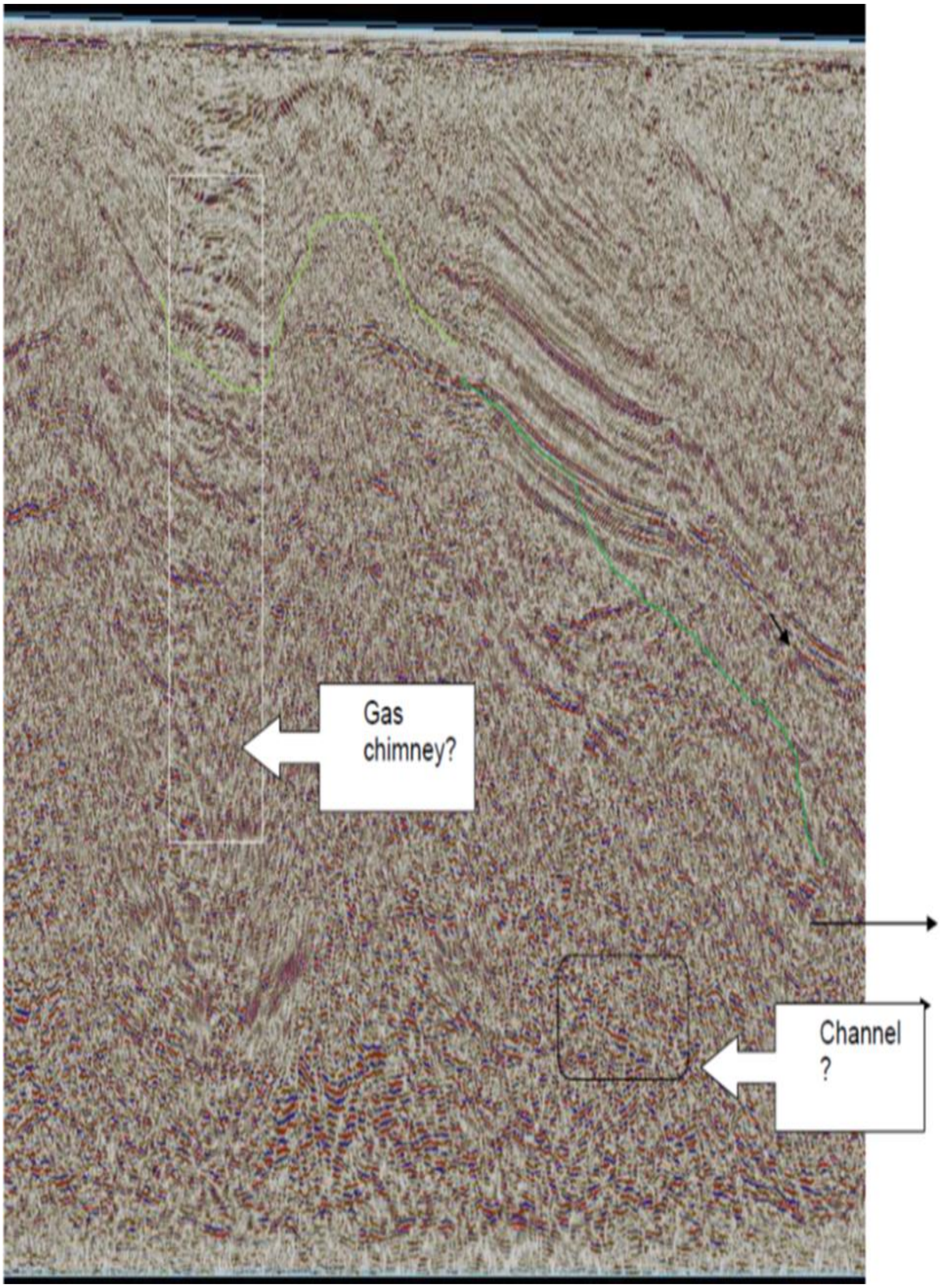

Figure 5.29. Gas chimneys and channel system of the horizons (Arku, 2012).

The Voltaian basin which is the only inland basin of Ghana has undergone less geophysical exploration work to be able to determine any possible petroleum and natural gas potential. This is due to the complexity of the geology of the basin and extensive geophysical and geological work is needed to be able to find any oil and gas.

5.5. Ghana's Oil and Natural Gas Potentials

Ghana has three offshore sedimentary basins namely Tano, Saltpond and Keta basins with the Tano basin as the most prolific of them all with significant oil and gas discoveries. The Saltpond and Keta basins have also some proven oil and gas potential and ongoing exploration works are been carried. The tectonism the Ghanaian shelf experienced is same as that of the Equatorial Atlantic (Gulf of Guinea) during the Cretaceous epoch. That of the Ghanaian shelf started between the Jurassic to Tertiary ages. The basins experienced the three stages of rifting (pre, syn and post transform) at a point in time. Figure 5.30 is the activity map of Ghana showing the various ongoing exploration activities in the various offshore basins.

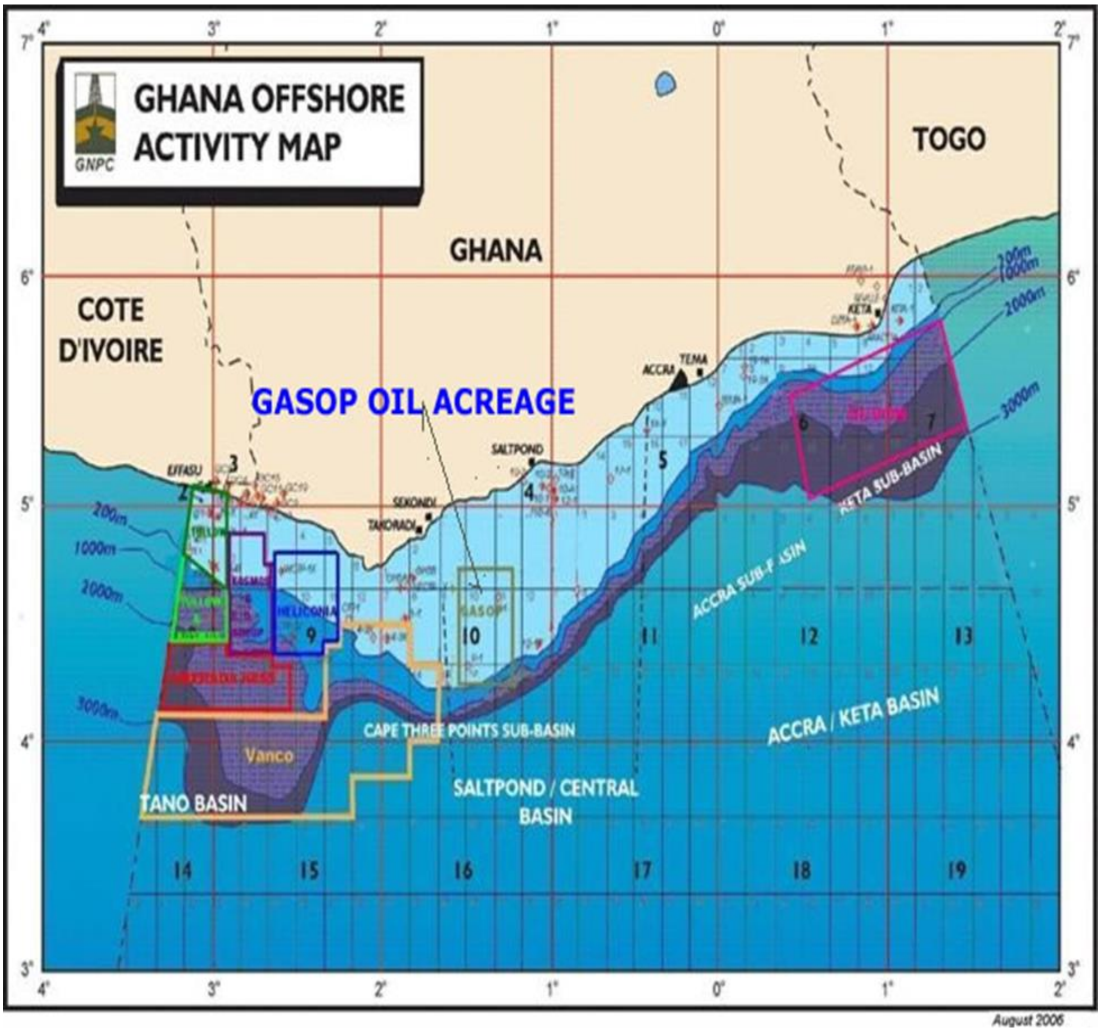

Figure 5.30. Ghana's offshore activity map (GASOP OIL, 2019).

5.5.1. Tano basin

The tectonism of the Tano basin happened between the Jurassic to Early Cretaceous, which is characterized by both block and transform faulting located along the Romanche Fracture Zone (RFZ). The RFZ served as a dam for transported sediments to be deposited and accumulated in the basin. The presence of both fluvial and lacustrine environment from several lakes and river systems along the Ghanaian shelf permitted large turbidite fan or channel complexes of thick clastic sequences to be deposited. The continuous continental rifting caused by the events of plate tectonics caused the deposited and accumulated sediments to be buried deeper into the crust due to subsidence with increasing temperatures and pressures. This phenomenon allows organic rich sedimentary source rocks to become matured enough to be able to expel oil and/ or gas. The source rocks are of Cenomanian, Turonian and Albian ages which serves as the major plays in the Tano basin. The reservoir sands were deposited by turbiditic currents during the upper Cretaceous times forming the Turonian turbidite sandstones (slope fan) and Albian sandstones (tilted faults). The sealing system was then created due to continuous deposition of mud over the reservoir sands leading to the Albian shale series, Cenomanian shale series and Turonian shale series serving as the seal plays in the Tano basin with the trapping mechanisms mainly both structural and stratigraphic as well as post- transitional anticlinal traps (fault-block). Figure 5.31 is an upside map of the potential of the new play fairways in the Tano basin. The reserves of some of the prospects discovered in the Tano basin have not yet been known due to possible commercial work done in them. Figure 5.32 is a west to east cross section of prospects in the Tano basin showing the number of wells drilled in them as well as known proven reservoirs in the various prospects. Figure 5.33 is a cross section and possible prospect of the Tweneboa giving two fairways (Campanian and Turonian) and geological information about the Tweneboa prospect. It has a giant Campanian fan-channel system (585 km2) with a gross upside potential of 750 mmbbls. Figure 5.34 is the Teak prospect showing the submarine channel systems (Turonian to Mid Campanian) and dip closures (four way) with a gross upside potential of 750 mmbbls. Figure 5.35 is the cross section of the Owo and Ntomme prospects. The Owo prospect has a stratigraphically trapped turbidite channel complex of

Turonian age at a water depth of 980 m- 1680 m with a gross upside of 200 mmbbls. It also has a sinuous deep marine channel equivalent in age to the Lower Jubilee fan complex. The Ntomme prospect has both stratigraphic and structural trap system (Turonian age), a frontal splay of a fan complex at water depth 1500 m – 17000 m with a gross upside of 120 mmbbls. The Onyina prospect has a large submarine fan or channel system with two distinct feeder systems at water depth of 600 m – 1050 m with a gross upside of 200 mmbbls as well as the geological information as shown in Figure 5.36. The Ebony prospect has two vertically stacked Upper Cretaceous fan (turbidite sandstones) with up-dip sands containing oil and gas shows at TP-1. It has a gross upside potential of 35 mmbbls. It has Cenomanian-Turonian source rock and a stratigraphic trapping mechanism at water depth of 87 m as shown in Figure 5.37 (Binks and Fairhead, 1992; Benkhelil et al., 1998; Brownfield and Charpentier 2006; Tullow oil, 2008; Arku, 2012; Bryant et al., 2012; CGG, 2013; Brownfield, 2016; Dailly et al., 2017).

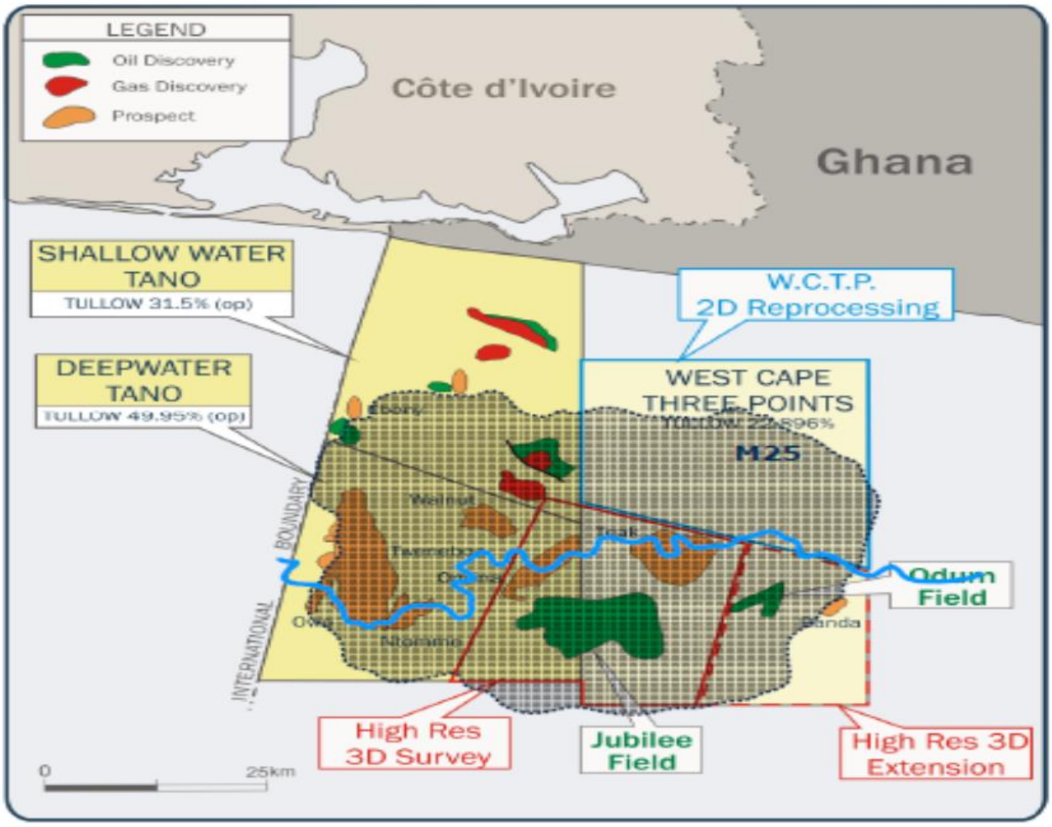

Figure 5.31. Map of the various potential prospects in the Tano basin (Tullow oil, 2008).

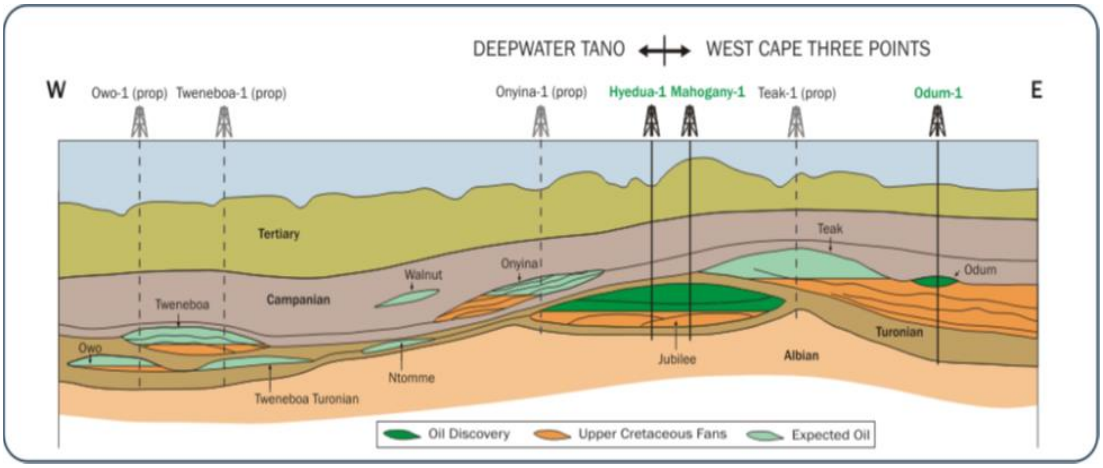

Figure 5.32. W-E cross section of prospects in the Tano basin (Tullow oil, 2008).

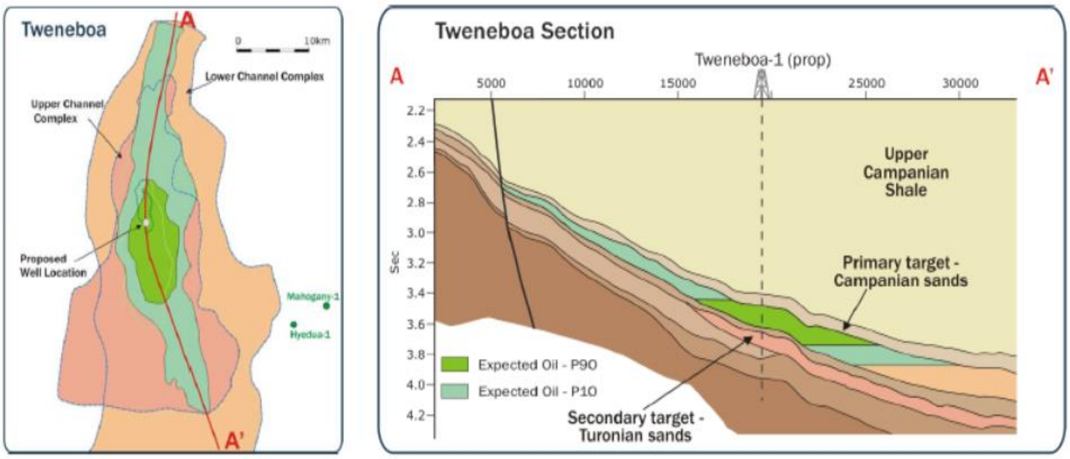

Figure 5.33. Tweneboa prospect of the Tano basin (Tullow oil, 2008).

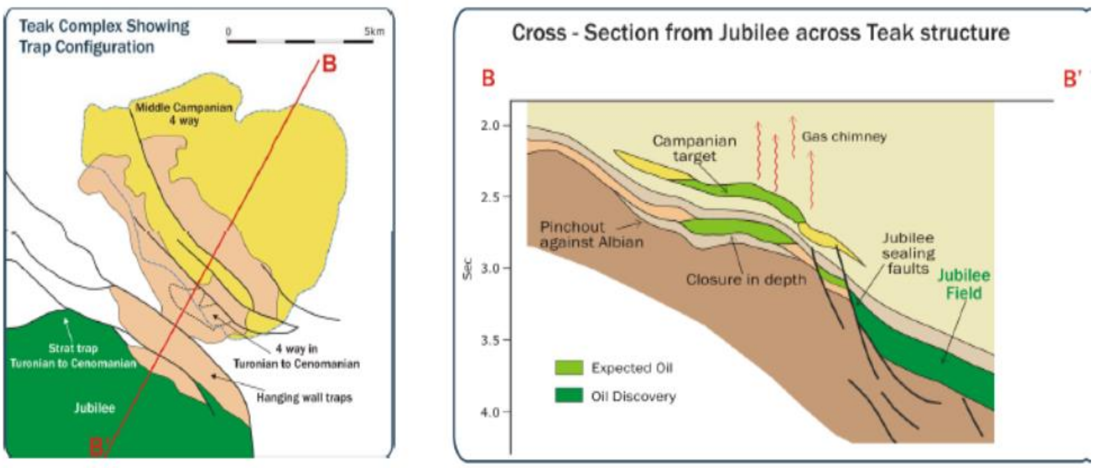

Figure 5.34. Teak prospect of the Tano basin (Tullow oil, 2008).

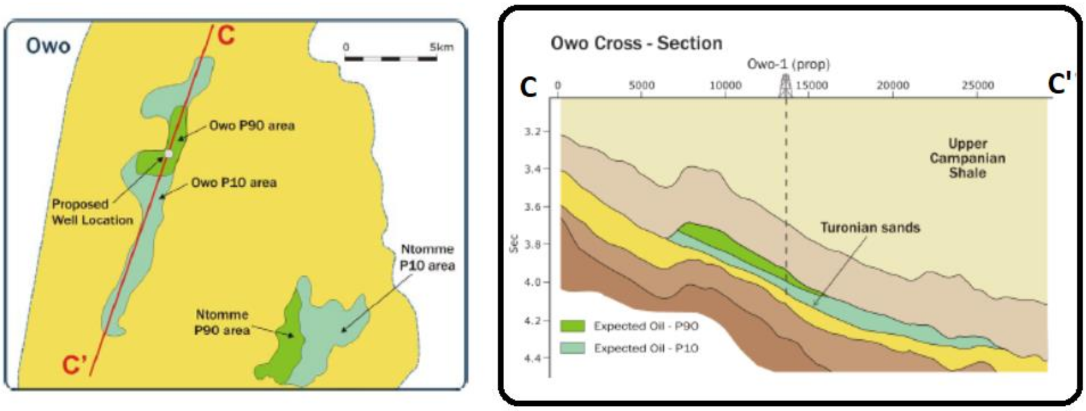

Figure 5.35. Ntomme and Owo prospects of the Tano basin (Tullow oil, 2008).

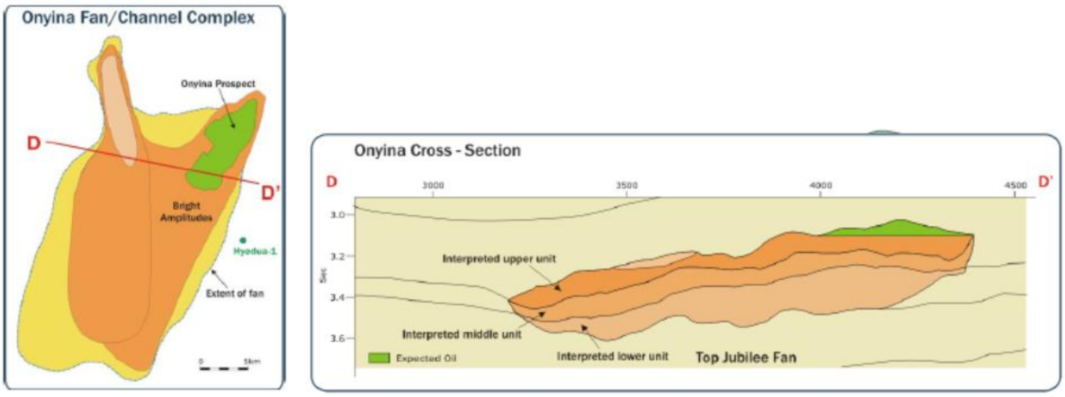

Figure 5.36. Onyina prospect of the Tano basin (Tullow oil, 2008).

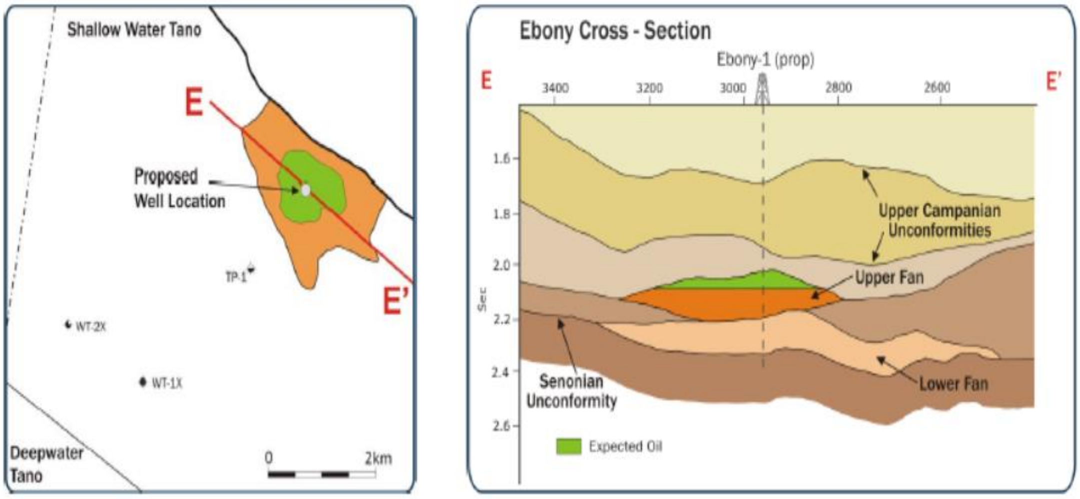

Figure 5.37. Ebony prospect of the Tano basin (Tullow oil, 2008).

All these major features present within the basin convinced oil companies of the possible presence of petroleum and natural gas within the basin. In 2007, the Mahogany-1 presently known as the Jubilee field was discovered by Kosmos Energy and Tullow Oil with an estimated reserve of about 1.2 billion barrels of recoverable oil reserves (Tap oil, 2010). This led to further exploration work for other possible potential in the basin leading to the discovery of the Tweneboa, Enyenra and Ntomme (TEN) fields at the western deep-water portion of the Jubilee field within the Turonian channel reservoir complex which was estimated to have recoverable oil reserves of about 240 million barrels and 360 billion cubic feet of both associated and non-associated natural gas reserves (Boas and Associates, 2018). The Teak, Odum and Akasa fields were then also discovered at the eastern portion of the Jubilee fan which are made of complex oil and natural gas condensates bearing reservoirs in the Campanian and Turonian formations (Kosmos Energy, 2013).

The Sankofa - Gye Nyame field is a gas field is located 60 km offshore deep water of about 600 to 1000 m. The field is estimated to have reserves of 500 MBOE within the Cenomanian reservoir sandstones and 270 MBOE of non-associated gas within the Campanian Turbiditic reservoir sandstones (Bempong et al., 2019).

Recently in 2019, a significant oil discovery of about 3 billion barrels of oil and gas were encountered in the Cenomanian sandstone and Turonian sands in the Tano basin offshore at water depths of 1030 meters drilling at 4085 meters deep (Afina-1 well) made by a local Ghanaian company Springfield Exploration and Production (SPE) Limited corporation with GNPC and GNPC EXPLORCO (World oil, 2019; Africa oil and Power, 2019). Presently, production is ongoing in the Tano basin and hopefully more discoveries will be made when further exploration work is carried in the deeper waters of the Tano basin region.

The discovery of the Jubilee field has aided oil companies to discover oil and gas in French Guyana - Suriname by using the plate tectonics principles and geology of the Tano Basin which has quite similar features as shown in Figure 5.38 and Figure 5.39.

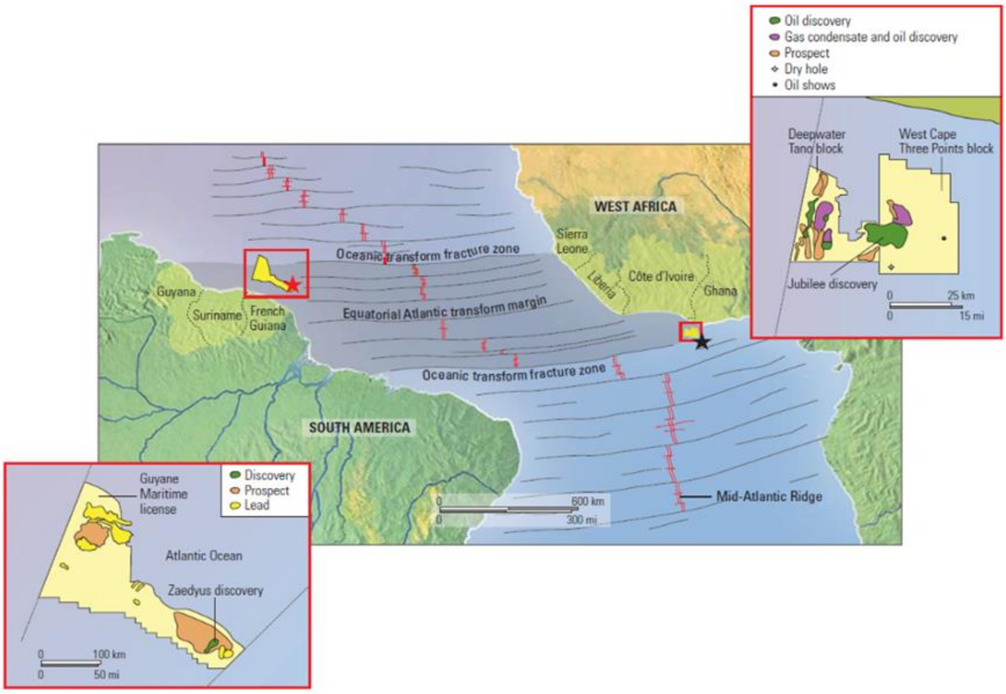

Figure 5.38. The Jubilee field of Ghana and French Guyana (adopted from Tullow oil cited in Bryant et al., 2012).

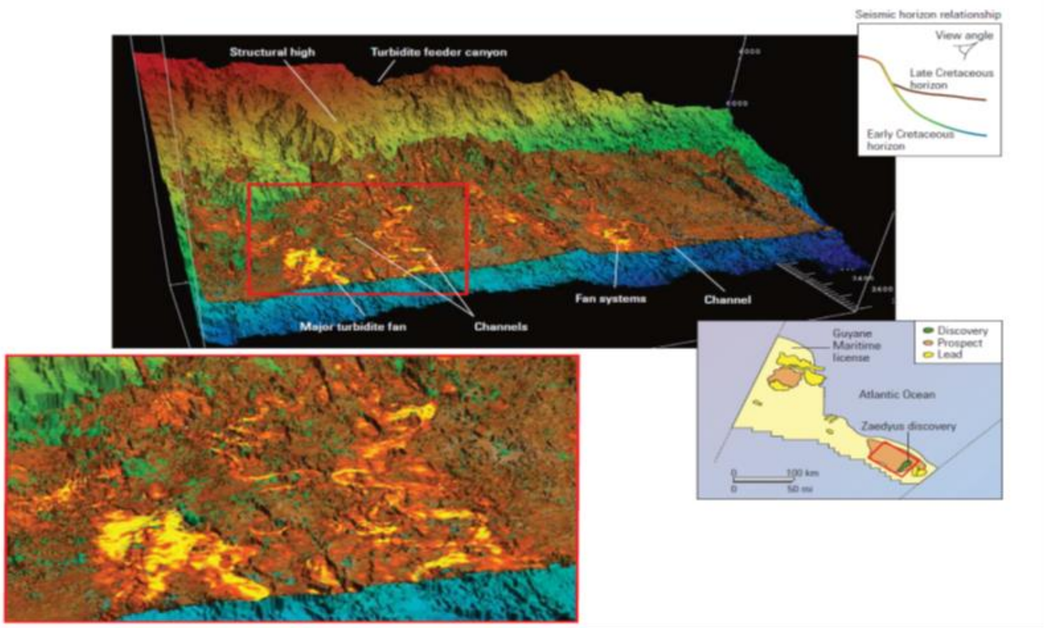

Figure 5.39. The use of the Jubilee field 3D seismic analogs for the search of oil and gas offshore French Guyana (Bryant et al., 2012).

5.5.2. Saltpond or central basin

The Saltpond / Central Basin which is also one of the wrenches pull-apart basins on the coastal shelf of Ghana is dominated by the Romanche Fracture Zone due to the opening of the Equatorial Atlantic during the Cretaceous age. The basin is characterized by both faults bounded grabens and horst (Atta-Peters et al., 2015). These features allowed the deposition of sediments during the Triassic and Jurassic ages into the basin (Aryeetey, 2014). The burial history of the basin indicates it is related to the Pre-rift stage which with rapid continuous subsidence during the Early Cretaceous allowing possible deposition, sedimentation and preservation. It also permitted the maturation of the source rock with increasing temperatures and pressures during the Middle Cretaceous allowing hydrocarbon generation (Atta-Peters et al., 2014). Palynofacies analysis done in the basin shows the depositional conditions that went on are distal mud-dominated oxic shelf conditions, distal dysoxic-anoxic shelf condition and distal dysoxic-anoxic shelf environment which indicates the presence of type III kerogens (gas generative potential) (Atta-Peters et al., 2015).

The Lower Paleozoic rock formation is the only known petroleum system in the Saltpond basin. The proven potential source rock in the Saltpond basin are the Devonian shales (Takoradi shales) with TOC values ranging between 3.5 - 4% and have good HI values (Aryeetey, 2014; Bansal et al., 2015). Rock oval data indicates the source rock of the basin have fair to good generative potential containing type II and III kerogens which can generate both oil and gas (Bansah et al., 2015). The main reservoir rocks of the Saltpond basin are the sandstones of the Takoradi sandstone formation which are of Devonian to Carboniferous age (Bansah et al., 2015). Both fault bounded blocks (structural features) and interfingering sandstones with shales (stratigraphic features) serve as the trapping mechanisms and the reservoirs of the basin are sealed or capped by the Takoradi shale formation. Generation and migration of hydrocarbons in the Saltpond basin may have occurred possibly during the Jurassic or Early Cretaceous ages in the Saltpond basin (Adda et al., 2015).

Possible petroleum and natural gas occurrences have been known to exist since 1970. According to Aryeetey, 2014, so far, a total of 26 wells since the beginning of exploration in the basin have been drilled, where there are six (6) development wells, three (3) appraisal wells and seventeen (17) exploratory wells/ the first well was drilled by Signal oil Company in 1970 at a depth of 2,967 m. They encountered oil in the Cretaceous with API of 31o (oil). It was estimated to have total reserves of about 7.5 million barrels with a production rate of 3600 barrels of oil per day. In 1971, Amoco Ghana exploration Company drilled two wells in the basin and estimated about 2.4 million barrels of recoverable oil with a possibility of 6.34 million barrels of recoverable oil within 422,01 ha. If further detailed test should be carried out within these wells. By 1979, the Saltpond basin was estimated to have reserves of 8.85 million barrels of oil (Kesse, 1986). Recent studies show in 2012, an average of about 8,855.98 bbl. of oil was produced and 2013 saw an average of 8,707.74 bbl. of oil produced from the Saltpond basin (Baos and Associates, 2014). In 2014, about 79,602 bbl. of crude oil was produced from the Saltpond basin (Baos and Associates, 2015).

5.5.3. Accra – Keta basin

The Accra- Keta basin which is located at the coastal eastern portion is one of the wrenches pull apart basins of Ghana. It is an extension of the western part of the Niger Delta through Benin. Togo and then to Ghana. The rocks in the basin are also Cretaceous of age which is bounded by the Chain Fracture Zone (CFZ) to the east and Romanche Fracture Zone (RFZ) to the west covering an area of 33,900 sq. km. with an onshore part of 1900 sq. km. (Brownfield, 2016; Petroleum Commission, 2019). Tectonically, the basin experienced the three stages of rifting of the opening of the Atlantic Ocean. The Pre-rift stages occurred during the Precambrian to Late Jurassic ages, syn-rift stages occurred in the Early Cretaceous and post¬-rift stage occurred during the Cretaceous to Tertiary ages within the basin (Brownfield, 2016). These rifting events led to the deposition of sediments and the deformation of the structures of the basin (Atta- Peters et al., 2016). The Volta River drainage system serves as the medium of transporting the sediments (clastic sequences) from inland into the grabens and horsts structures of the basin. These sediments were organic rich which formed shale formations during the Cenomanian to Turonian ages. Extensive erosion due to uplifting in the Late Cretaceous also created a peneplain in the basin (Brownfield and Charpentier, 2006; Wright et al., 2009; Atta- Peters et al., 2016).

The possible petroleum system in the Keta basin is within the Albian-Devonian series. The source rocks of the Keta basin are the Devonian shales, Lower Cretaceous shales and Late Cretaceous shales (Apesegah and Hotor, 2013; Abu et al., 2010 as cited in Atta - Peters et al., 2016) which can also be observed in the Tano and Ivory Coast basin (Brownfield, 2016). The Cretaceous shales are kerogen type II and III organic rich (Adda, 2013) while the Devonian shales are kerogen types III and IV organic rich from palynology, palynofacies and paleoenvironmental studies (Atta-Peters et al., 2016). Brownfield and Charpentier, 2006 concluded that in some parts of the basin of the offshore have the presence of Coniacian to Paleocene rocks which are observed to be rich in kerogen type II-III source rocks which can also be observed in the Benin basin. The reservoir rocks are Albian, Late Cretaceous and Tertiary age indicating they were created during the syn-rift stages of rifting deposited in fluvial-deltaic environments and the trapping mechanisms are both structural and stratigraphic (Brownfield and Charpentier, 2006; Adda, 2013). The Keta basin has similar hydrocarbon generative periods with that of the Benin Basin. The generation of hydrocarbons in the Keta basin began in the late Miocene to present which is same as that of the Benin basin (Brownfield and Charpentier, 2006). Exploration works so far haven’t yielded any success and with further exploration deep offshore the basin may produce some promising results for commercial oil and gas production.

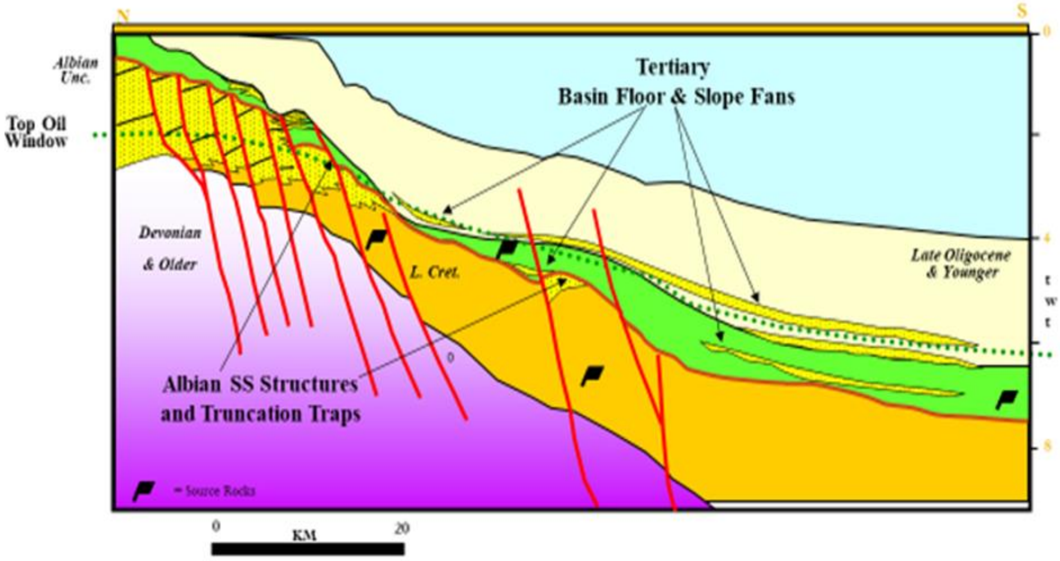

Figure 5.40. Cross section of the possible play systems in the Accra- Keta basin (Asiedu, 2012)

5.5.4. Voltaian basin

The Voltaian Basin is the only onshore sedimentary with no offshore portion. The basin was formed during the Pan-African – Dahomeyide Orogeny. Exploration for oil and gas potential within the Voltaian basin was first done in 1957- 1966 under the Ghana – Soviet Union friendship pact. Some traces of oil and gas were encountered in some boreholes drilled. Later between 1972 - 1979, a well was drilled in Premuase which up to date is the only known exploratory well (Petroleum Commission, 2019). So far, the possible known petroleum system in the Voltaian is the Oti Group made of sandstones, shales and siltstones from the work done by Soviet Geologist encountering a viscous black oily bitumen from the core samples obtained (Petroleum Commission, 2016) during a hydrogeological test of boreholes in Nasia and Prang (Kalsbeek, 2014). The chemical composition of the bitumen encountered had 82.51% of Carbon, 11.08% of hydrogen, 0.45% of Sulphur and 6% of nitrogen and oxygen. Infra-red spectrum analysis suggested the bitumen were aromatic hydrocarbons, hydrocarbon groups CH2, CH and paraffin structures (Kalsbeek, 2014). The sandstones within the lower Voltaian (Morago Series) has been observed can serve as a good reservoir rock. Complex internal structures observed from drilling and geophysical data indicates the presence of good trapping mechanisms both structurally and stratigraphically

(Kalsbeek, 2014). The Voltaian basin is observed to have Precambrian aged rocks which is a good indication that possible oil and gas occurrences may be in place when detailed exploration work is carried out since oil and gas is known to occur in Precambrian rocks globally like in Siberia (Yamoah, 2015).

Table 5.1. Summary of all the four sedimentary basins in Ghana

BASIN	SOURCE ROCK	RESERVOIR ROCK	SEAL ROCK	TRAP
TANO	Upper Albian, Cenomanian, and Turonian Shales mainly with kerogen type II and III and I and IV at some parts.	Albian series, Maastrichtian sandstones, Cenomanian Series, Turonian Series, and Campanian sandstones.	Marine shales of Turonian Shale series, Albian Shale series and Cenomanian Shale series.	Structural and stratigraphic trap mechanisms.
SALTPOND	Middle to Upper Devonian aged Shale rocks (dark grey shales with type II kerogen of the Lower and Upper Takoradi Shales).	Devonian to Carboniferous sandstones (Takoradi Sandstone Formation).	Takoradi Shale Formation	Structural and stratigraphic trapping mechanisms.
KETA	Early Cretaceous lacustrine shales (type II and III kerogens) and Turonian-Cenomanian organic shales	Late Cretaceous, syn-rift Albian, and Tertiary aged rocks.	Cretaceous-Tertiary shales.	Both structural and stratigraphic (more dormant in the basin) traps.
VOLTAIAN	Oti group shales (possible)	Lower Voltaian sandstones and limestones	Middle Voltaian shales	Stratigraphic features and faults

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

Systematic qualitative review method was used to extract relevant secondary data which include, tectonic, geological, geophysical and other data to investigate the petroleum and natural gas potential of Ghana and the role of plate tectonics and the opening of South Atlantic Ocean in petroleum accumulation.

The breakup of the Pangea leading to the opening of the Atlantic Ocean as well as the Gulf of Guinea has aided in the accumulation of petroleum and natural gas along the shores of West Africa where Ghana is located. The driving forces of crustal movement such as divergent, convergent and transform movements is the convection in the mantle. These plate tectonic events lead to the depositions of sediments and thereby creating sedimentary basins. These events also paved way for continental sediments eroded by the agents of erosion such as rainwater and wind to be deposited into onshore and offshore basins. Within these basins there are formations of fluvial and marine unoxic environments where dead microorganisms are buried over long periods of time and with continuous burial into the crust with increasing temperatures and pressures allows petroleum to be generated from organic rich source rocks and accumulated into reservoirs with proper trapping and sealing systems.

Ghana has four sedimentary basins, one inland (Voltaian) and three offshore (Tano, Saltpond and Keta) basins. The three offshore basins experienced the rifting stages of tectonism which from this study shows how plate tectonics has played a major role in the petroleum and natural gas accumulations in the offshore sedimentary basins of Ghana. The study shows that the Tano has proven to be the most prolific of all the basins with extensive exploration done in it which has led to significant petroleum and natural gas discoveries using the principles of plate tectonics alongside advanced exploration methods and technology. The Tano basin has proven to have about 1.2 billion barrels of oil from the Jubilee field with a recent discovery of 3 billion barrels of oil gas in the Afina-1 well. There are other major discoveries made in the Tano with recoverable reserves as well with ongoing exploration to further make more discoveries.

The Saltpond basin is the second prolific sedimentary basin after Tano which has proven to have some petroleum and natural gas potential and more extensive work like that of the Tano basin is likely to begin in it. The Keta basin has seen less exploration work; therefore, the petroleum and natural gas is yet to be found when extensive exploration work is carried. The Voltaian basin has not shown any possible petroleum and natural gas potential due to its geological complexity, although in some parts of the basin, bitumen traces have been encountered. It can be either the source rocks in the Voltaian are over matured or cooked that they can't expel petroleum and natural gas.

Geophysical explorations are used in the oil and gas industry as a tool for locating tectonic and geological structure which might host oil and gas. In technical terms, geophysical methods are used to delineate reservoir zones, fault zones and to determine the hydrocarbon potential. The most widely used geophysical exploration methods are seismic reflection method and well logs. In this work results from geophysical exploration works obtained from secondary sources were used to discuss the geological structures within the basins. There were very few geophysical data available to the author of this thesis work. The secondary geophysical data were mostly obtained from few published articles and some unpublished thesis work.

The major contribution of the study is to use the principles of plate tectonics to understand the accumulation of petroleum and natural gas in sedimentary basins which was applied to that of the sedimentary basin of Ghana which led to significant discoveries some of the basins which has contributed greatly to the economy of Ghana. Continuous extensive exploration is still ongoing in both the Tano and the other three basins for possible recoverable petroleum and natural discoveries.

From literature survey, this work is the first comprehensive document containing information about all the major basins in Ghana, their geology, tectonics, and their oil and gas potentials. The available works before this thesis contain only some information on individual basins and some aspect of their oil and gas potentials.

6.2. Recommendation

It is recommended that;

The underexplored sedimentary basins in Ghana should be explored more extensively with more updated geological and geophysical work, drilling more wells, as well as using much more advanced technology for more complex geological formations.

Oil and gas companies should be able to provide some available data to researchers interested in researching about the sedimentary basins.

The Government of Ghana should be more transparent about the oil and natural gas potential of Ghana to the Ghanaian public especially to geoscientist, academicians and students.

More papers, books, reports, maps etc., should be published about the petroleum and natural gas potential of the sedimentary basins of Ghana.

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RESUME

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