

ASSESSING COAL-BED METHANE POTENTIAL IN MALAWI: CASE STUDY OF MCHENGA COAL MINE

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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 (Oil and Gas)

April, 2023.

DECLARATION

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

Signature: 

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Supervisor: Mr W. Tchongwe Signature: 

Assessor: Signature: _____

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ABSTRACT

The aim of this study was to assess the potential of coal at Mchenga coal mine for coal-bed methane generation. This was carried out by using proximate data that included moisture, volatile matter, ash, and fixed carbon content of four coal samples from varying coal seams of K2 upper formation at Mchenga coal mine. Volatile matter on a dry ash free basis was used to estimate methane content and calculate vitrinite reflectance of the four coal samples. Microsoft Excel software was used to analyze the results, and the analysis indicated that based on the values of volatile matter on a dry ash free basis and vitrinite reflectance, the coal samples under study belong to the subbituminous coal rank. This is according to the coal rank classification table by Teichmüller (1982) and Diessel (1992). The values of vitrinite reflectance also indicate that the coal samples under study have the potential to generate coal-bed methane gas. However, since the coals belong to the subbituminous coal rank, the generation of the gas is in its early stage. In addition, when the estimated methane content was correlated with moisture, fixed carbon on a dry basis, and volatile matter content, a negative correlation was observed. Conversely, a positive correlation was observed when it was correlated with fixed carbon on a dry ash free basis and vitrinite reflectance. Therefore, based on the results and the analysis, it was suggested that the coal samples from the study area have the potential to generate coal-bed methane gas. This information will help the mine authorities to come up with appropriate mitigation measures for the mine against any potential gas disaster explosion that are caused by the presence of coal-bed methane in a coal mine. Hence, further exploration for coal-bed methane can be carried out in the study area, in order to determine the exact quantity of the gas and its production potential.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank God Almighty for sustaining and helping me in each and every step of my academic journey at the Malawi University of Science and Technology, and for the successful completion of the research project.

I would also like to express my deepest gratitude to my research project supervisor, Mr. Tchongwe, who provided insightful knowledge, guidance, and advice that helped in each and every stage of writing my research project. His professional advice and knowledge helped me to improve and get to the completion stage of my work. This work would not have been possible without his generous guidance.

I would also like to extend my deepest appreciation to my earth science department lecturer, Mr. Brave Manda, for providing the dataset that was used in this study. I also deeply appreciate Mr. Mpanje, from Kanengo Coal Lab in Lilongwe, for providing and thoroughly explaining the write ups of the methodologies used for proximate analysis. This research would not have been possible without their generous support.

I am also thankful to the Malawi University of Science and Technology for the monetary support that was given for data collection and other activities involved in my research project. The support helped in the completion of this research project.

I would also like to extend my sincere thanks to my family: mom (Grace Zgambo), dad (Ellie Mhone), twin sister (Rachel), and brother (Elisha) for their prayers, emotional, moral, and financial support, and their inspiration that kept my motivation high during the whole process. I am also extremely grateful to my mom for always being there for me and believing in me throughout my academic journey.

I would also like to thank my friends (Bridget Banda, Sibongile Jere, and Zaithwa Katuwa) for all the good moments, moral support, and always inspiring me in each and every stage of my academic journey. Finally, I am thankful to all of my petroleum geoscience classmates that contributed to this work both directly and indirectly.

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ABBREVIATIONS

A – Ash Percentage

CBM – Coal Bed Methane

DAF - Dry Ash Free

FC - Fixed Carbon

ICCP - International Committee for Coal and Organic Petrology

ISO – International Organization for Standardization

LVB - Livingstonia Basin

VM - Volatile Matter Content

VR - Vitrinite Reflectance

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Coal-bed methane is a hydrocarbon gas that is largely composed of methane (CH_4), and is generated and stored in coal beds in the adsorbed state (Zou et al., 2017). Along with heavier hydrocarbons like ethane (C_2H_6), propane (C_3H_8), and butanes (C_4H_{10}), coal-bed methane gas also contains varying amounts of carbon dioxide (CO_2) and elemental nitrogen (N_2) (Gao et al., 2014). Coal-bed methane is produced during the coalification process by two different mechanisms depending on the depositional environment, and they include: biogenic and thermogenic processes (P. . Singh, 2011). Coal-bed methane gas of biogenic origin is produced by the decomposition of coal organic matter by the methanogenic consortiums of microorganisms, usually at low temperatures of less than 56 °C (Gao et al., 2014). Whereas coal-bed methane gas of thermogenic origin is generated by chemical degradation and thermal cracking of coal organic matter mostly at temperatures above 100 °C (Gao et al., 2014).

The methane gas that has been produced during the coalification process either moves to the surface or into adjacent coal reservoirs or other rocks. However, a significant amount of the produced gas is trapped and stored within the coal bed (Nalinikant et al., 2015). For this reason, coal-bed methane gas is regarded as an unconventional gas because the coal seam is both the source rock, reservoir rock and seal (Rajput & Thakur, 2016). Coal-bed methane gas is stored within coal in four different ways. Firstly, it is stored as a free gas within the micro pores and cleats of coal. Secondly, it is stored in a dissolved state in the water that is present in coal. Thirdly, it is stored in adsorbed state on the organic elements that make up the coal mass. Fourthly, it is stored in absorbed state within the molecular structure of the coal molecules (Rajput & Thakur, 2016).

Coal-bed methane is also one of the upstream petroleum industries' exploration targets. This is so because, it is a viable energy source with substantial long term potential for

discovery and development (Pal et al., 2015). Additionally, the gas has the potential to be a significant energy resource for both domestic and industrial purposes and utilizing the gas for fuel and economic purposes is of great economic benefit to a country (Nalinikant et al., 2015). When assessing the potential of a coal mine to generate coal-bed methane gas, it is essential to understand the factors that lead to the generation and accumulation of methane gas in the coal seam. These factors include proximate and maceral composition of coal, depth and rank of the coal seams, pressure and temperature of the reservoir, local hydrological conditions and information on the coal seams' adsorption capacity (Pophare et al., 2008).

In Malawi, there are four major coal-bearing regions: two in the Shire Valley, in the southern region, and two in the northern region, close to Lake Malawi (Umali et al., 2016). In the southern region, deposits of coal are found in Mwabvi and Lengwe sub basins (Onuma et al., 2013). Whereas in the northern region, the most significant and potential coalfields are located at Livingstonia, and close to Ngana which is on the Tanzania border (Umali et al., 2016). In addition to that, Lufira, North Rukuru, and Nthalire sub basins within the northern region, are also known of hosting substantial coal deposits (Dulanya & Kaonga, 2015). The coal mines that are located within the Livingstonia coalfield include: Mchenga coal mine, Kaziwiziwi coal mine, Chombe coal mine, and Mean Jalawe coal mine (Malema, 2006).

1.2 Problem Statement

In accordance with the available estimates, there are thirteen coal fields in the northern region of Malawi, and two coal fields in the southern region of the country, with possible reserves amounting to as much as 800 million tonnes (Onuma et al., 2013). The northern coal deposits, such as those in the Livingstonia coalfield, are of large extent, prospective, and generally of good quality (Dulanya & Kaonga, 2015). The Livingstonia basin is the main basin in the northern region of Malawi, that is significant in terms of its potential of hosting coal, and the coalfield is also the south-western extension of the Ruhuhu Basin in

Tanzania, with which it shares many similarities (Hancox, 2016). Within the Livingstonia coalfield, coal deposits are distributed within locations that have potential areas for mining, such as the Mchenga and Kaziwiziwi areas (Maneya, 2012). Currently, Mchenga coal Mine is the only major coal producer in Malawi (Onuma et al., 2013). Despite, Mchenga coal mine being a major coal producer and having economic potential and significance, there is no documentation on the assessment of the area for coal bed methane gas generation. Therefore, this research aims at solving this problem by providing information and an overview of the potential of Mchenga coal mine for coal-bed methane generation and storage.

1.3 Main and Specific Objectives

1.3.1 Main objective

The main objective of this research is to assess coal-bed methane potential at Mchenga Coal Mine.

1.3.2 Specific objectives

The specific objectives of this research include:

1. Determine the moisture content of coal seams at Mchenga coal mine.
2. Determine the volatile matter content of coal seams at Mchenga coal mine.
3. Determine the fixed carbon content of coal seams at Mchenga coal mine.

1.4 Research Questions

The research questions include:

1. Is the moisture content of coal seams at Mchenga a coal mine appropriate for coal-bed methane generation?
2. Is the volatile matter content of coal seams at Mchenga coal mine appropriate for coal-bed methane generation?
3. Is the fixed carbon content of coal seams at Mchenga coal mine appropriate for coal-bed methane generation?

1.5 Significance of Study

Firstly, this study is significant because it will help to prevent the creation of non-conducive environment to workers and gas disaster explosions in the coal mine that may eventually result in a fatal accident (Yan et al., 2021). This is so because, the presence of coal-bed methane gas in an underground coal mine creates a risk of explosion as well as the creation of an oxygen poor environment that would not support human life (James et al., 2008; Mondal et al., 2021). Therefore, the information from this study will help the mine authorities to come up with appropriate mitigation measures for the mine against any potential gas disaster explosion or environments that are not conducive to workers.

Secondly, this study is significant because it will serve as a relevant foundation for the exploitation of coal-bed methane gas at Mchenga coal mine. This is so because, for exploitation of the gas to occur, there is a need for a detailed study to assess if the coal mine has the potential to generate, accumulate, and store coal bed methane gas effectively.

CHAPTER 2: LITERATURE REVIEW

This chapter will summarize available literature and studies on coalbed methane subject. The chapter will describe and explain how geochemical analysis and other techniques are used to assess and evaluate the potential of coal seams within a coal mine to generate, accumulate and preserve coalbed methane gas.

2.1 Coal

Coal is an organic sedimentary rock that is complex, heterogeneous, and made of terrestrial land plants which have been consolidated between other rock strata and transformed by the pressure and heat over a long period of time (Baysal, 2012). Coal acts as the source, reservoir and trap for significant amounts of methane and trace amounts of other gases (Bustin & Clarkson, 1998).

2.2 Coal-bed Methane

Coal-bed methane gas is regarded as an unconventional gas resource that is self-generating and self-accumulating, and is extremely important in maintaining the safety of coal mines, protecting the environment and production of clean energy (Li et al., 2017). According to literature, different parameters of coal substantially influence coal-bed methane gas generation and accumulation within coal.

2.3 Geochemical Analysis of Coal for Coalbed Methane Potential Assessment.

Identification of the parameters responsible for coal bed methane generation and accumulation is essential when assessing a coal seam for coalbed methane potentiality. The identified parameters assist in choosing the appropriate method to use for the assessment. For instance, according to the available literature, geochemical analysis method is mostly chosen when proximate parameters of coal have been identified as one of the main parameters that are influencing coalbed methane gas generation and accumulation in a coal seam. Geochemical analysis of coal mainly involves proximate and ultimate analyses

of coal, and plays a great role in the assessment of the quality, quantity and maturation of hydrocarbon gases present in coal samples (Lakshmi et al., 2014).

2.3.1 Proximate composition of Coal that Influence Coalbed Methane Generation.

Some of the proximate parameters of coal that are essential when assessing the potential of a coal seam for coal bed methane generation and accumulation include: moisture content, ash content, volatile matter content, fixed carbon content, and vitrinite reflectance (Varade et al., 2013). These parameters are determined through proximate analysis of coal samples.

In a study conducted by Talukdar et al., in 2015, proximate analysis was conducted on prepared coal samples in order to determine the ash, moisture, volatile matter and fixed carbon content of the samples. The aim of the study was to estimate coal bed methane potential of coal seams of Margherita coal field in India. Rice's (1993) equation was used to calculate the vitrinite reflectance, while Meissner's equation was used to estimate the volume of methane gas that was generated within coal seams of the coalfield. According to Meissner's equation, coal with a volatile matter content that exceeds 37.8% should not produce any methane at all because the volume of methane gas generated is experimentally proportional to volatile matter content of the coal (Talukdar et al., 2015). The proximate analysis data and vitrinite reflectance values of the coal samples were used to determine the coal rank and grade of the coal samples under study. Coal rank determination was also essential in assessing the potentiality of the study area for coal-bed methane gas generation. However, using a single methodology to assess the potential of coalfield's to generate and store coal-bed methane has limitations and creates a possibility for errors in results (Li et al., 2017). Hence it is important to use more than one method in order to have accurate and reliable results.

In another study conducted by Kumar et al., in 2015, both proximate and ultimate parameters of coal seams within a coalfield were analyzed for coal-bed methane

potentiality. This was done by using petrographic analysis which incorporated both proximate and ultimate analyses of coal. Proximate analyses involved determination of ash, moisture, volatile matter and fixed carbon content. Ultimate analyses mainly involved determination of elemental composition of the coal samples under study. Some of the determined elements such as hydrogen, oxygen and carbon are used to assess the potential of the coal beds to generate methane gas and the thermal maturation of the methane gas that has been generated (Kumara et al., 2018).

Proximate analysis is also conducted in order to determine actual gas adsorption capacity of coal seams. In a study conducted by Kalkreuth et al., in 2020, the characteristics of coal hosted within the coal seams in the Chico-Lom~a coalfield, in Brazil and its potential for coal-bed methane was determined and evaluated. In order to achieve this, proximate analysis was conducted to determine the actual gas adsorption capacity of the coal seams. In addition, since assessing a coalfield for coal-bed methane potentiality based on a single methodology has limitations, other methods were also used and they include: petro graphical analysis, 3D modelling and gas chromatography. Petrographic composition of the coal seams was determined by using the ICCP-established maceral classification (1963, 1998, 2001), where (ISO 7404/3, 1984) method is used to determine maceral composition of coal samples. Using 3D modelling, a 3D geological model for the research region was created to estimate the amount of coal within the study area and assess the amount of methane gas that is associated with the estimated coal (Kalkreuth et al., 2020). Additionally, gas chromatography method was used to determine the composition of the methane gas. The results were used to assess if the coal seams within the study area have the potential to generate and accumulate coal-bed methane gas.

2.4 Petro-physical Analysis of Coal for Coal-bed Methane Potential Assessment.

Petro-physical parameters of coal that are mostly considered when assessing the potential of a coal mine to generate and store coal-bed methane gas include: permeability, porosity, coal rank and pore size distribution of the coal samples being used. These are the most

important parameters for coal-bed methane potential assessment (Yufu, 2018). In addition to that, other intrinsic properties of coal that are essential for coal-bed methane assessment include: adsorption capacity, coal seam thickness and rank of the coal samples being used (P. . Singh, 2011). This section will summarize the different methods that are used to assess and analyze petro physical parameters of coal that influence coal-bed methane generation, accumulation and storage in a coal seam.

In a study conducted by Pal et al., in 2015, well logging techniques were used to assess if the coal seams found in Jharia coalfield in India have the potential of being a coal bed methane reservoir. The well logs that were used include: sonic, density, gamma, and resistivity logs. The data from these well logs was used to approximate the permeability of the coal seams, determine the relationship between permeability and in situ stress, and most importantly, estimate gas content of coal seams and determine potential areas for coal-bed methane discovery and development. The estimated gas content was then used to calculate the gas adsorption capacity of the coal seams.

In 2017, a study was conducted by Li et al., in China, where 3D seismic data was used to evaluate the geological conditions of a coal seam, in Yangquan coalfield of Qinshui basin which could influence coal-bed methane occurrence within the area. Based on the 3D seismic data, the geological parameters that influence coal-bed methane occurrence were interpreted. Firstly, the seismic horizons were used to compute the thickness and depth of the coal seam and the 3D seismic structural interpretation was used to determine geological features such as faults, collapse columns and folds. Secondly, multi-attribute probabilistic neural network inversion and prestack elastic impedance inversion methods were used to construct natural gamma attribute volumes and 3D elastic impedance, that depicts the lithology of the roof and floor, and the different types of coal structure.

In another study that was conducted by Fu et al.,in 2021, the Langmuir isotherm model was employed to analyze the desorption and adsorption capacity of methane in a coal

reservoir. The capacity of coal to store methane gas is indicated by the Langmuir isotherm, which also predicts the discharge of gas from a reservoir when the pressure within reservoir decreases (Ertürk & Sinayuc, 2013). According to Aminian & Rodvelt, (2014), the Langmuir isotherm defines the maximum gas adsorptive capacity of coal as a function of pressure. Both methane adsorption and desorption capacities are essential in determining potential areas for coal-bed methane gas within a coalfield.

Therefore, in order to have clear, consistent and reliable data concerning assessment of coal seams for coal-bed methane potentiality, there is a need to conduct a detailed assessment, using reliable methods and techniques.

CHAPTER 3: METHODOLOGY

3.1 Study Area

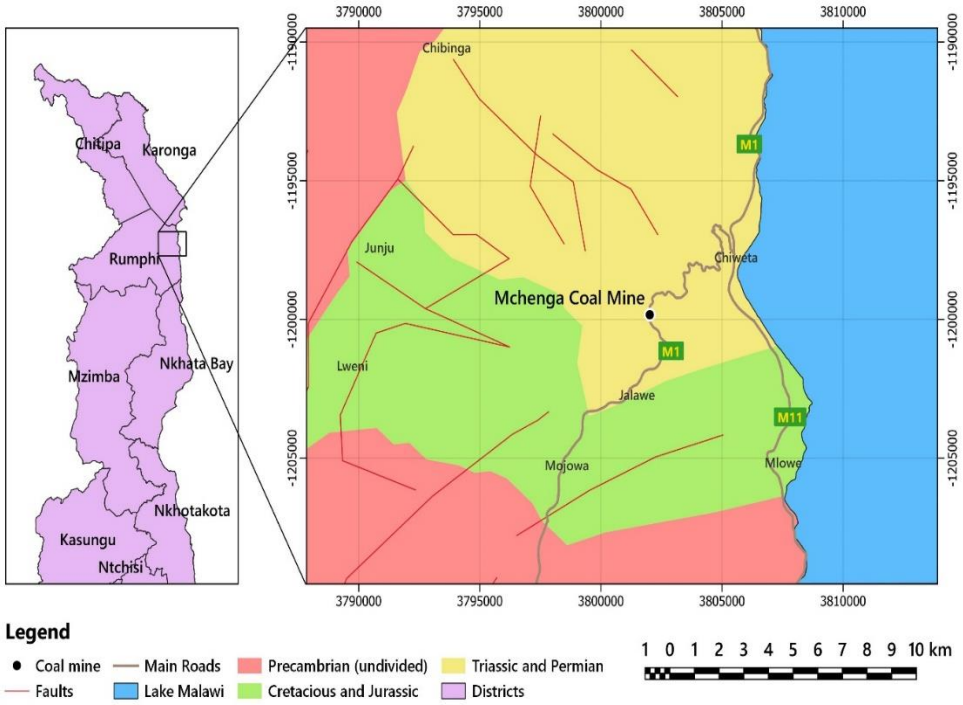


Figure 1. Geologic map showing location of study area; Mchenga coal mine.

Mchenga Coal mine is located in the south eastern side of the Livingstonia coalfield found within Rumphi district, in the northern region of Malawi. Livingstonia coalfield extends over 90km^2 within the district, while the coal mine extends over 17.5km^2 within the coalfield (Maneya, 2012). Mchenga coal mine is an underground mine which uses room and pillar mining method, and almost all the underground mining sections have well-built canopies and accessible adits (Umali et al., 2016). Room and pillar mining method is used because it is suitable and appropriate for the rocky terrain and stability of the hanging walls in the Livingstonia coalfield, within which the coal mine is found (Umali et al., 2016). Mchenga coal mine falls within latitude: S10°42′55″, longitude: E34°9′14″ and is the second largest mine in the country, after the Kasikizi coal mine (Yasidu et al., 2019). The mine

produces 0.3 million tonnes per annum and has mineable reserves that amount to 26.5 million tonnes, where 1.5 million tones are proven reserves and 25 million tonnes are probable reserves (GlobalEnergyMonitor, 2022).

3.1.1 General Geology of Mchenga Coal Mine

Mchenga coal mine is hosted within the Livingstonia basin which is one of the widely distributed twelve Karroo basins found in the northern region of Malawi (Maneya, 2012). The area is stratigraphically made up of Karroo system strata, preserved in a number of North-South trending basins and down faulted troughs, and they exhibit both unconformable and faulted relationships to the underlying basement complex gneisses (Umali et al., 2016). The Karroo system mainly incorporates Permian and Triassic period (Umali et al., 2016).

The succession of the strata of the Karroo sequence consists of conglomerates and sandstones from the Dwyka (Carboniferous) and lower Ecca series (Permian). Then a sequence of carbonaceous shales and coal measures of lower Ecca series (Permian) overlies them ,and the roof stratum dominantly consists of sandstone and shale of the upper Ecca group (Permian) (Yasidu et al., 2019). The geology of Mchenga coal mine is comprised of the Karroo sediments of basal beds, lower and upper Ecca Group, and lower Beaufort Group, all of which are underlain by the Mafingi System that forms part of the Malawi basement complex (Chipili, 1987).

Mchenga coal mine has been chosen as the study area because, it is a major coal producer and of great economic importance to our country. In addition, the coal mine is hosted within one of the significant coalfield, where the Karoo system strata is well preserved (Mshali, 2009). Therefore, the coal mine is suitable for assessing its potential to generate coal bed methane.

3.2 Research design

This study was designed as a case study and quantitative research methodology was used. All variables used are independent and they include: Ash, fixed carbon, volatile matter and moisture content. The study used secondary data. Below is the research design framework.

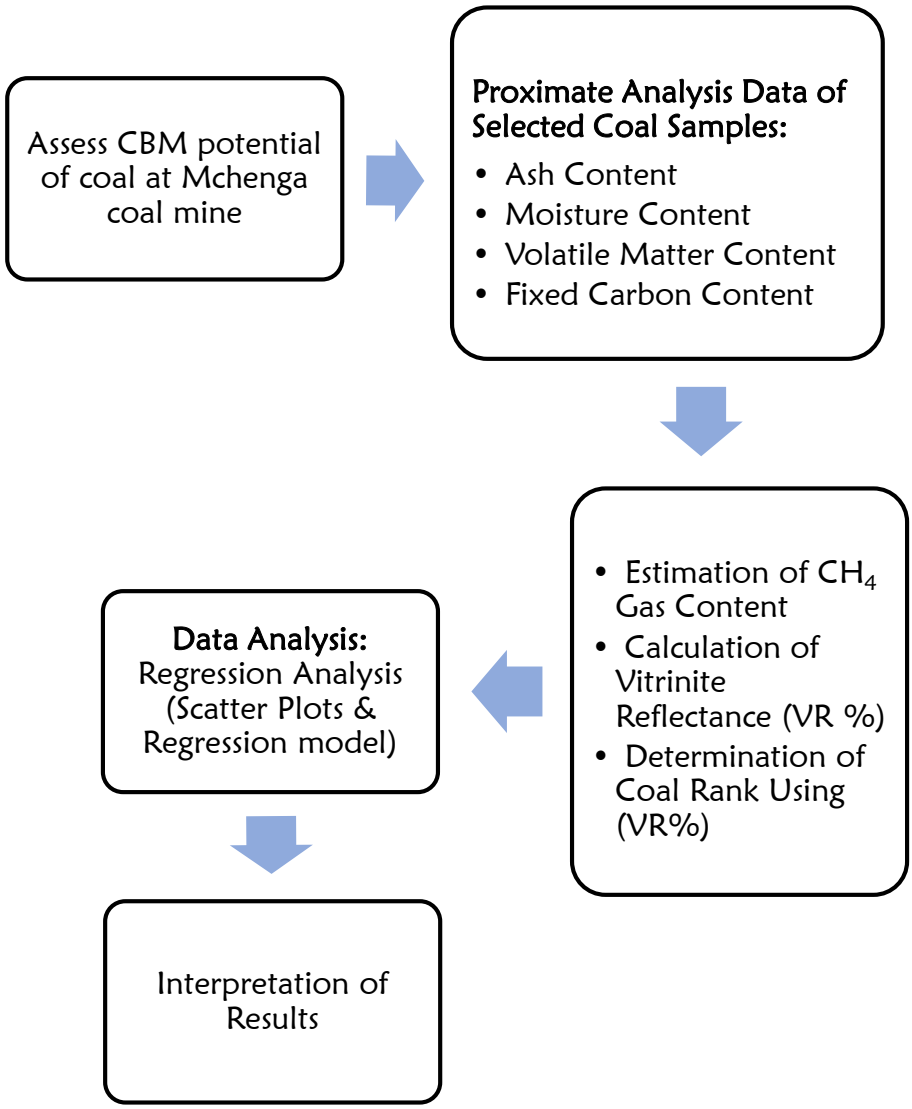


Figure 2. Research Design Framework

3.3 Methodology

3.3.1 Coal Sampling

The study used secondary data, and the data used was proximate analysis data of four coal samples which were collected from four different coal seams of K2 upper formation (coal measures) at Mchenga coal mine. The samples were collected from freshly exposed coal mining surface within the underground coal mine, and they were sampled by hammering the exposed coal seam. All the coal from the hammered section was collected in air tight cover bags to prevent moisture loss. **Table 1** below shows the details of the four coal samples that were used for the analysis.

Table 1. Details of coal samples that were used for the analysis

Sample	Basin	Formation	Lithology	Description
NY20576_1	LVB	K2upper	Coal	Middle Coal seam + Py + Ash (Mchenga Coal Mine)
NY20576_2	LVB	K2upper	Coal	Middle Coal seam (Mchenga Coal Mine)
NY20583_2	LVB	K2upper	Coal	Upper Coal seam (abandoned Mchenga Coal Mine)
NY20584_1	LVB	K2upper	Coal	Middle Coal seam (abandoned Mchenga Coal Mine)

3.3.2 Sample Preparation

Materials

Materials that were used when preparing the coal samples include: steel table. roll crusher, cross-split plate and a small sized desiccator.

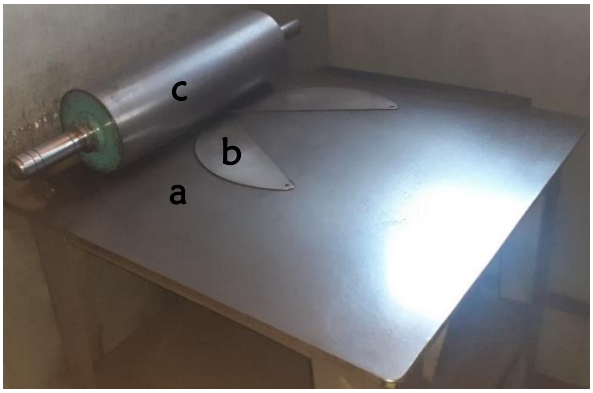


Figure 3. (a) Steel table, (b) Cross-split plate and (c) Roll crusher used for coal sample preparation



Figure 4. Small sized desiccator used for storing prepared coal samples



Figure 5. A sample of prepared coal sample

Procedure:

Firstly, the coal samples were laid out on the steel table and crushed into small pieces by rolling the roll crusher over them. Secondly, the coning and quartering method was used for the division process, where the pulverized coal samples were heaped up into cone-shaped heaps and flattened using a cross-split plate. After that, a cross-split plate was put in the center of it and forced all the way to the bottom.

Then, the pulverized coal samples were divided into four equal sectors, with two opposing sectors being maintained as the final sample to be used for the analysis. Thirdly, the final sample was then sieved to remove non-conforming samples from the other samples and further compress them to the required size to lessen sample division bias. The sieved sample was then stored in a small sized desiccator.

3.3.3 Geochemical Analysis of coal samples

The proximate analytical method was used to determine the geochemical analysis of the four coal samples. Proximate analysis is the study of physico-chemical parameters of coal (Ghosh et al., 2010). The procedures outlined by the International Organization for Standardization (ISO, 1981) were used to determine ash content (ISO 1171-1981 (E)), moisture content (ISO 589-1981 (C)) and volatile matter content (ISO 562-1981 (E)). Fixed carbon content was determined by difference. All values were given to the nearest 0.1 weight percent (wt%). The analysis was conducted at the Kanengo coal lab in Lilongwe.

3.3.3.1 Apparatus

The following apparatus were used for the determination of ash, moisture and volatile matter content and they include: muffle furnace (815^0 C), analytical balance, porcelain dishes, metal tray, desiccator, metal crucible, heat resistant tray, air oven controlled at a temperature range within 105^{0}C to 110^{0}C, Support and Silica crucibles with lids.



Figure 6. Analytical balance



Figure 7. (a) Closed muffle furnace and (b) Opened muffle furnace.

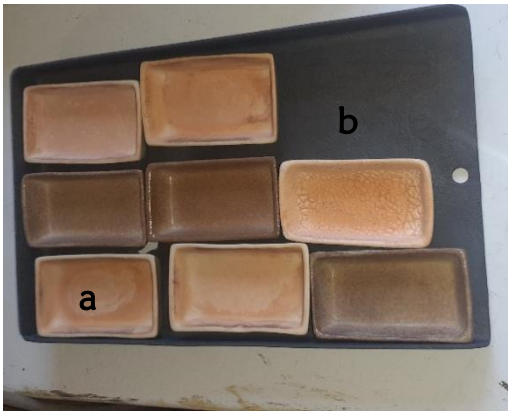


Figure 8. (a) Metal crucibles and (b) a Metal tray

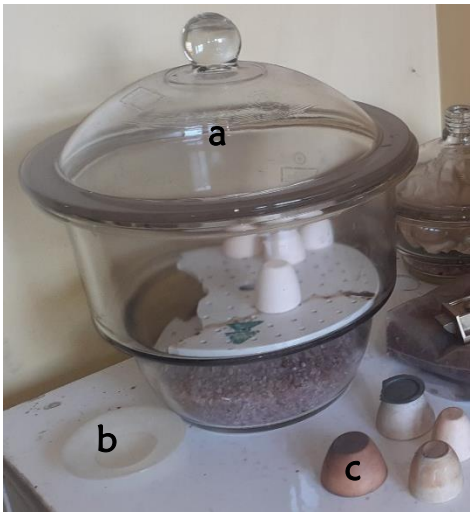


Figure 9. (a) Desiccator, (b) Lid for a silica crucible and (c) Silica crucibles

3.3.3.2 Determination of Ash Content in Coal Samples

Apparatus

Apparatus used include: muffle furnace (815^0 C), analytical balance, porcelain dishes and metal tray.

Procedure

Ash content of coal was determined using standard test method ISO 1171-1981, Method E. Firstly, the porcelain dish was weighed accurately, its weight (A) was recorded, and the balance was tared. Secondly, 1.000g of ground (less than 0.2 m) sample was weighed into the porcelain dish in duplicate and its weight (B) was recorded. Thirdly, the sample was evenly spread by shaking the crucible, and both the crucible and the sample were placed in a metal tray. Fourthly, the tray was then inserted into a muffle furnace at room temperature. Fifthly, the temperature was raised to 500^{0}C, then 600^{0}C and maintained at 600^{0}C for 20 minutes. Afterward, the temperature was raised to 700^{0}C and maintained at 700^{0}C for 20 minutes. Then the temperature was raised to 815^{0}C and the furnace was opened by clamping the handle on the hook of the wire. The red mark on the side of the furnace was observed, and the condition was maintained for 1 hr. During the sixth step, the furnace was opened after 1 hour, and it was opened very slowly. The tray was removed, and the furnace was cooled to room temperature for 1 hour. During the seventh step, the crucible and the ignited sample (C) were weighed. Then the ash percentage was calculated using the following equation:

$$\text{Ash } \% = \frac{(\text{Wt of crucible + Ignited sample - Wt of crucible} \times 100)}{\text{Wt of Sample}}$$

$$= \frac{C\text{-}A}{B} \times 100$$

Where, A= Weight of crucible

B= Weight of sample

C= Weight of crucible and ignited sample

Ash percentage on dry basis was calculated using the following formula:

$$A_{d,}(\text{dry basis}) = \frac{A\% \times 100}{100\text{-}M}$$

Where, A_d = Ash percentage on dry basis

A%= Ash percentage

M = Moisture

The results were reported to nearest 0.1%.

3.3.3.3 Determination of Total Moisture in Coal Samples

Sample preparation

The sample mass was not less than 1.2kg, the particle did not exceed 02.mm and the sample was crushed gently to less than 3mm in size.

Materials

Materials which were used include: desiccator, analytical balance, metal crucible, heat resistant tray, air oven controlled at a temperature range within 105^{0}C to 110^{0}C.

Procedure

The moisture content of coal was determined using standard test method ISO 589-1981, Method C. Firstly, a clean metal crucible was weighed and its weight (A) was recorded; the balance was then tared. Secondly, 10,000 g of the sample was weighed in the clean metal crucible in duplicate, the weight (B) of the sample was then recorded. Then the sample was spread gently by shaking the crucible. Thirdly, the weight (C) of the crucible and sample was calculated and recorded. Fourthly, the crucible was then put in a heat-resistant tray, which was then inserted in the oven. Afterward, the sample was heated in the oven for 3-6 hours until the mass was constant (constancy in mass is a change not exceeding 0.2% of the total loss in the mass during a further period of heating of greater than 12 hour). During the fifth step, after 3 hours of heating, the samples were removed and placed in a desiccator, then weighed (D) while still hot to avoid absorption of moisture when cooling. Then the sample was reheated and weighed for constant mass. The moisture percentage was calculated using the following equations:

$$M=\frac{\text{(wt of crucible + sample before heating-wt of crucible+ sample after heating)}}{\text{sample weight}}\times 100$$

Total Moisture = $\frac{(C-D)}{B}\times 100$, For a non-air dried sample

Where, B = Sample weight

C = Weight of crucible and sample before heating

D = Weight of crucible and sample after heating

Total moisture, $M_a = X+M(1-X/100)$, For an air-dried sample

Where M = Moisture percentage

X = moisture (%) lost during sample preparation

3.3.3.4 Determination of Volatile Matter Content in Coal

Apparatus

Materials which were used include: Analytical balance, Support, Silica crucibles with lids, Muffle furnace (maintained at 912^{0}C) and a metal tray.

Procedure

The volatile matter content of coal was determined using standard test method ISO 562-1981, Method E. Firstly, the sample was ground to pass through a 0.2-meter aperture. Secondly, the support, crucible, and lid were weighed on the balance, and the weight of the crucible (A) was recorded and the balance was tared. Thirdly, 1.000 g of the ground sample was weighed into the crucible in duplicate, and the weight of the sample (B) was recorded. Then the sample was spread gently by shaking the crucible, its cover was inserted, and the crucible, together with the sample, was put in a perforated metal tray. Fourthly, the total weight (C) of the crucible, lid, support, and sample was calculated. During the fifth step, the tray was charged with crucible and was quickly put in a furnace, which was immediately closed. During the sixth step, the sample was left in the furnace for 7 minutes

when the temperature had reached 912 ^{0}C. During the seventh step, the tray was quickly removed and cooled at room temperature for 50 minutes. During the eighth step, the support, crucible with lid, and sample were weighed, and the weight (D) was recorded.

The results were calculated by using the following equations:

$$\text{Volatile matter} = \frac{(C-D)\times 100}{B}$$

Where, B = Sample weight

C = Weight of crucible and sample before heating

D = Weight of crucible and sample after heating

Volatile matter percentage on dry basis was calculated using the following formula:

$$V \text{ (on dry basis)} = \frac{\%V_w \times 100}{100-M}$$

Where, V_w= Volatile matter percentage on wet basis

M= Moisture percentage

Volatile matter percentage on dry ash free basis was calculated using the following formula:

$$V \text{ (on dry ash free basis)} = V_{\text{dry basis}} \times \frac{100}{100-A}$$

Where, $V_{\text{dry basis}}$ = Volatile matter percentage on dry basis

A = Ash percentage

Calculations for volatile matter percentage on dry ash free basis has been shown in **Appendix B**

3.3.3.5 Determination of Fixed carbon content

Fixed carbon is the amount left after evaporation of the volatile material, moisture and ash (Kumar et al., 2015). Fixed carbon of the samples was determined by using the following formula;

$$FC = 100\% - (Ash + M + VM)$$

Where, FC= Fixed Carbon percentage

Ash= Ash content percentage

M= Moisture content percentage

VM= Volatile Matter content percentage

Fixed carbon percentage on dry ash free basis was calculated using the following formula:

$$FC \text{ (on dry ash free basis)} = FC_{\text{dry basis}} \times \frac{100}{100\text{-}A}$$

Where, $FC_{\text{dry basis}}$ = Fixed carbon percentage on dry basis

A = Ash percentage

Calculations for both fixed carbon and fixed carbon on dry ash free basis has been shown in **Appendix C.**

3.3.4 Estimation of Methane Content

The methane content was estimated by using Meisner's (1984) equation, which explains that the amount of methane gas (V_{CH4}) is related to volatile matter on dry ash free basis. Calculations for estimated methane content has been shown in **Appendix D**, and the Meisner's (1984) equation that was used for the estimation is as follows:

$$V_{CH4} = -325.6 \times \log\left(\frac{VM}{37.8}\right)$$

3.3.5 Calculation of Vitrinite Reflectance

The vitrinite reflectance (Ro%) was calculated using the formula given by Rice (1993), the calculations have been shown in **Appendix D**, and the formula which was used is as follows:

$$Ro\% = -2.712 \times \log(VM) + 5.092.$$

The application of this formula is restricted to a particular range of Volatile Matter percentage and the range that is applicable is: 15% < VM < 40% (Rice 1993). The VM% of the coal samples of Mchenga Coal Mine are within this limit, hence the Rice formula was applicable.

3.3.6 Determination of Coal Rank

Volatile matter on dry ash free basis and the calculated vitrinite reflectance values of the four coal samples were used to determine the coal rank of the area. This was done by using the coal rank classification table by (Teichmüller, 1982) and (Diessel, 1992) displayed in **Appendix A**.

3.4 Data Analysis

The data was analyzed by using Microsoft excel software, where regression analysis was used to estimate the relationship and show correlation between the dependent variable (estimated methane content) and the independent variables (moisture, fixed carbon, volatile matter content and vitrinite reflectance values).

Regression analysis incorporated the use of a linear regression model and a scatter plot. Regression model was used to describe the relationship between dependent and independent variables and also estimate the magnitude of change in the dependent variable due to changes in the independent variable.

Scatter plot was used to show how closely related the two variables are, and also the trend and pattern between the independent variable and dependent variables. This led to the creation of charts where the relationship between the variables was clearly shown.

3.5 Study Limitations and their Solutions

Despite the successful completion of the research project, there was a limitation that was encountered. The limitation was limited information in the research data. This study used secondary data, and the data that was provided was not broad, but rather mainly centered on the proximate composition of the four coal samples from Mchenga coal mine. However, this was solved by comprehensively checking and studying the current literature about the studies that were carried out at Mchenga coal mine. This assisted in getting some of the information that was not included in the research data that was given.

CHAPTER 4: RESULTS & DISCUSSION

The potential of coal from Mchenga coal mine to generate coal-bed methane gas was assessed by using proximate analysis data of four coal samples. After the proximate data was analyzed, tables and charts were used to display and interpret the data that was used, together with the correlations between the parameters.

4.1 Coal Quality Analysis

At Mchenga coal mine, the coal samples were taken from an average working depth of **150m**. The value for each of the weight percentages of the components of moisture, ash, volatile matter, and fixed carbon in the coal samples has been presented in **Table 2** below.

Table 2. Proximate analysis data of the four coal samples

Sample	Description	Ash	Moisture	FC	FC (daf)	VM	VM (daf)
Ny20576_1	Middle coal seam + Py + Ash	52.3	2.3	28.7	60.2	16.7	35.0
Ny20576_2	Middle coal seam	21.4	2.1	43.8	55.7	32.7	40.0
Ny20583_2	Upper coal seam (abandoned)	18	1.5	49.8	60.7	30.7	37.4
Ny20584_1	Middle coal seam (abandoned)	7.8	1.3	58.2	63.1	32.7	35.5

As shown in **Table 2** above, ash content percentage ranges from 7.8 to 52.3, moisture content percentage ranges from 1.3 to 2.3, fixed carbon content ranges from 28.7 to 58.2, volatile matter content percentage ranges from 16.7 to 32.7, volatile matter content percentage on dry ash free ranges 35.0 to 40.0 and fixed carbon content percentage on dry ash free basis ranges from 55.7 to 63.1. The volatile matter and fixed carbon percentage

on dry ash free basis was calculated in order to prevent the impact of moisture and ash on the volatile matter and fixed carbon weight percentages.

Based on the data shown in **Table 2** above, it is observed that the coal samples have high ash, fixed carbon and volatile matter content. On the other hand, moisture content is noticeably very low in all coal samples. In addition to that, ash content is different between coal seams, and the coal seam (middle coal seam + Py + Ash) with high ash content has low volatile matter and fixed carbon content. Similar trend was also observed in a study conducted by Pal et al., in 2015, where it was observed that an increase in ash content resulted in a decrease in volatile matter and fixed carbon content.

In addition, according to Meissner's equation, any coal having volatile matter that exceeds 37.8% should generate no methane at all (Talukdar et al., 2015). All the four coal samples that were used from Mchenga coal mine have volatile matter values within the range of 16.7 to 32.7%, hence this suggests that they have the potential to generate methane gas.

Using the values of volatile matter content on dry ash free basis, both the vitrinite reflectance percentage and methane content of each of the four coal samples was calculated and estimated respectively. **Table 3** below shows the calculated and estimated values.

Table 3. Vitrinite reflectance and estimated methane content values

Sample	Volatile Matter (daf)	Vitrinite Reflectance (R_o %)	Estimated CH_4 Content (cm^3/gm)
Ny20576_1	35.0	0.9	10.9
Ny20576_2	40.0	0.7	-8.5
Ny20583_2	37.4	0.8	1.5
Ny20584_1	35.5	0.9	8.9

The vitrinite reflectance values were calculated using the equation given by Rice (1993), where the volatile matter and vitrinite reflectance are correlated. As indicated by **Table 3** above, the vitrinite reflectance percentage ranges from 0.7 to 0.9. The volume of methane estimates of the total amount of methane generated was calculated by using Meissner's equation, and as indicated by **Table 3**, the values range from -8.5 cm^3/gm to 10.9 cm^3/gm. Based on results shown in **Table 3** above, the coal seam with low volatile matter content on dry ash free basis has high vitrinite reflectance percentage value and a high estimated methane value.

Commercial coalbed methane generating coals have values of vitrinite reflectance between 0.7 to 2.0 (K. . Singh, 2010). The vitrinite reflectance values of the coals under study are within this range. This suggests that the coal under study has the potential to generate coalbed methane. In addition to that, 8.5 cm^3/gm of methane is the minimum amount required for commercial-grade coal for coal-bed methane (K. . Singh, 2010). This also suggests that the coal seams from which coal sample Ny20576_1 and Ny20584_1 was taken from, contains the commercial-grade coal for coal-bed methane.

4.2 Rank of Coal Under Study

Coal rank was determined by using the value of vitrinite reflectance and volatile matter on dry ash free basis. Based on the value of vitrinite reflectance (Ro %) in **Table 3** and volatile matter on dry ash free basis in **Table 2**, the coal samples under study belong to subbituminous coal rank. Under subbituminous coal rank, the coal samples belong to A and B subclass. This is according to Mastalerz et al., (2011), where the coal rank classification table by (Teichmüller, 1982) and (Diessel, 1992) displayed in **Appendix A**, indicates that vitrinite reflectance values within the range of 0.7 to 0.9 and volatile matter content percentage on dry ash free basis within the range of 35.0 to 40 corresponds to subbituminous coal rank, of A and B sub class.

Another study conducted at Mchenga coal mine by Maneya in 2012, also found that the coal rank of coal from the study area belong to sub-bituminous coals. Subbituminous coal rank is the rank where the initial stages of methane gas generation takes place and this was established by Gao et al., in 2014. However, the methane gas generated is not in large quantities compared to the other high ranks (Gao et al., 2014).

4.3 Correlation Between Gas content and Proximate Composition of Coal

The potential of coal to generate, accumulate and store coalbed methane gas is influenced by a number of parameters. Some of the basic parameters include: moisture content, ash content, fixed carbon content, volatile matter content and vitrinite reflectance (K. . Singh, 2010). In this study, the proximate parameters of the four coal samples from Mchenga coal mine were correlated with estimated methane content to determine the effect of these parameters on methane gas in coal and check if these parameters are suitable for coalbed methane generation and preservation. The correlation of different proximate parameters of coal with gas content was established using statistical methods as shown in **Charts 1,2,3,4,5** and **6** and their interpretations have also been made.

4.3.1 The Effect of Moisture Content on Coal-bed Methane Gas.

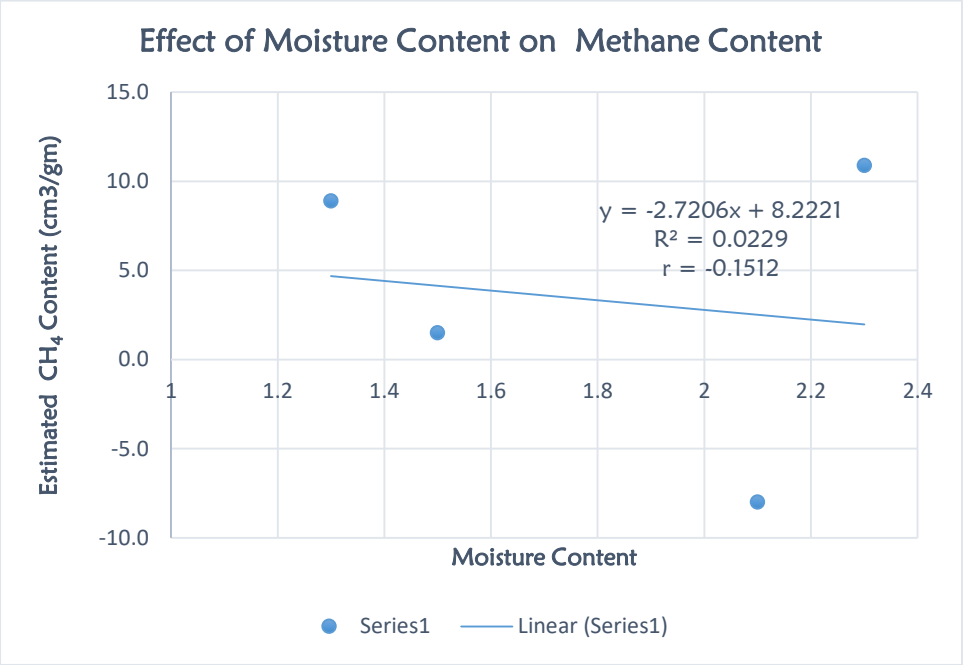


Chart 1. Effect of Moisture on Methane Gas Content.

Chart 1 shows the effect of moisture content on methane gas content within the coal seam. The correlation coefficient (r) as indicated by the chart is -0.1512 and this shows that there is a negative correlation between the variables, as such an increase in the moisture content is resulting in a decrease in the estimated methane content. The coefficient of determination (R^2) is 0.0229 as indicated by the chart above. This shows that 0% of the variations in estimated methane gas content are being influenced by variations in moisture content. Hence, the moisture content within the coal seam has little effect on the methane gas.

This type of moisture is the natural intrinsic moisture, and the capacity at which coal adsorbs the gas into its matrix is dependent on this type of moisture, such that the adsorption capacity of coal decreases with an increase in moisture content (Chen et al., 2018). As a result of the decrease in adsorption capacity, less amount of gas is stored.

The negative correlation between moisture content and estimated methane content indicated by **Chart 1**, agrees with the observation made by Ojha et al.,in 2011 where it was found that 1% and 5% of moisture content in coal reduced the adsorption capacity by 25% and 65%, respectively. Hence, an increase in moisture content led to a decrease in the amount of methane gas content stored within coal.

4.3.2 The Effect of Volatile Matter on Coal-bed Methane Gas.

The volume of the methane gas generated within coal is related to the volatile material of the coal. When showing the effect of volatile matter on coal-bed methane gas, volatile matter on dry ash free basis was also used. The effect of volatile matter on coalbed methane gas has been indicated in **Chart 2** below.

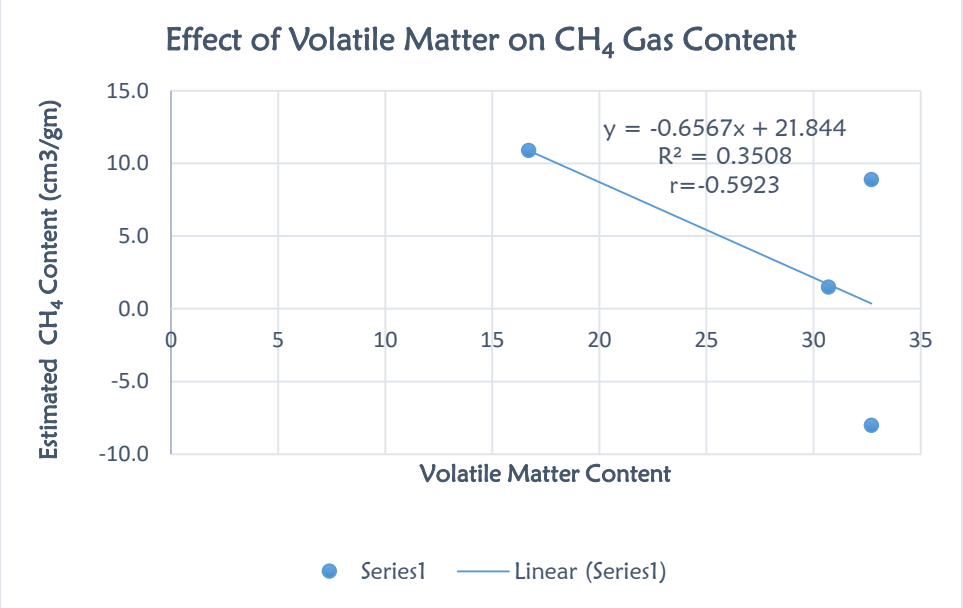


Chart 2. Effect of Volatile Matter on Methane Gas Content

Chart 2 shows the effect that volatile matter has on methane gas content within the coal seam. The correlation coefficient (r) as indicated by the chart is -0.5923 and this shows that there is a negative correlation between the variables, as such a decrease in the volatile matter content is resulting in an increase in the methane gas content within the coal. The

coefficient of determination (R^2) is 0.3508 as indicated by the chart above. This shows that 35% of the variations in estimated methane content is being influenced by variations in volatile matter content within the coal seam. Similar observations were also made by Cheng et al., in 2017, where it was concluded that gas content increases with decreasing volatile matter. Based on **Chart 2** above, volatile matter has a small effect on methane gas content in coal.

In order to avoid the effect of moisture and ash on volatile matter, the volatile matter on dry ash free basis was also used. The effect of volatile matter on dry ash free basis on coalbed methane gas has been indicated in **Chart 3** below.

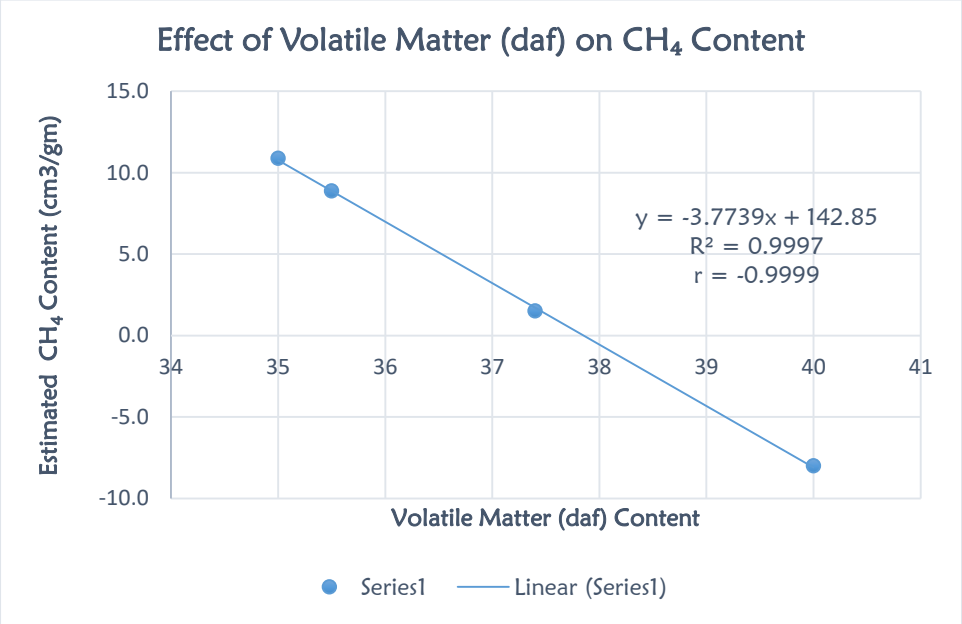


Chart 3. Effect of Volatile Matter (daf) on Methane Gas Content.

Chart 3 above shows the effect that volatile matter on dry ash free basis has on methane gas content within a coal seam. The correlation coefficient (r) as indicated by the chart is -0.9999 and this shows that there is a perfect negative correlation between the variables, as such a decrease in the volatile matter content is resulting in an increase in the methane content. This is so because, when the volatile matter content of coal gradually decreases,

more space is created for methane gas in the coal matrix such that methane adsorbs itself in the empty space and this is used to indicate the potential of the coal seam to generate coal bed methane gas (Banik, 2020).

The coefficient of determination (R^2) is 0.997 as indicated by the chart above. This shows that 99.7% of the variations in estimated methane content is being influenced by variations in volatile matter content on dry ash free basis within the coal seam. Similar observation was also made by Kumar et al., in 2015, where it was found that gas content in coal increases with decreasing volatile matter on dry ash free basis. Based on **Chart 3** above, volatile matter on dry ash free basis has a greater effect on methane gas content in coal.

4.3.3 The Effect of Fixed Carbon Content on Coal-bed Methane Gas

When showing the effect of fixed carbon on coal-bed methane gas, fixed carbon on dry ash free basis was also used. The effect of fixed carbon on coalbed methane gas has been indicated in **Chart 4** below.

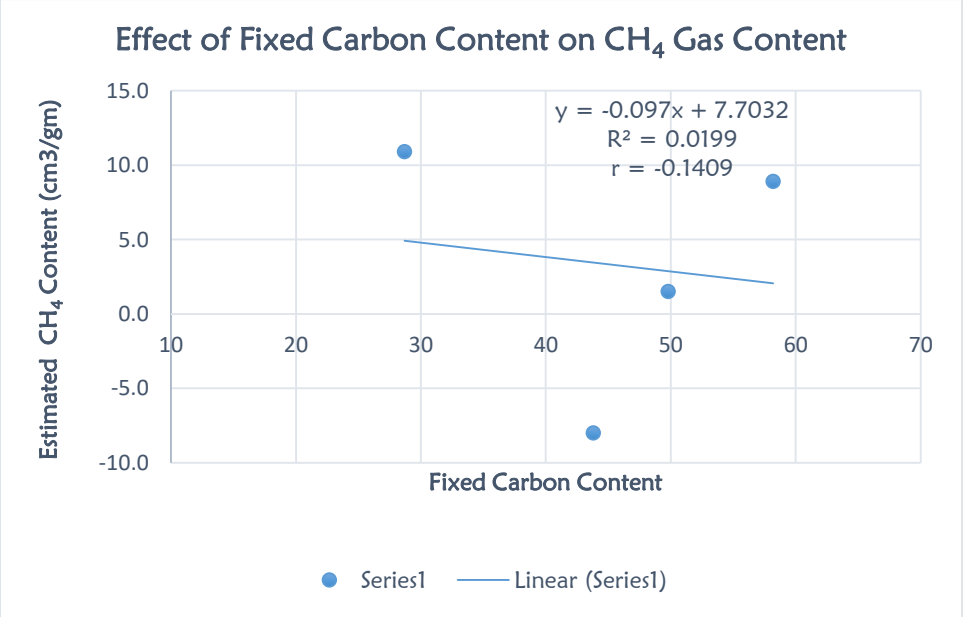


Chart 4. Effect of Fixed Carbon Content on Methane Gas Content

Chart 4 above is showing the effect of fixed carbon content within the coal seam on methane gas content. The correlation coefficient (r) as indicated by the chart 4 above is -0.1409 and this shows that there is a negative correlation between the variables, such that as the fixed carbon content is increasing, the estimated methane content within the coal seam is decreasing. The coefficient of determination (R^2) is 0.0199 as indicated by **Chart 4** above. This also indicates that 0% of the variations of estimated methane gas content are being influenced by variations in fixed carbon content. Hence based on **Chart 4** fixed carbon has a very small effect on the amount of methane found in the coal.

However, this observation contradicts with the observation that was made by Banik, in 2020 which explained that an increase in fixed carbon content results in an increase in the amount of coal bed methane gas. This is so because, fixed carbon is mostly made up of carbon elements, a small amount of hydrogen, sulfur, oxygen, and nitrogen, and an increase in fixed carbon content indicates an increase depth. Therefore, when depth increases, coals' carbon content progressively increases, which causes methane content to gradually increase as well, and thermal maturation of coal is also improved (Cheng et al., 2017)

In this study fixed carbon on dry ash free basis was also used in order to avoid the effect of moisture and ash on fixed carbon weight percentage. The effect of fixed carbon on dry ash free basis on coal-bed methane gas has been indicated in **Chart 5** below.

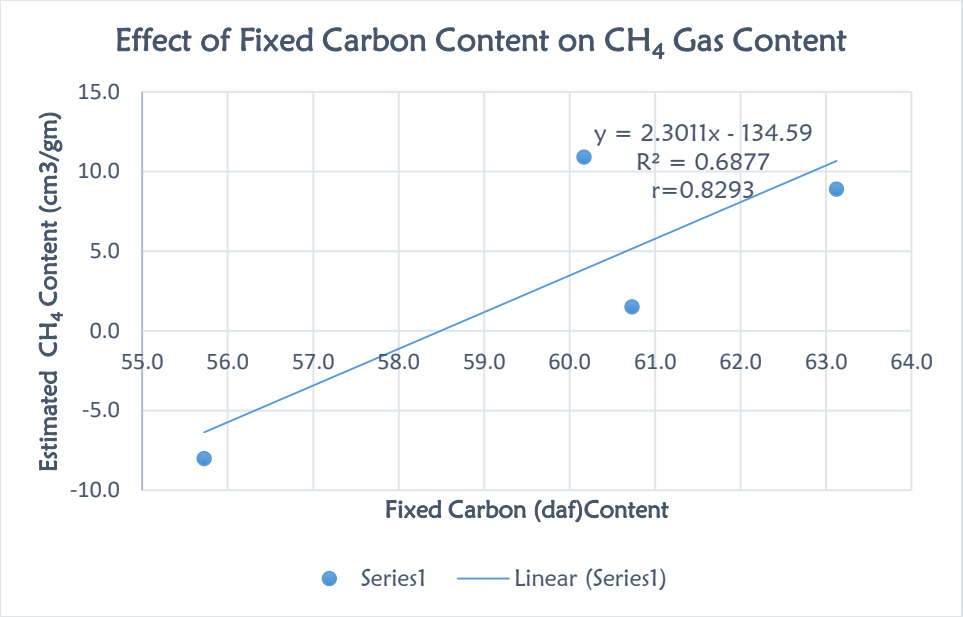


Chart 5. Effect of Fixed Carbon (daf) on Methane Gas Content

Chart 5 above is showing the effect of fixed carbon content on dry ash free basis(daf) within the coal seam on methane gas content. The correlation coefficient (r) as indicated by the chart 1 above is 0.8293 and this shows that there is a positive correlation between the variables, such that an increase in fixed carbon content, is resulting in an increase in the estimated methane content. Similar observation was also made by Kumar & Mishra, in 2019 and Ghosh et al., in 2010, where a positive linear correlation between fixed carbon content (dry ash free basis) and methane gas content in coal was obtained and established respectively.

The coefficient of determination (R^2) is 0.6877 as indicated by **Chart 5** above. This indicates that 69% of the variations of estimated methane gas content is being influenced by variations in fixed carbon content. Hence based on **Chart 5**, fixed carbon has a greater effect on the amount of methane found in the coal.

4.3.4 The Effect of Vitrinite Reflectance on Coalbed Methane Gas.

Vitrinite reflectance is one the most important parameter in determining coalbed methane potentiality of a coal mine. The typical range of maturity for commercial coalbed methane varies between 0.7 to 2.0% (K. . Singh, 2010). Since the vitrinite reflectance values of the four coal samples is within the range 0.7 to 0.9%, it suggests that the coal may have the potential for coalbed methane gas. In this study, estimated methane gas content was correlated with vitrinite reflectance in **Chart 6** below.

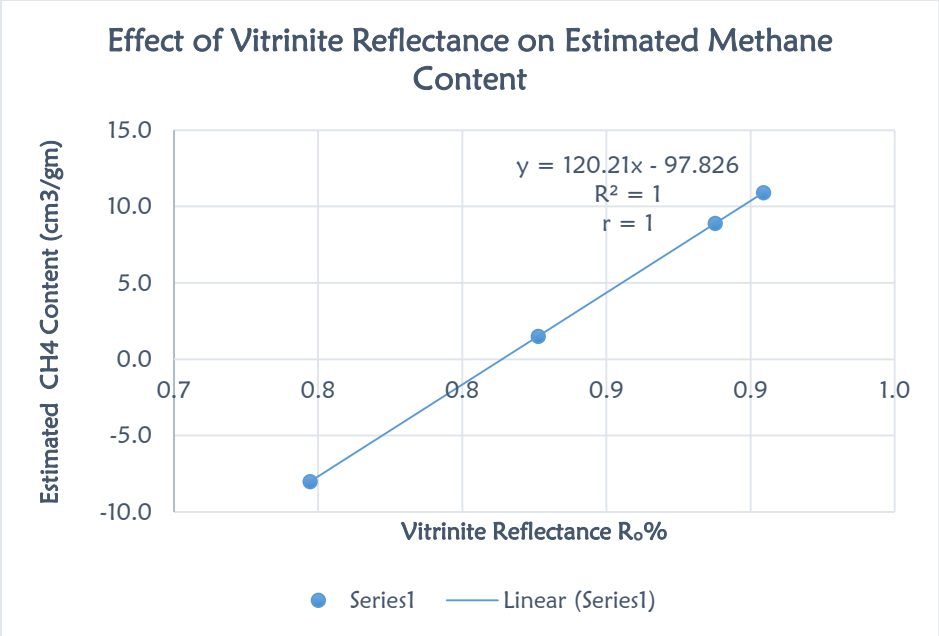


Chart 6. The Effect of Vitrinite Reflectance on Methane Gas Content.

Chart 6 above is simply showing the effect of vitrinite reflectance on methane gas content within the coal seam. The correlation coefficient (r) as indicated by **Chart 6** above is 1 and this shows that there is a perfect positive correlation between the variables, such that an increase in vitrinite reflectance, is resulting in an increase in the methane content. Similar observation was also made by Panwar et al., in 2017 and Pophare et al., in 2008, where they observed that an increase in vitrinite reflectance resulted in an increase in the methane gas content.

The coefficient of determination (R^2) is 1 as indicated by **Chart 6** above. This shows that 100% of the variations in estimated methane content is being influenced by variations in vitrinite reflectance. Therefore, based on **Chart 6** above vitrinite reflectance has a greater effect on estimated methane content within the coal seam.

4.4 Strength of Research Project

One of the research studies that was carried out at Mchenga coal mine by G. Maneya, in 2012, found that coal from the area belong to sub-bituminous coal rank. However, assessing the potential of coal from the study area for coalbed methane generation was not part of the objectives of the study, thereby leaving a gap which has been addressed in this study. Furthermore, according to Umali et al., (2016), the calorific values of most coal samples analyzed by the coal analysis laboratory of the Geological Survey Department in Lilongwe show that most coal in Malawi is predominantly sub-bituminous in rank. This observation corresponds to the observation made in this research study, where by based on the results and their analysis, it was suggested that the coal samples from the study area belong to subbituminous coal rank. The determination of the coal rank assisted in determining the stage at which the methane gas is being generated within the coal and also estimate the quantity of methane being generated.

CHAPTER 5: CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

In this study, coal seams at the Mchenga coal mine were assessed to determine their coal-bed methane generation potential. This was done by using proximate analysis data, where the moisture, ash, volatile matter, and fixed carbon content of four coal samples from varying coal seams was used. The coal quality of the samples is characterized by low moisture content, and high ash, volatile matter, and fixed carbon content. Volatile matter on a dry ash-free basis was used to estimate the methane content and calculate the vitrinite reflectance of the coal seams from which each of the four coal samples was extracted from. The average amount of estimated methane in the coal seams is 12.8cm^3/gm. Furthermore, when the estimated methane content was correlated with the proximate data parameters, a higher percentage of fixed carbon content on dry ash free basis and vitrinite reflectance, reflected more methane in the coal, whereas a higher percentage of volatile matter both on dry basis and dry ash free basis, and fixed carbon content on dry basis reflected less methane in the coal. In addition, based on the value of vitrinite reflectance and volatile matter on a dry ash free basis, it was suggested that the coal in the study area has the potential to generate coal bed methane gas, and the coal samples under study belong to the sub-bituminous coal rank. However, since the coal rank is sub-bituminous, the generation of methane gas is in the early stages. Significantly, this research will play an important role in gas disaster prevention in the coal mine. This is so because, the presence of methane gas in a coal mine creates a risk of explosion, hence this study will help the mine authorities to come up with appropriate mitigation measures for the mine against gas disaster explosions caused by the presence of methane gas in a coal mine.

5.2 Recommendations

Based on results from this research, it was suggested that the coal seams at the study have the potential to generate coal-bed methane gas. However, the generation of the gas is in its early stages, and due to that it is recommended that further exploration and analysis of

coal-bed methane gas should be carried out for the study area in order to determine if the reserves of the methane gas that can recovered is economical, and also determine the production feasibility of the gas.

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APPENDICES

Appendix A: Coal Rank Classification Table

Table 4. The maximum value of rank parameters (after Diessel, 1992) with further subdivisions of lower rank coals after Teichmüller (in Stach et al., 1982).

					Vitrinite reflectance (%) (Oil, 546 nm) (Teichmüller, 1982)		Vitrinite reflectance (%) (Oil, 546 nm) (Diessel, 1992)	
Rank stage	Carbon (daf) (%)	Volatile matter (daf) (%)	Gross-specific energy (MJ/kg)	In situ moisture (%)	R_{random}	R_{max}	Rank subclass	R_{random}
Wood	50	>65						
Peat	60	>60	14.7	75	0.20	0.20		0.26
Lignite	71	52	23	30	0.40	0.42		0.38
Subbituminous	80	40	33.5	5	0.60	0.63	C	0.42
							B	0.49
							A	0.65
High volatile bituminous	86	31	35.6	3	0.97	1.03	C	0.65

							B	0.79
							A	1.11
Medium volatile bitum0inous	90	22	36	<1	1.47	1.58		1.50
Low volatile bituminous	91	14	36.4	1	1.85	1.97		1.92
Semi anthracite	92	8	36	1	2.65	2.83		2.58
Anthracite	95	2	35.2	2	6.55	7.00		5.00

Source: spontaneous combustion and coal petrology

Appendix B: Calculations of VM(daf)

Equations that were used are as follows:

$$V \text{ (on dry ash free basis)} = V_{\text{dry basis}} \times \frac{100}{100\text{-}A}$$

The following table contains the calculations.

Table 5. Calculations of VM(daf)

Sample	Ash	VM	VM (daf)
Ny20576_1	52.3	16.7	$=16.7 \times \frac{100}{100\text{-}52.3}$ $= 35.0$
Ny20576_2	21.4	32.7	$=32.7 \times \frac{100}{100\text{-}21.4}$ $=40.0$
Ny20583_2	18	30.7	$=30.7 \times \frac{100}{100\text{-}18}$ $=37.4$
Ny20584_1	7.8	32.7	$=32.7 \times \frac{100}{100\text{-}7.8}$ $=35.5$

Appendix C: Calculations of FC and FC(daf)

Equations that were used are as follows:

$$FC = 100\% - (Ash + M + VM)$$

$$FC\ (\text{on dry ash free basis}) = FC_{\text{dry basis}} \times \frac{100}{100\text{-}A}$$

The following table contains the calculations.

Table 6. Calculations of FC and FC(daf)

Sample	FC	FC (daf)
Ny20576_1	= 100 – (52.3 + 2.3 + 16.7) = 28.7	$= 28.7 \times \frac{100}{100\text{-}52.3}$ = 60.2
Ny20576_2	= 100 – (21.4 + 2.1 + 32.7) = 43.8	$= 43.8 \times \frac{100}{100\text{-}21.4}$ = 55.7
Ny20583_2	= 100 – (18 + 1.5 + 30.7) = 49.8	$= 49.8 \times \frac{100}{100\text{-}18}$ = 60.7
Ny20584_1	= 100 – (7.8 + 1.3 + 32.7) = 58.2	$= 58.2 \times \frac{100}{100\text{-}7.8}$ = 63.1

Appendix D: Calculations of Estimated Methane (V_{CH4}) and Vitrine Reflectance (R_O%)

Equations used are as follows:

$$V_{CH4} = -325.6 \times \log\left(\frac{VM}{37.8}\right)$$

Ro% =-2.712×log(VM)+5.092.

The following table contains the calculations.

Table 7. Calculations of Estimated methane (V_{CH4}) and Vitrinite Reflectance (R_0%)

Sample	VM (daf)	Estimated CH_4 Content (cm^3/gm)	Vitrinite Reflectance (R_O %)
Ny20576_1	35.0	$V_{CH4} = -325.6 \times \log\left(\frac{35.0}{37.8}\right)$ = 10.9	Ro% =-2.712×log(35.0)+5.092. = 0.9
Ny20576_2	40.0	$V_{CH4} = -325.6 \times \log\left(\frac{40.0}{37.8}\right)$ = -8.5	Ro% =-2.712×log(40.0)+5.092. = 0.7
Ny20583_2	37.4	$V_{CH4} = -325.6 \times \log\left(\frac{37.4}{37.8}\right)$ = 1.5	Ro% =-2.712×log(37.4)+5.092. = 0.8
Ny20584_1	35.5	$V_{CH4} = -325.6 \times \log\left(\frac{35.5}{37.8}\right)$ =8.9	Ro% =-2.712×log(35.5)+5.092. =0.9