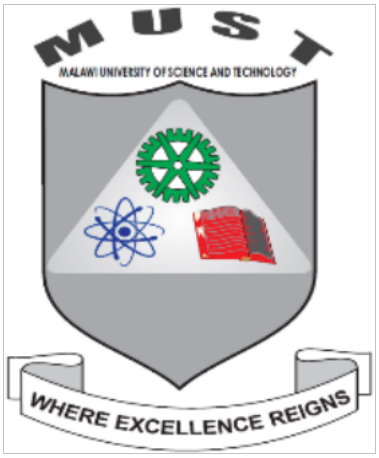


THE GEOCHEMICAL ASSESSMENT OF POTENTIAL PETROLEUM ACCUMULATION IN LIVINGSTONE BASIN(KARONGA) MALAWI

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DISSERTATION SUBMITTED TO NDATA SCHOOL OF CLIMATE AND EARTH SCIENCES OF THE MALAWI UNIVERSITY OF SCIENCE AND TECHNOLOGY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE BACHELOR OF SCIENCE DEGREE IN PETROLEUM GEOSCIENCE (GAS AND OIL)

November, 2023

DECLARATION

I Veronica Kampazaza declare that this research project presents my work and that it has never been submitted to this institution or any institution for any academic purpose. All sources of information have been appropriately acknowledged.

Signature :



Date : November ,2023

DISSERTATION APPROVED BY:

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ABSTRACT

The geochemical assessment of potential petroleum source rock is very crucial step in petroleum exploration, since it helps to determine the potential petroleum accumulation in different areas.it facilitate key decision on whether further stages of exploration can be carried out. This paper has described the assessment of the potential petroleum accumulation in Livingstone basin in karonga Malawi. The Livingstone basin is a lift basin located in Malawi, Africa. It is part of the east African rift system, which is a zone of active tectonic extension. The basin is approximately 300km long and 100km wide and it is filled with a thick sequence of sedimentary rocks that are up to 10km thick. The Livingstone basin was formed during the Miocene epoch, approximately 10million years, The formation of the basin was initiated by the rifting of the African continent which was by the movement of Nubian plate away from the Somali plate.

The study methodology includes TOC and Rock eval Pyrosis analysis and it involves the geochemical parameter (TOC, HI, OI, S1, S2 etc.) These parameters helped to classify organic matter richness, kerogen type and their thermal maturity level of hydrocarbons present in collected samples. It was discovered that the Livingstone Basin has TOC values ranging from 2.29 to 3.80 weight percent, and HI values of 120-270 mg HC/g TOC. These results indicate a very good source rock potential, with type II kerogen and early mature to mature organic matter.

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ACRONYMS/ABBREVIATION

TOC Total Organic Carbon

Wt% Percentage by weight

S1 Volatile hydrocarbon content in mg per g of samples

S2 Remaining hydrocarbon content in mg per g of sample

S1+s2 Hydrocarbon Potential

OI Oxygen Index

HI Hydrogen Index

PI Production Index

Tmax Temperature Maximum

1. CHAPTER ONE

1. Introduction

The exploration and assessment of petroleum resources are of paramount importance for energy security and economic development in many regions around the world. This research project seeks to investigate the petroleum source rock potential in the Livingstone basin found in Northen part of lake Malawi. By conducting a comprehensive analysis of its thermal maturity, type of kerogen, and organic content of source rock

1.1 Background

1.1.1 Geology of petroleum in Malawi

Geology is the underlying control on accumulations of oil and gas, it was established that petroleum sedimentary rock which could contain petroleum accumulations in Malawi are present in only two areas the lake Malawi where lacustrine sediments are presently being deposited and lower shire valley in the southern part of Malawi Crow (1982). Seismic reflection survey indicates that large structural features capable of trapping and migrating petroleum are present but there is no evidence to suggest that petroleum has been thermally generated at depth.(Mattick, 1984) At the present time, sediments with a high organic carbon content are being deposited in those areas occupied by deep-water lakes with highly anoxic bottom conditions such as Lake Malawi and Lake Tanganyika (Madukwe, 2014)

In 1980, Dumestre (1980) reviewed the petroleum geology of Malawi and concluded that the existence of petroleum accumulations beneath Lake Malawi and the Lower Shire Valley would depend on the presence of thermally mature source rock. Malunga also studied the oil and gas potential in Malawi, He studied that the potential for oil and gas discovery in Malawi is very high especially in Blocks 2 (Karonga), 3(NkhataBay – Nkhota Kota) and (Chikwawa – Nsanje). Blocks 1 (Chitipa) and 5 (Phalombe) have relatively shallow sediments. (Wyson & Malunga, n.d.).

1.1.2 The geology of the Livingstone basin

The Livingstone basin is a lift basin located in Malawi, Africa. It is part of the east African rift system, which is a zone of active tectonic extension. The basin approximately 300km long and 100km wide and it is filled with a thick sequence of sedimentary rocks that are up to 10km thick. (Accardo et al., 2018a)The Livingstone basin was formed during the Miocene epoch, approximately 10million years, The formation of the basin was initiated by the rifting of the African continent which was by the movement of Nubian plate away from the Somali plate. The lifting process extension caused the crust to thin, which led to the formation of a series of faults which down dropped the Livingstone basin.(Macgregor, 2015a) The basin is filled with a thick sequence of sedimentary rock that were deposited during the rift stage and the post rift stage, during the lift stage, the basin was filled with lacustrine sediments such as shales and limestones. During the post the post rift stage, the basin was filled with fluvial and alluvial sediments such as sandstone and conglomerates.(Accardo et al., 2018a) The deposition environment of the Livingstone basin varied over time, During the rift stage, the basin was a lake, this lake was fed by rivers that flowed from the surrounding highlands and also ground water. The lacustrine sediments that were deposited during this time are now the source rocks for petroleum in the basin. (Macgregor, 2015a)During the post-rift stage, the basin was filled by rivers and streams, the fluvial and alluvial sediments that were deposited during this time are now the reservoir rocks for petroleum in the basin.(Macgregor, 2015a)

The Livingstone basin has a number of characteristics that make it a potential target for petroleum exploration. These characteristics includes the source rocks, the lacustrine shales and carbonaceous shales in the Livingstone basin are rich in organic matter, which is the precursor to oil and gas. (Scholz et al., 2020a) reservoir rocks is another characteristic, the sandstones and limestones in the Livingstone basin are porous and permeable, which makes them ideal for storing oil and gas. The Livingstone basin also has Cap rocks, The mudstones and shales in the Livingstone basin are impermeable to oil and gas, which prevents them from escaping from the reservoir rocks.(Scholz et al., 2020a)

1.2 Problem statement

Primary energy demand is increasing rapidly, and is expected to grow by 41% from 2012 to 2035, this is due to industrialization and population growth. (BP, 2014) The increase in demand is driving up oil prices, which is disadvantageous for importing countries like Malawi, as it destabilizes their economy and reduces their economic power. To boost the Malawian economy, it is important to reduce its dependence on imported natural resources. This can be done by using locally available resources, such as crude oil. Searching for oil reservoirs in Malawi is a good place to start, as this could attract investors to conduct seismic surveys and facilitate exploration. This would help to meet global oil demand in the future and boost the Malawian economy.

Many oil explorations have been conducted in Malawi, including the Livingstone Basin, where a geophysical survey was conducted. The results of this survey were impressive, but there is lack of geochemical survey has been conducted to identify and deduce information on the geochemical properties of the rocks, which could provide insights into the storage and expulsion of organic matter and their maturity. Characterizing the rock sediments in terms of their carbon content, quantity, quality, and maturation stage provides basic information about the petroleum source rock potential. Therefore, this study will investigate whether the Livingstone Basin has potential source rocks, the type of kerogen present, and whether it is gas or oil prone.

1.3 Significance of study

The assessment of petroleum accumulation in Malawi holds significant importance for various stakeholders, as it addresses critical gaps in knowledge and has numerous potential implications. The study's significance can be outlined as follows; firstly, economic Development, Malawi is a country with limited natural resources, and by conducting this research of assessing the petroleum accumulation, it can be provided with valuable insights into the economic viability of petroleum exploration and

exploitation projects. The findings can guide investment decisions, promote job creation, and foster economic growth in Malawi.

Another significant is energy Security, Petroleum is a vital energy resource globally, and Malawi heavily relies on imported fuels to meet its energy needs. Assessing the petroleum accumulation within the country can contribute to enhancing its energy security by reducing dependence on external sources.

Scientific Knowledge of this research aims to fill the existing research gap regarding petroleum accumulation in Malawi. By conducting detailed assessments and analyses, it can generate new scientific knowledge and insights into the geology, hydrocarbon potential, and distribution patterns within the country.

1.1 Main objective

To evaluate the presence of source rock within Livingstone basin

1.5 Specific objective

i. To determine kerogen type of each rock sample of Livingstone basin
ii. To quantify the organic content in rock samples of Livingstone basin
iii. To assess the thermal maturity of organic matter of Livingstone basin using rock samples

1.6 Research question

i. What is the kerogen type of each rock sample
ii. What is the quantity of organic content in the rock samples?
iii. What is the thermal maturity level of the organic matter?

2 CHAPTER 2

2.1 Literature Review

The exploration and assessment of potential petroleum accumulation have been subjects of significant scientific inquiry due to the global importance of hydrocarbon resources. This literature review aims to provide an overview of key findings and trends in the field of petroleum accumulation assessment

2.1.1 The source rock evaluations

The term source rock refers to an organic-rich fine-grained sedimentary rock which can produce hydrocarbons due to thermal maturation.(Barker, n.d.-a 2014) Source rock is one of the main elements of a hydrocarbon system, Therefore, to identify a region of hydrocarbon generation, it is necessary to investigate the source rock and its characteristics first.(Al Arouri, 1996) . Thermal maturity is the primary factor that determines whether a source rock can produce oil, gas, or condensate. In order to evaluate the source rocks various laboratory methods and/or burial history are used. Among these techniques, Rock–Eval pyrolysis has been widely used in the industry as a standard method in petroleum exploration. From laboratory methods, the Rock–Eval pyrolysis method has been extensively used, worldwide, for oil and gas exploration in sedimentary basins. This method is used in determining the thermal maturation of kerogen. In 2014, Mohamed M. El Nady and Mahmoud M. Hammad conducted a study where they assessed the organic material for petroleum potential in the Abu Tartur area of Egypt by analyzing 14 samples from the shales of the Dakhla and Duwi formations using Rock-Eval pyrolysis. The results showed that the organic matter has a total organic carbon content of 0.56 to 1.96 wt% and is predominantly composed of type II kerogen, which is prone to oil and oil/gas production. The kerogen was deposited in a shallow and restricted marine environment under reducing conditions. All of the studied samples showed that it’s a good thermal maturation, indicating that the organic matter has reached a favorable thermal window for hydrocarbon generation.

The thermal maturation is found using the Tmax value, the Tmax value for the

beginning of the oil window is usually 445–435 ˚C, for the peak is 450–445 ˚C, and for the end is 470–450 ˚C. Although organic matter undergoes many types of evolution and thermal maturation, it is important in assessing hydrocarbon generation. (Madukwe, 2014)The maturity of organic matter is, however, one of the most important parameters in the evaluation of oil–gas.(Higley, n.d.) The purpose of this study is to establish reliable indices for an integrated assessment of organic material for petroleum potential evaluation, in addition, to characterize the relationship between the organic matter, thermal maturity, and the type of kerogen. This is done in the shales of Livingstone basin using advanced Rock–Eval pyrolysis techniques. Source rock evaluation therefore is a multifaceted process that involves the analysis of sedimentary rocks for their organic content, maturity, hydrocarbon generation potential, retention capacity, and migration pathways.(Mahdi & Abu-Ali, 2013) To understand the rock evaluation hydrocarbon generation potential may be considered.

2.1.2 Hydrocarbon generation potential

Petroleum generation is the natural process by which organic materials buried deep within the Earth's crust are transformed into crude oil and natural gas over millions of years.(Mahdi & Abu-Ali, 2013) Based on the organic content and maturity analysis, it is possible to estimate the potential quantity and type of hydrocarbons (oil or gas) that the source rock might have generated over geological time periods.(Hakimi et al., 2020) This is done using kinetic models and mathematical equations that describe the transformation of organic matter into hydrocarbons under different temperature and pressure conditions.(Hakimi et al., 2020) Petroleum generation begins with the accumulation of organic materials, primarily the remains of marine plankton and algae, in sedimentary basins. These organic materials are typically rich in carbon and hydrogen, which are essential components of hydrocarbons found in petroleum.(Hakimi et al., 2020) Over time, sediments like mud, silt, and sand accumulate on top of the organic-rich layers. The weight of these sediments compresses the underlying organic material, increasing pressure and temperature within the Earth's crust.(Lawson et al., 2018) The temperature interval where oil generation is in progress is referred to as the ‘liquid window’ or ‘oil window’, where the temperature extends over the interval of about

90-160°C, at this range the organic material in the source rock is heated to the point where it starts to release hydrocarbons in form of oil, primarily crude oil.(Madukwe, 2014) The temperature requirement for oil window depends on the age of the rock. A Mesozoic rock requires less temperature than a Cenozoic rock. As the most oil source rock is formed during the Mesozoic.(Mahdi & Abu-Ali, 2013) Again, temperature requirement for oil and gas generation depends on the type of kerogen. Type II variety of kerogen, containing Sulphur (i.e., type IIS) requires lower temperature range compared to type I kerogen. Oil generation in the appropriately mature source rock initiates at a temperature of about 60°C for a Mesozoic source rock and continues until at a temperature of 150°C. This range of temperature is called as 'oil window'. In areas of higher geothermal gradient, the oil window exists at a shallower depth and the depth range is less. For a Cenozoic source rock, the oil window temperature is slightly higher (90 to 200°C) than its Mesozoic counterpart(Higley, n.d.)

Beyond the oil window lies the gas window, this is the temperature range at which the organic matter has been heated to the point where it primarily generates natural gas, which consists mainly of methane (CH4)(Barker, n.d.-a). The gas window temperature range is typically between 160°C and 225°C, although these values can vary depending on the specific composition of the organic matter and geological conditions.(Barker, n.d.-a) In the gas window, the organic material breaks down further, and the long-chain hydrocarbons found in oil are cracked into shorter-chain hydrocarbons, with methane being the dominant product. (Lawson et al., 2018)The natural gas generated in this window can migrate through porous rock formations and accumulate in reservoirs if suitable conditions exist, forming potentially economically valuable deposits.(Fildani et al., 2005).

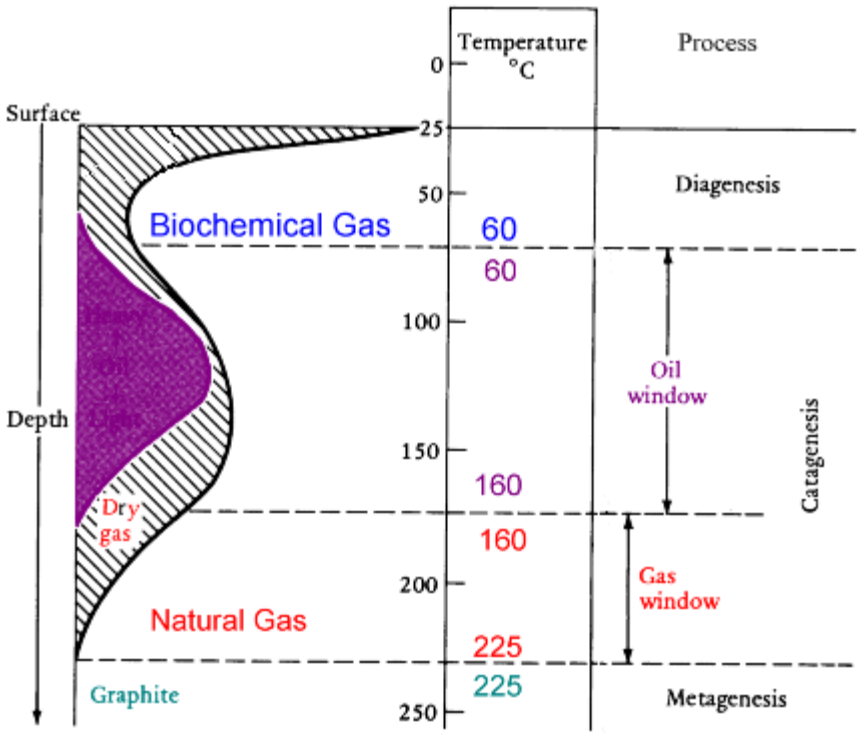


FIGURE 2 OIL AND GAS WINDOW(MILLAYANTI ET AL., 2019)

2.1.3 Assessment of Organic Content

Organic content refers to the presence of organic matter within sedimentary rocks that has the potential to generate and store hydrocarbons, such as oil and natural gas.(Mahdi & Abu-Ali, n.d.-b) This organic matter is primarily composed of the remains of ancient plants and microorganisms that accumulated and were buried over millions of years.(Dwivedi, n.d.) The organic content is a critical factor in determining whether a particular rock formation has the potential to become a petroleum reservoir. The key factor in source rock evaluation is determining the organic content of the selected rocks. (Madukwe, 2014)This is done by analyzing the rock samples for total organic carbon (TOC) content. Evaluation of TOC gives a measure of the abundance of organic matter and it is an important indicator to evaluate the hydrocarbon generation potential of source rocks (Peters and Cassa, 1994). TOC values (wt. %) are categorized as excellent (>4), very good (2–4), good (1–2), fair (0.5–1) and poor (<0.5) hydrocarbon generation capacity (Peters and Cassa, 1994). The TOC threshold for a good source rock is 0.5 wt.% for shale, 0.3 wt.% for carbonate, and 1 wt.% for clastic rock (Killops

and Killops, 1993). The higher the TOC content, the greater the potential for hydrocarbon generation. Rocks with a high organic content, often referred to as "source rocks," are the primary contributors to the formation of hydrocarbons.(Li et al., 2022) These rocks typically contain a signific]ant amount of organic material and are buried deep enough for heat and pressure to convert the kerogen into oil and gas.(Madukwe, 2014) Understanding the organic content in petroleum potential rock samples is crucial in the exploration and production of hydrocarbons, It helps geologists and petroleum engineers assess the viability of a particular geological formation as a potential source of oil and gas and guides decision-making in the oil and gas industry.(Zhi et al., 2023)

2.1.4 Maturation Analysis

The organic material undergoes a process of thermal maturation over geological time, where it is exposed to increasing temperatures and pressures as it gets buried deeper in the Earth's crust.(Kraml et al., 2012a) This process transforms the solid organic matter (kerogen) into liquid hydrocarbons (oil) and gaseous hydrocarbons (natural gas).(El Nady & Hammad, 2015a) Thermal maturity is a key parameter for the determination of potentially immature prospective shale oil and gas accumulations at initial stages of exploration. Based on thermal maturity values, source rocks are categorized as thermally immature, mature and post-mature rocks in terms of capability to generate hydrocarbons.(Hickey, n.d.)

Immature source rocks are those that are still at relatively small at depths, and may generate (biogenic) natural gas which is formed by certain bacteria species as a result of their metabolic activity.(Mahdi & Abu-Ali,2013) .Normally, these processes occur at temperatures below 50˚C, and the degree of organic matter alteration, as expressed by reflectance index, is not in excess of 0.5% Ro.(Fleur Matateyou, 2022) As the source rock is buried, for example under an increasingly thicker overburden, the processes of bacterial organic matter alteration subside, while temperatures and pressures of the rock increase and gradually trigger chemical changes that lead to the generation of oil and smaller quantities of natural gas. (Higley, n.d.)A rock which had been heated so as to generate crude oil is called mature rock in the oil generation phase or in the so-called

“oil window”, and its alteration degree, expressed as vitrinite reflectance index, ranges from 0.5 to 1.2% Ro.(Barker, n.d.-b)

If buried deeper, the source rock will generate mostly (thermogenic) natural gas. Accordingly, a mix of the previously generated oil and of the “newly generated” natural gas (the so-called condensate) is expected to occur in the rock. If the rock medium is even deeper buried, organic matter will generate (thermogenic) natural gas only.(Gilbert et al., 2021) . Moreover, any oil previously accumulated in the rock will be transformed into (thermogenic) natural gas. This degree of thermal alteration called the “gas window” occurs at temperatures in the order of 120 – 150˚C and is expressed by reflectance index values ranging from approx. 1.2 to 2.0% Ro.(Fleur Matateyou, 2022) The process will continue until alteration processes reach the degree at which the source rock becomes overmature and its hydrocarbon generative potential is exhausted (>3.0% Ro). This occurs at temperatures in excess of 200oC. The petroleum basins vary in terms of hydrocarbon generation conditions. According to El Nady (2015) each basin has its specific thermodynamical conditions, different type of organic matter distributed within the rocks, different rock-building minerals, different burial rates and several other factors.(El Nady & Hammad, 2015a)

2.1.5 Kerogen classification and Maturation

Maturation is a combination of complex processes through which complex biological molecules created by living organisms are first converted into simple bio-molecule and finally cooked to give petroleum.(Vandenbroucke, 2003a) In the early stage of alteration called diagenesis an intermediate form of organic matter called kerogen is formed. Kerogen is a complex organic macromolecule that is formed through the physical and chemical changes that occur in sediments after they are deposited.(Barker, n.d.-b) Diagenesis is driven by compaction, burial, and temperature increases. As sediments are buried, they are compacted by the weight of the overlying sediments, this forces out water and other fluids, and increases the temperature and pressure. Microorganisms in the sediments break down organic matter, including proteins and carbohydrates. This process releases nutrients that are used by other microbes, and produces gases such

as methane and carbon dioxide.(Fleur Matateyou, 2022)

Chemical reactions also occur between the organic matter and the minerals in the mud layer, these reactions can produce new organic compounds, including kerogen.(El Nady & Hammad, 2015b) Over time, the mud layer is transformed into a shale, and the organic matter is transformed into kerogen. The kerogen is now buried deep in the Earth, and it is ready to be transformed into petroleum. The type of kerogen that is formed depends on the composition of the original organic matter and the conditions of diagenesis.(El Nady & Hammad, 2015a) The type of kerogen that is formed depends on the composition of the original organic matter and the conditions of diagenesis.

There are four main types of kerogens which are type I kerogen which is Formed from algae and other lipid-rich organisms. It is the most oil-prone type of kerogen, type II kerogen which is Formed from a mixture of lipid-rich and protein-rich organisms and it is moderately oil-prone. Type III kerogen is the last type Formed from terrestrial plants and other lignin-rich organisms; it is the least oil-prone type of kerogen.(Barker, n.d.-a) . Type IV kerogen is formed from remnants of non-biological organic matter such as resins and waxes that have been deposited in arid environments over millions of years, unlike other types of kerogens which can generate hydrocarbons under certain conditions type IV kerogen is considered inert and has no significant potential to produce oil and natural gas.(Vandenbroucke, 2003b) Catagenesis is the second stage of sediment transformation. It occurs at higher temperatures and pressures than diagenesis typically at depths greater than 10,000 feet. During catagenesis, kerogen begins to break down into smaller hydrocarbon molecules, such as oil and gas. The specific chemical reactions that occur during catagenesis are complex and not fully understood. However, it is known that the breakdown of kerogen is accompanied by the release of water and carbon dioxide. (Barker, n.d.-a)The rate of catagenesis depends on a number of factors, including the temperature, pressure, and composition of the kerogen. In general, the higher the temperature and pressure, the faster the rate of catagenesis.(Fildani et al., 2005) Metagenesis is the third and final stage of sediment transformation. It occurs at even higher temperatures and pressures than catagenesis typically at depths greater than 20,000 feet.(Kraml et al., 2012a) During metagenesis, kerogen is completely broken down into hydrocarbons, such as oil and gas. The exact depth at which it occurs depends on the geothermal gradient, which is the rate at which

temperature increases with depth.(Kraml et al., 2012a) The type of petroleum that is generated depends on the type of kerogen and the conditions of catagenesis and metagenesis, for example, type I kerogen is the most oil-prone type of kerogen, and it is likely to generate high-quality crude oil. Type III kerogen is the least oil-prone type of kerogen, and it is more likely to generate gas.(Li et al., 2022)

TABLE 2 SUMMARIZES THE THREE STAGES OF SEDIMENT TRANSFORMATION

STAGE	TEMPERATURE AND PRESSURE	PROCESS	PRODUCT
Diagenesis	Low temperature and pressure	Formation of kerogen	Kerogen
Catagenesis	Moderate temperature and pressure	Breakdown of kerogen into hydrocarbons	Oil and gas
Metagenesis	High temperature and pressure	Complete breakdown of kerogen into hydrocarbons	Oil and gas

It is important to note that diagenesis, catagenesis, and metagenesis are continuous processes. There is no sharp boundary between the three stages. Rather, the stages are defined by the dominant processes that are occurring.(El Nady & Hammad, 2015a) The maturation of kerogen and hydrocarbon production can be best studied using Van-Krevelen diagram which is across plot between atomic H/C and O/C of kerogens types I, II, III and IV can be distinguished in the Van-Krevelen plot

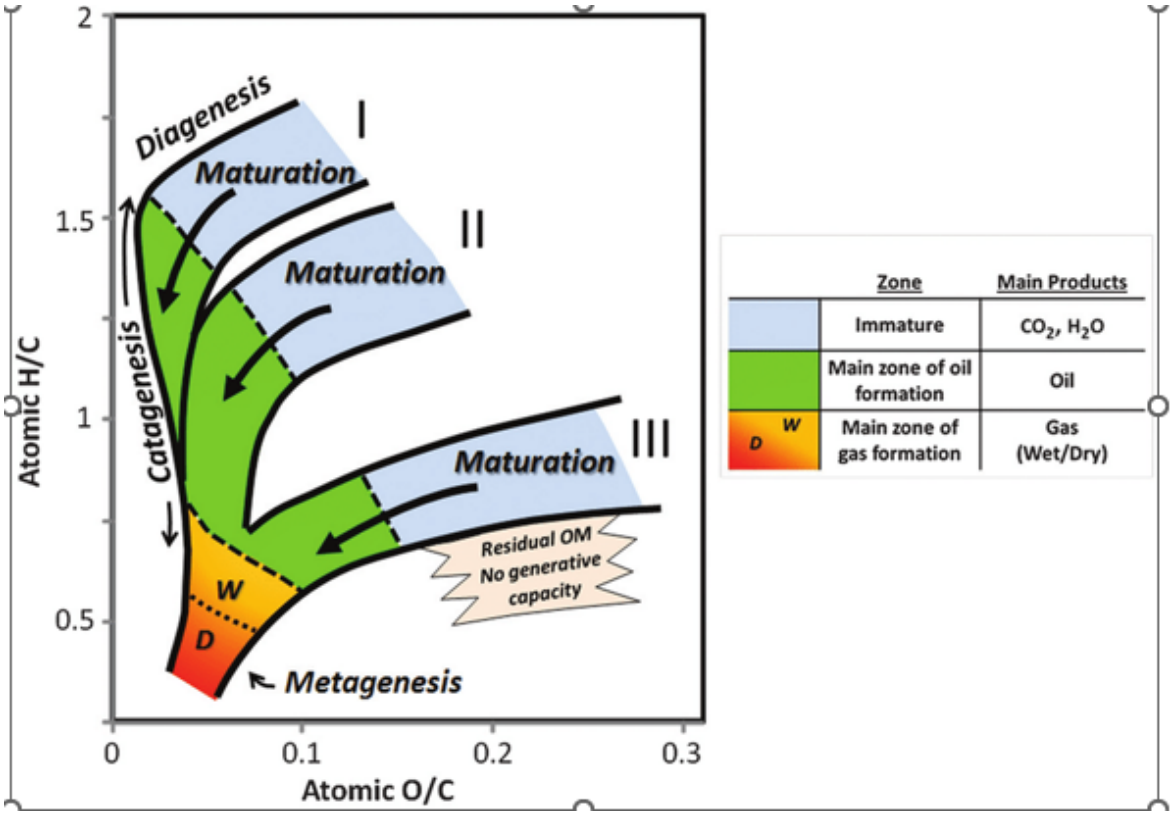


FIGURE 3 VAN -KREVELEN PLOT SHOWING TYPES OF KEROGENS(EL NADY & HAMMAD, 2015B)

The ideal temperature range for kerogen maturation is 100-150 degrees Celsius, and most of the oil in the North Sea basin is generated at temperatures around 130-140 degrees Celsius. If temperatures higher than 170-180 degrees Celsius persist for a few million years, only gas will be generated. (Zhi et al., 2023)The composition of kerogen also changes during maturation, kerogen with a high initial oxygen content will give off mostly carbon dioxide gas, while kerogen with a high initial hydrogen content will give off mostly methane gas, as a result, the hydrogen-to-carbon ratio and oxygen-to-carbon ratio of kerogen both decrease during maturation(Scholz et al., 2020b)

3 CHAPTER THREE

3.1 Methodolody

3.1.1 Introduction

This chapter presents the methods, materials and technical approach that were used to attain the objectives of this study. Discussion below is more detail descriptions of the research strategy, research methods, data collection, management methods and the type of data analysis.

3.1.2 Study Area

3.1.2.1 Location and Geological setting

The Livingstone Basin is a sedimentary basin located in the northern region of Malawi, on the western shores of Lake Malawi. It is a rift basin that is part of the East African Rift System. The basin is about 100 kilometers long and 20 kilometers wide.(Macgregor, 2015b) The Livingstone Basin is bordered by the Livingstone Fault to the east and the Karonga Fault to the west and it is filled with a thick sequence of sedimentary rocks, including sandstones, shales, and limestones. These rocks were deposited in a lake environment over a period of millions of years.(Accardo et al., 2018b) The geological history of the Livingstone Basin is complex and spans millions of years. The basin began to form during the Jurassic period (201-145 million years ago), when the East African Rift System began to develop. The basin was initially filled with volcanic rocks, but these were later covered by a thick sequence of sedimentary rocks that were deposited in a lake environment.(Scholz et al., 2020b)

Livingstone basin is considered to be the most promising basin in Malawi for petroleum exploration since it has a number of geological features that are favorable for the formation and accumulation of oil and gas, which includes: thick sedimentary rocks with porosities and permeabilities that are suitable for hydrocarbon storage, Source rocks that are capable of generating oil and gas, Reservoir rocks that are capable of trapping oil and gas, Cap rocks that are impermeable to oil and gas, preventing them from escaping and Structural features that can create traps for oil and gas just to mention a few.(*Mineral Potential of Malawi*, n.d.) The Livingstone Basin is also home to a number of hot springs and geothermal vents, these features indicate that the basin has a high geothermal gradient, which can help to mature source rocks and generate oil and

gas.(Kraml et al., 2012b)

Figure 2

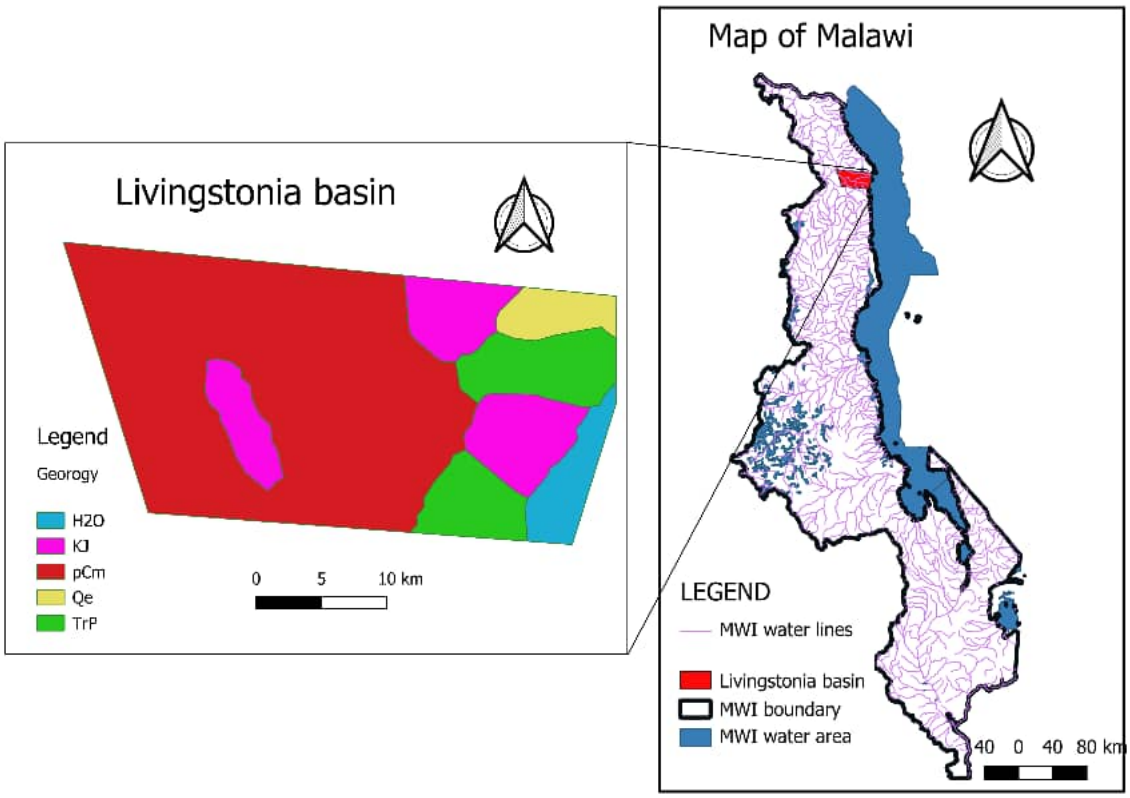


FIGURE 4 MAP OF LIVINGSTONE BASIN

3.1.3 Sample size and Technique

This research involves sampling technique such as random sampling where the samples within selected areas around Livingstone basin in karonga that where highly concentrated of complex sedimentary rocks were collected to reflect the true reflection of area. In total, 8 representative cutting samples were collected from the exploration well at Livingstone basin, the cutting samples are represented by shale and coal intervals within the Mid-Late Cretaceous, this enabled the comparison of the estimated parameters.

3.1.4 Data collection

Data used in this research is geochemical data from programmed pyrolysis of the rock

samples which includes TOC, S1, S2, S1 + S2, HI, OI and Tmax which were collected at Malawi geological survey in Zomba. The samples were analyzed using geochemical method, including TOC content and Rock-Eval pyrolysis analysis. The TOC analysis was carried out on crushed samples of less than 200 mesh size and then was measured using a LECO CS-125 equipment. The bulk pyrolysis was performed using a Rock Eval-II. Several parameters such as free hydrocarbon (S1, mg/g), total hydrocarbon yield from cracking of kerogen (S2, mg/g), and oven temperature at maximum S2 generation (Tmax) were measured during the pyrolysis process. some data were delivered from measured parameters using simple mathematics formulas as shown in the appendix.

3.1.5 Materials and Methods

This research will use geochemical methods and dwell much in rock eval pyrosis and will use both qualitative and quantitative method to evaluate the petroleum source rock in the basin.

3.1.6 Research Design

The research used secondary geochemical data, including Rock-Eval pyrolysis results (TOC, HI, OI, Tmax) from existing studies and reports. Then Ensure the reliability and quality of the collected data by verifying the sources and checking for data consistency. The data was interpreted by scatter plot graph of S1+S2 versus TOC to determine the organic richness of the source rocks. The organic matter types (kerogen types) based on the established classification (Type I, II, III, and IV) were interpreted using the van krevelen plot graph of HI against OI. The scatter plot diagram of HI versus Tmax were used to assess the thermal maturity levels of the source rocks. Integration of these findings led to the identification of potential source rock intervals within the Livingstone Basin and the evaluation of their quality based on organic richness, kerogen type, and thermal maturity.

3.1.7 Averaging and references for the result evaluation

TABLE 3 REFERENCE FOR THERMAL MATURATION

Thermal maturation stage	Tmax ©	Depth (KM)
Immature	<435	<2
Mature	435-460	2-4
Post mature	>460	>4

The estimation of maturity level is a very important criterion to predict the petroleum generation from the organic matter in a source rock and further hydrocarbon exploration (Tissot and Welte 1984; Espitalie and Bordenave 1993; Hunt 1996). Tmax is a measure of the thermal maturity of a source rock, and it is determined using a Rock-Eval pyrolysis instrument. It is the temperature at which the maximum rate of hydrocarbon generation occurs. Immature source rocks have low Tmax values, indicating that they have not been heated enough to generate significant hydrocarbons. Mature source rocks have Tmax values in the range of 435-460 °C, indicating that they are at the optimal temperature for hydrocarbon generation. Post mature source rocks have Tmax values greater than 460 °C, indicating that they have been heated too much and that most of the hydrocarbons have been generated and expelled

TABLE 4 REFERENCE TYPES OF KEROGENS

HI (mg/g)	Type of kerogen	Product
< 150	Type III	Gas
150-300	Type III	Gas and Oil
> 300	Type II	Oil and minor gas
> 600	Type I/II	Oil

The kerogen type classification based on HI and OI is a simple and widely used method for evaluating the petroleum potential of source rocks. Kerogen type I is the most oil-prone type of kerogen, while kerogen type IV is the most gas-prone type of kerogen. Kerogen types II and III are intermediate in terms of their oil and gas-generating potential. The HI and OI values of a kerogen sample can be plotted on a van Krevelen diagram to determine the kerogen type.

TABLE 5REFERENCE FOR ORGANIC MATTER RICHNESS

Organic matter richness TOC (%)	Source rock quality
< o.5	Poor
0.5 -1	Fair
1 -2	Good
2-4	Very good
>4	Excellent

These values are based on the American Association of Petroleum Geologists (AAPG) classification system. Source rocks with a high TOC content are typically more likely to

generate hydrocarbons. However, even source rocks with a low TOC content can be productive if they contain the right type of organic matter and have been buried to the correct depth and temperature.

4 CHAPTER FOUR

4.1 Data interpretation, Results and discussions

This study investigates the hydrocarbon potential of source rocks in the Livingstone basin in karonga by using rock pyrolysis. Rock pyrolysis was used to determine the total organic carbon (TOC) content, hydrogen index (HI), oxygen index (OI), Tmax, and S1+S2 values of the rock samples. The results of this study will be presented in the following sections. The results section will present the TOC, HI, OI, Tmax, and S1+S2 values for each rock sample. The discussion section will discuss the implications of these results for the hydrocarbon potential of the Livingstone basin.

4.2 Sample size, results and evaluation

Eight rock samples were collected at different depths in the Livingstone basin and analyzed for TOC, HI, OI, Tmax, and S1+S2 using rock pyrolysis. The sample size is considered to be small, but the results can still be informative and provide valuable insights into the hydrocarbon potential of the source rocks in the basin. Below is the data table that was obtained from the result of rock aval pyrosis of Livingstone basin.

TABLE 6 SHOWS TOTAL ORGANIC CARBON ANALYSIS, AND ROCK-EVAL PYROLYSIS DATA FOR LIVINGSTONE ROCK SAMPLES AND ITS DEPTH

Sample name	TOC (Wt. %)	S1 MgHC/g	S2 mgHC/g	S1+S2 MgHC/g	HI mgHCg\TOC	OI mgCOg/TOC	Tmax (°C)	Water depth (m)

M01-6GB	2.34	0.48	5.25	5.73	225	97	435	20.23
M01-76GB	3.80	0.44	10.23	10.67	269	106	431	16.35
M01-8GB	2.29	0.43	4.85	5.28	212	109	430	12.32
M01-9GB	2.43	0.20	2.90	3.10	120	117	440	8.27
M01-11GB	2.48	0.21	2.93	3.14	118	143	450	9.71
M01-13GB	3.6	0.51	9.91	10.43	278	106	437	5.87
M01-36GB	3.07	0.22	6.89	7.11	224	101	423	0.86
M01-37GB	3.61	0.44	9.74	10.18	270	90	424	7.79

These rock sediments were collected in Livingstone basin at the same area but different depth. The above table illustrates the values of total organic carbon and Rock–Eval pyrolysis for the shales of the Livingstone basin formations. The obtained data show that the total organic carbon values are between 2.29 and 3.80wt% with an average of about 2.79 wt% for the Livingstone formation. This TOC content refers to the organic richness of the rocks of this formation is very good. The organic richness of the shales of the Livingstone is mainly very good.

4.3 Interpretation of the results

4.3.1 Kerogen type

Based on pyrolysis data kerogen classification diagrams were constructed using the HI versus OI plot

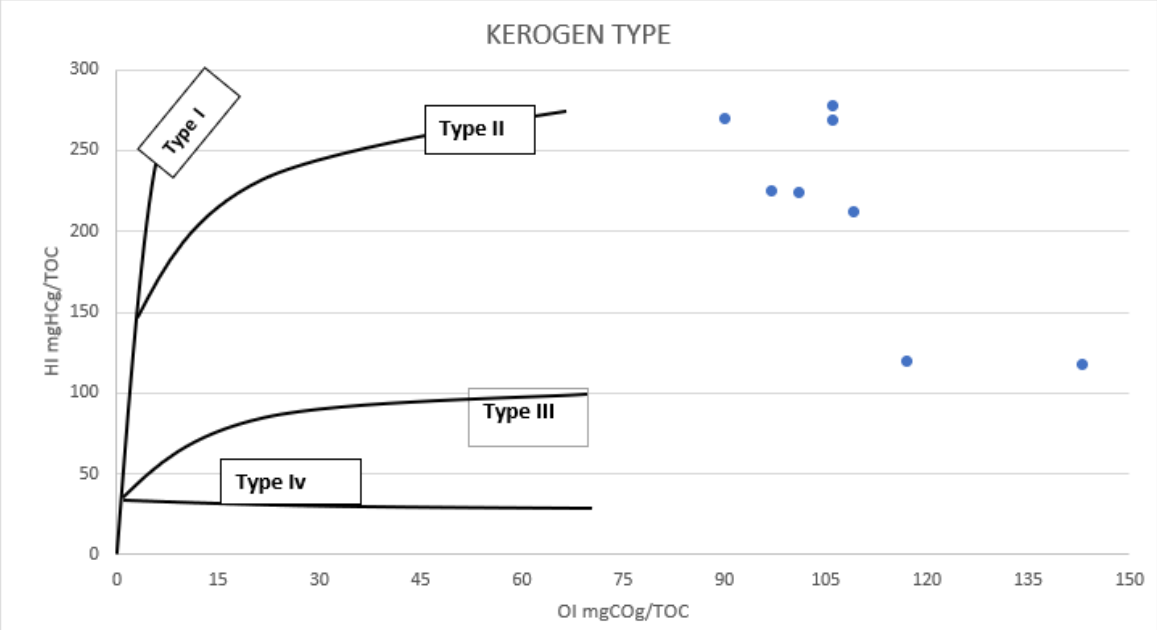


FIGURE 5 SHOWING A PLOT OF HI AGAINST OI SHOWING THE TYPE OF KEROGEN

An examination of the provided graphs reveals that all samples fall within the Type II region, indicating a high hydrogen content and a relatively low oxygen content. This characteristic makes Type II kerogen a prime source of oil. As evidenced in Table 3, Type II kerogen is prevalent in numerous oil-producing basins worldwide. The variability of kerogen type is primarily influenced by the types of organisms that contributed to the organic matter and the preservation conditions of the organic matter itself. In this instance, the Type II kerogen suggests that the organic matter originated from marine algae, phytoplankton, and zooplankton and was deposited in an oxidizing environment (Peters & Cassa, 1994). If Type II kerogen is discovered in a formation with the appropriate maturity, temperature, and pressure conditions, and there are no other factors hindering petroleum generation, then the petroleum potential of that formation is considered favorable.

Therefore, the presence of Type II kerogen in a formation with the right conditions suggests a high potential for oil generation. However, it's important to note that other factors, such as the presence of natural fractures and effective migration pathways, also play a role in determining the ultimate oil potential of a formation.

4.3.2 Thermal maturation

Figure below shows thermal maturation level of all samples after plotting scatter plot to show the relationship between hydrogen index(mgCH/gTOC) and Tmax.

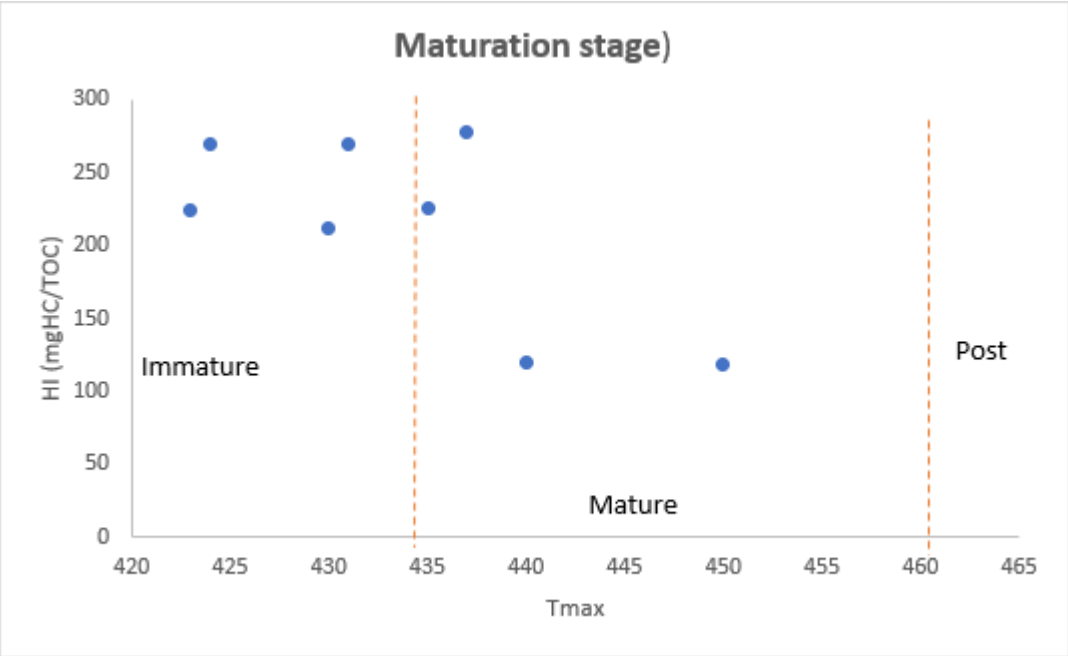


FIGURE 6 SHOWING RESULTS OF THERMAL MATURITY LEVEL OF THE SOURCE ROCK

An examination of the basin's samples reveals that half are mature and the other half are immature, with none falling into the post-mature category. This distribution suggests that the basin is still in the early stages of thermal maturation, gradually transitioning towards a fully mature state. Mature source rocks, unlike their immature counterparts, possess the capability to generate hydrocarbons. The presence of both mature and immature samples within the basin indicates that the thermal maturation process is ongoing, with the basin nearing full maturity. This implies that the conversion of kerogen to petroleum has commenced but has not yet reached its maximum potential. The basin's relatively young age contributes to this observation, suggesting that the sediments have not been subjected to sufficient time for complete conversion processes to occur. Additionally, the burial rate experienced by the basin

throughout its geological history has not been substantial enough to elevate the temperature to a level that would accelerate the conversion process.

4.3.3 The organic richness and petroleum potential

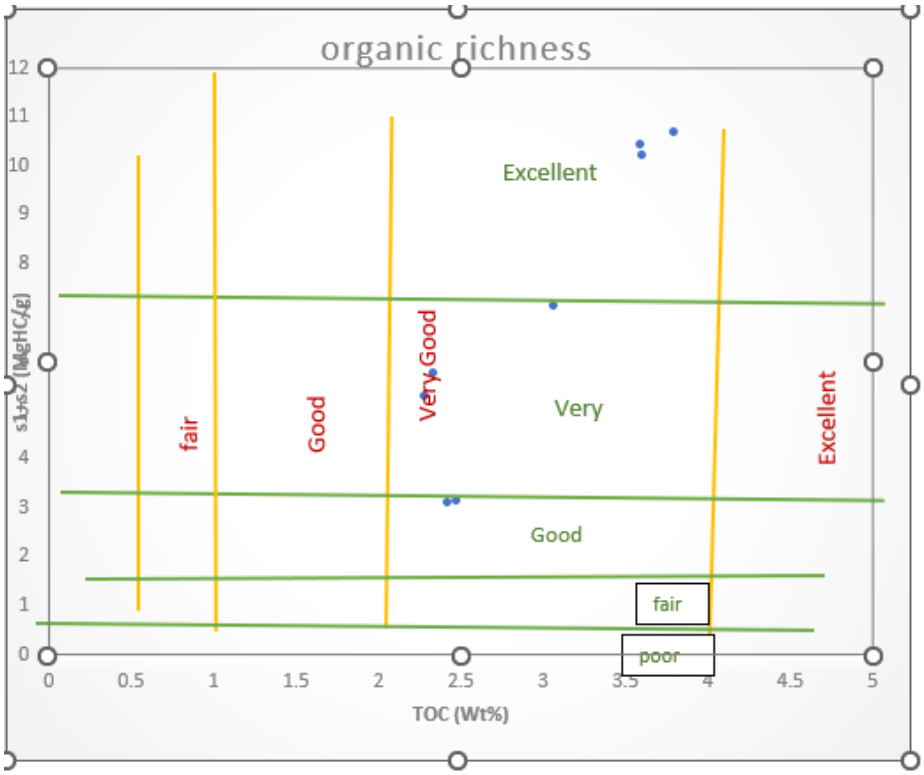


FIGURE 7 SHOWS ORGANIC RICHNESS AND PETROLEUM POTENTIAL

The findings depicted in the diagram reveal that the total organic carbon (TOC) content values for the Livingstone basin source rocks range between 2.29 and 3.8 weight percent, indicating their classification as very good source rocks. This categorization is based on the established TOC scale, where values between 2 and 4 weight percent signify very good source rocks. This implies that the organic matter present within these rocks possesses substantial hydrocarbon-generation potential.

Furthermore, the relationship between S1+S2 and TOC further corroborates the potential of the Livingstone basin source rocks for petroleum generation. S1 represents the free hydrocarbons released during Rock-Eval pyrolysis, while S2 represents the hydrocarbons generated during the thermal cracking of kerogen. The sum of S1 and S2,

S1+S2, provides an overall indication of the hydrocarbon-generating potential of the source rock. In this case, the relationship between S1+S2 and TOC indicates a generation potential level ranging from fair to good. This suggests that the source rocks have the capability to generate significant quantities of hydrocarbons, particularly oil.

The combination of these findings strongly supports the conclusion that the Livingstone basin source rocks possess significant potential for petroleum generation. Their high TOC content, coupled with their fair to good hydrocarbon-generating potential, makes them attractive targets for oil exploration and development.

5 CHAPTER FIVE

5.1 Conclusions and Recommendations

5.1.1 Conclusions

A comprehensive geochemical analysis was conducted to evaluate the source rock potential of the Livingstone Basin. Total organic carbon (TOC) measurements revealed an abundance of organic matter within the basin's shales, with TOC values ranging from 2.29 to 3.80 weight percent, indicating a very good source rock potential. Further investigation using Rock-Eval pyrolysis, a technique that simulates the thermal breakdown of organic matter, provided valuable insights into the type of kerogen, quality of organic matter, and thermal maturity of the source rock.

The pyrolysis results indicated that the organic matter within the Livingstone Basin is predominantly composed of type II kerogen, derived from marine algae and other aquatic organisms. This type of kerogen is considered highly oil-prone, suggesting a favorable potential for oil generation. The hydrogen index (HI), a measure of the relative abundance of hydrogen in the organic matter, is also high which further confirming the oil-prone nature of the kerogen.

Analysis of the pyrolysis data also revealed a variable maturity level of the organic matter, ranging from the initial stage to the maturation stage of catagenesis. This suggests that the organic matter has undergone varying degrees of thermal alteration

due to burial depth and geothermal gradient. The presence of early mature to mature kerogen indicates that the source rock has reached a favorable thermal window for hydrocarbon generation.

In conclusion, the geochemical analysis provides compelling the evidence that the Livingstone Basin harbors very good source rock potential. The abundance of type II kerogen, combined with the variable maturity levels, suggests a significant potential for oil generation within the basin's shales. Further exploration and development efforts are warranted to fully assess the hydrocarbon potential of this promising geological basin.

5.1.2 Recommendations

Further studies are needed for better understanding of the hydrocarbon potential of the studied source rocks. These studies could include, Vitrinite reflectance measurements: Vitrinite reflectance measurements serve as an independent and complementary method for evaluating the thermal maturity of source rocks. By analyzing vitrinite reflectance values, researchers can corroborate or refine the thermal maturity estimates obtained from Rock-Eval pyrolysis, enhancing the overall assessment of hydrocarbon potential.

Biomarker analysis is the second recommendation, Biomarker analysis offers valuable insights into the origin of the organic matter within the source rocks and the depositional environment in which they were formed. By identifying and characterizing specific biomarkers, researchers can gain a better understanding of the factors that influenced the hydrocarbon potential of the source rocks.

Basin modeling: Basin modeling utilizes geological, geophysical, and geochemical data to simulate the thermal evolution of a sedimentary basin over time. This allows researchers to predict the timing and volume of hydrocarbon generation from source rocks within the basin, providing a more comprehensive assessment of the overall hydrocarbon potential of the area.

By undertaking these additional studies, researchers can gain a more comprehensive understanding of the hydrocarbon potential of the studied source rocks, enabling informed decision-making regarding further exploration and development activities.

5.1.3 Limitations of the study

The study was based on a limited number of samples. This means that the results may not be representative of the entire basin. Another limitation of this study is that it did not use any other geochemical techniques to confirm the results of Rock-Eval pyrolysis, this could lead to misinterpretations of the data. Lastly the Inadequate funding as well as time were limited.

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6 APPENDICES

6.1 Appendix A

Rock Eval Pyrolysis

Rock-Eval pyrolysis is a source-rock assay technique that involves heating small quantities (50-400 mg depending on carbon content) of pulverized rock and measuring the mass of hydrocarbon gases evolved as a function of temperature. (El Nady & Hammad, 2015b) The carbon dioxide evolved during heating is saved in a trap during heating and later analyzed to estimate the total organic carbon content of the sample. During the initial stages of heating, sorbed or free hydrocarbons in the sample are driven off and are recorded as the Si peak. With increasing temperature, the organic matter in the sample breaks down to hydrocarbons and CO2. which are recorded as the S2 peak and S3 peak respectively, and other compounds which are not analyzed. Specific definitions for Rock-Eval data reports are S1 and S2 are the first and second peaks of hydrocarbon (HC) yield occurring during pyrolysis of the sample. S3 is the amount of C02 generated during pyrolysis, TOC is total organic carbon. Tmax is the temperature at which the S2 peak occurs during pyrolysis of kerogen. (El Nady & Hammad, 2015b) Derivative values from these basic measurements are the hydrogen index (HI) =(S/TOC) x100; the oxygen index (OI) = (S3/TOC) x100; the genetic potential (S1+S2) and the Transformation ratio = PI = S1/ (S1 +S2). TOC when used in these derivative values is reported as grams carbon (g C). (Selwi A, 2015)

The analytical results of Rock-Eval pyrolysis are unreliable if the TOC content of the rock sample is less than 0.5 wt-% (Peters, 1986; Bordenave et al., 1993). Rocks with less than 0.5 wt-% TOC are probably incapable of expelling hydrocarbons and therefore are not source rocks. Samples with less than 0.5 weight-% TOC are included in the data tables but are not included in the interpretative plots. It must be emphasized that Rock-Eval pyrolysis only gives a semiquantitative estimate of organic matter properties during rapid heating to extreme temperatures under dry conditions which at best can only be considered a rough analog to natural conditions. (Barker, n.d.-b)

6.2 Appendix B

Table showing the TOC content and rock eval pyrosis data that was used in the research.

Sample name	TOC (Wt. %)	S1 MgHC/g	S2 mgHC/g	S1+S2 MgHC/g	HI mgHCg\TOC	OI mgCOg/TOC	Tmax (°C)	Water depth (m)
M01-6GB	2.34	0.48	5.25	5.73	225	97	435	20.23
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M01-8GB	2.29	0.43	4.85	5.28	212	109	430	12.32
M01-9GB	2.43	0.20	2.90	3.10	120	117	440	8.27
M01-11GB	2.48	0.21	2.93	3.14	118	143	450	9.71
M01-13GB	3.6	0.51	9.91	10.43	278	106	437	5.87
M01-36GB	3.07	0.22	6.89	7.11	224	101	423	0.86
M01-37GB	3.61	0.44	9.74	10.18	270	90	424	7.79