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Petroleum potential from Permian-Triassic strata of the Maniamba Basin, Mozambique: A preliminary characterisation

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Abstract

In order to further our understanding regarding the petroleum potential of the Maniamba Basin, Mozambique, organic rich sediments from four outcrops were investigated. Organic-rich shales, claystones, sandstones and siltstones were sampled for geochemical organic analyses that included Total Organic Carbon (TOC), and Rock Eval Pyrolysis. The pyrolysis analysis showed that the TOC ranges from good to excellent, thus indicating a potential for hydrocarbon generation. Based on the hydrogen index (HI) versus oxygen index (OI) diagram, most samples were classified as kerogen type III or IV, however, a mixed type II and III was also observed. These data suggest that the Organic Matter (OM) is of terrigenous origin with the occurrence of organofacies C, CD and D. The majority of the studied samples are found to be at mature to overmature stages. The overmaturation of the OM may be associated with tectonic events during the process of basin subsidence, and close proximity to igneous intrusions. Further, an indigenous nature of

the hydrocarbon has been identified. Similar organic matter properties of the studied sections are correlatable with those from Moatize Minjova, Sanangoé-Mefidezi (Mozambique), Ruhuhu (Tanzania) and the Main Karoo Basin in South Africa. Overall, the results of this study suggest a good potential for gas.

Introduction

Organic geochemistry is an important tool to evaluate the hydrocarbon potential of rocks (Van Krevelen, 1993; Hao et al., 2011) using, for instance, the Pyrolysis Rock Eval. The Rock Eval Pyrolysis is the most common and routinely used method in the petroleum industry providing inputs regarding the content, origin and maturity of Organic Matter (OM) in the rocks (Espitalie et al., 1977; Lafargue and Pillot, 1998; Shalaby et al., 2020; Qin et al., 2021).

In Mozambique, organic geochemistry studies on dispersed OM are mostly restricted to the southern portion of the country and concern primarily Mesozoic and Cenozoic rocks [(e.g., the Paleogene Cheringoma Formation, and turbidites and shales in the Senonian to Paleocene Grudja Formation (Kihle,1983)]. For the Palaeozoic, recent studies by Mussa et al. (2018) using organic-rich shales from the Nemo-1x well, reported the existence of kerogen type III (gas-prone) and IV (non-productive or residual) for the samples studied from the Mozambique Basin. Another detailed geochemical study was performed by Loegering and Milkov (2017), using data provided by SASOL from Inhassoro, Pande and Temane fields, where a pure thermogenic gas with no evidence of primary microbial or biodegradation was found. Some other reports from sites apart from the Maniamba Basin do exist, but they are part of internal reports of oil companies (Lineback et al., 1986; Salman et al., 1990; ECL, 2000).

Permian fine to coarse-grained sandstones, siltstones, shales and highly carbonaceous shales of four outcrops from the Maniamba Basin, Mozambique are investigated for their petroleum potential herein. The Maniamba Basin is one of the best-known basins in Mozambique extending over an area of 8 000 000 km^2 and comprising Precambrian to Recent sedimentary deposits (Figure 1). This basin has been regarded as a potential area for gas exploration by ECL (2000) because its OM is assumed to be of a terrigenous origin; however, no survey regarding OM content and the petroleum generation potential have been done so far (ECL, 2000). Coal quality studies and related research, however, has been reported (JOGMEC, 2015).

This study represents the first of its nature being undertaken in the Maniamba Basin, which will become useful for a better understanding of the source rock quality, type of kerogen, source rock maturation and migration thus, assisting in identifying future exploration targets.

Geological setting

The Metangula Graben (Figures 1 and 2) is subdivided into the following groups: Lower Karoo, Middle and Upper Karoo. The most comprehensive study of the Metangula sediments was done by Jacques Verniers and colleagues from the "Brigadas de Cartografia Geológica da Bacia Carbonífera de Metangula" from 1977 to 1980. According to Verniers et al. (1989), the stratigraphy of the Maniamba Basin consists of Lower Karoo, which includes the K2, K3 and K4 formations. The Middle Karoo comprises two units, the K5 and K6 formations and the Upper Karoo consists of five units, KSa, KSb, KSc, KSd and KSe (Figures 1 and 2). The investigated outcrops in this study named Luchai and Nhamago, lie within the K4 Formation. The K4 Formation (Lower Permian) consists of coal seams, carbonaceous intercalations and green-grey sandy siltstone. The palaeobotanical record is represented by *Glossopteris* leaves assigned to three different species: *Glossopteris ampla*, *G. browniana* and *G. indica* (Verniers et al., 1989). The thickness of this formation varies from 171 m to 186 m. The Michunwa outcrop belongs to the Middle Permian K6 Formation that is divided into four members which are K6a1, K6a2, K6a3 at the base and K6b at the top. A Permian age of the K6 Formation has been interpreted based on the presence of *Glossopteris* leaves and vertebrate fossils. These fossil bones consist of fragmented skeletal and cranial elements of therapsids with a black colour (Araújo et al., 2020). Finally, the Luiga site is positioned in the KSb Formation. The KSb Formation (Middle Triassic) overlies the Mount Lilonga Formation (KSa, Early Triassic) conformably (Araújo et al., 2020). The lithology of the Fubué Formation (KSb, Middle Triassic) consists of coarse-grained conglomeratic sandstones. The deposition of this unit seems to have occurred under braided river system (Verniers et al., 1989). Typically, the thickness of the formation is up to 200 m.

Materials and methods

Sampling

Fifteen samples were obtained from four outcrops in the Maniamba Basin during a field campaign in 2021. The sampling sites was Luiga, Michunwa, Luchai and Nhamago (Figures 3 to 4). For each outcrop 1 kg of samples were collected through a horizontal excavation on the walls of the outcrop in order to avoid weathered and oxidised surfaces. The most preferable sampled rocks were fine-grained siltstone, carbonaceous shale, sandstone and claystone because these are the ones with potential for OM preservation. The samples were then submitted to pyrolysis rock eval at the Universidade Federal do Rio Grande Sul (Brazil).

Pyrolysis rock eval analysis

The detailed geochemical analyses of the outcrop samples were carried out at the Núcleo de Estudos de Carvão e Rocha Geradora de Petróleo, Institute of Geosciences, Universidade Federal do Rio Grande do Sul. Samples were sieved to pass mesh of 9 and 16µm and taken for Wildcat Technologies' HAWK Pyrolysis and Total Organic Carbon (TOC) analyses. Rock Eval pyrolysis consists of heating the samples at elevated and programmed temperatures in an inert atmosphere (helium) in

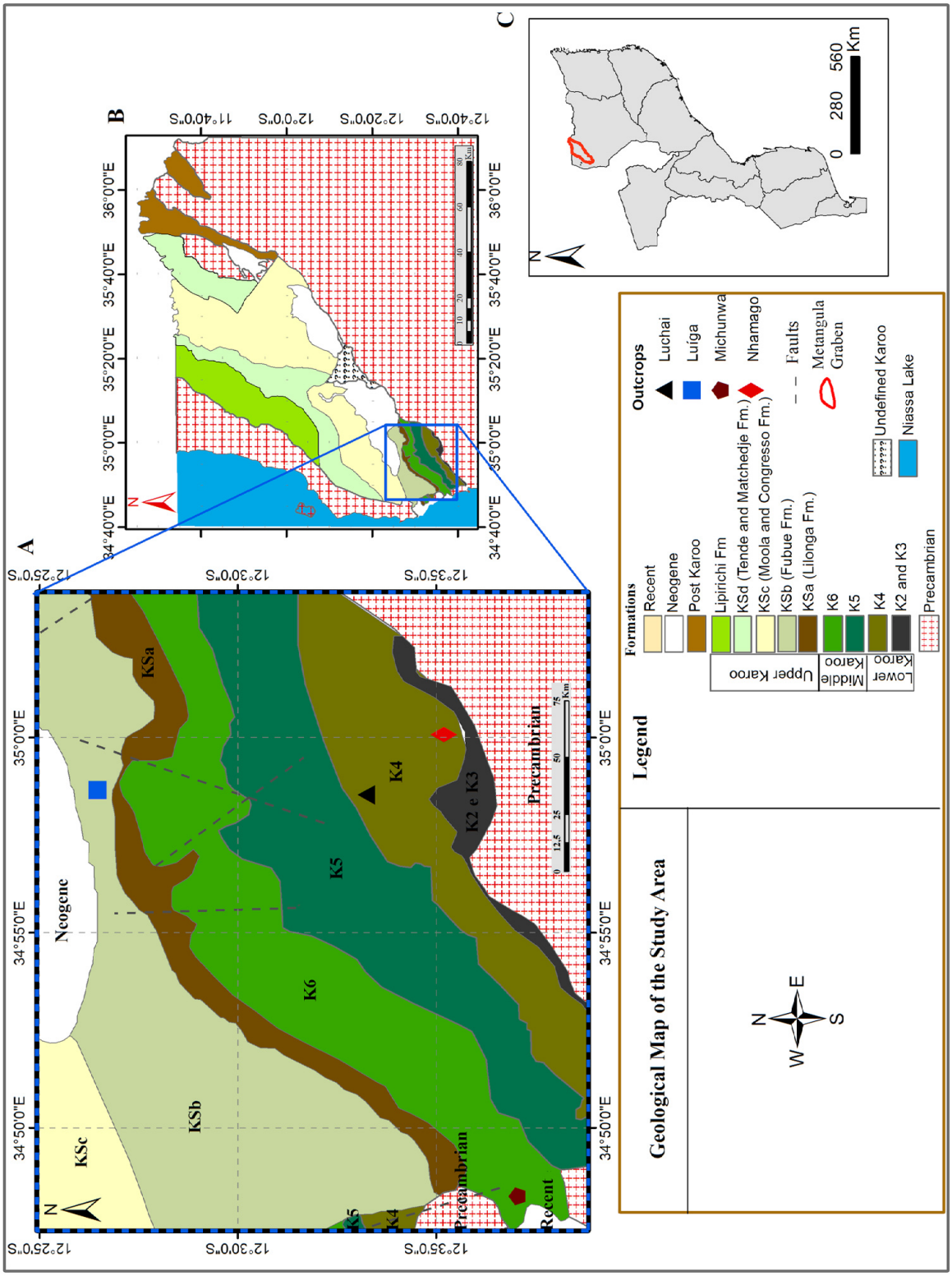


Figure 1. *Three map illustrations of the Maniamba Basin with* ***(A)*** *Detailed map of the Maniamba Basin showing the location of the outcrops,* ***(B)*** *General Map of the Maniamba Basin (the rectangle represents an overview of the geological formations studied in the present work),* ***(C)*** *Map of Mozambique with the red polygon in the northern part representing the location of the Maniamba Basin. Maps (A) and (B) were both adapted from Verniers et al. (1989).*

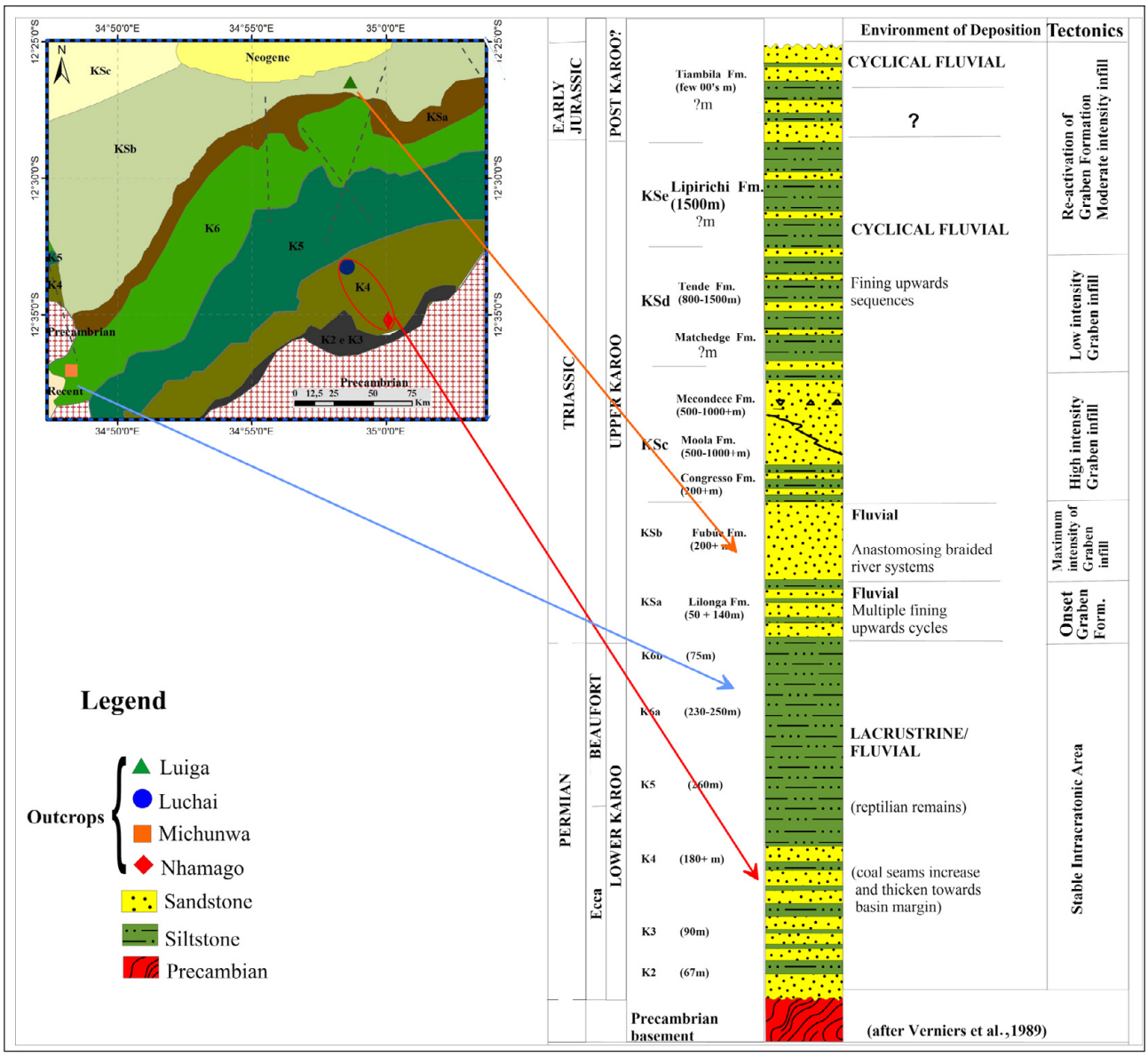


Figure 2. *Stratigraphic column showing the lithostratigraphy and palaeoenvironments of the Maniamba Basin adapted from Verniers et al. (1989) and ECL (2000).*

order to determine the type of kerogen, thermal maturity, and the transformation of the OM into petroleum and natural gas (Espitalié et al., 1977; Tissot and Welte, 1984).

For analysis on the HAWK instrument, the samples were ground using a mortar and pestle to pass 60 mesh size and weighed to about 100 mg, after which they were pyrolysed in the HAWK for the following parameters: S1 (which represents the amount of free hydrocarbon liberated at 300^0 C without cracking the kerogen), S2 (the amount of hydrocarbon released from cracking of kerogen (mg HC/g rock) during temperature programmed pyrolysis (300 to 600^{0}C), S3 (the amount of CO_2 from breaking oxygen-containing compounds in kerogen at 300 to 390^{0}C)], and from the S2 peak, the Tmax values are obtained. The Tmax values represent the temperature at which the maximum generation of hydrocarbons from pyrolysis cracking of the kerogen occurs (°C). The interpreted parameters obtained from pyrolysis analysis are: Hydrogen Index (HI) (mg HC/gTOC) and Oxygen Index (OI) (mg CO_2/gTOC), which are related to the amount of oxygen and hydrogen respectively. The Production Index (PI) which characterises the level of maturation of the OM. The Rock Eval pyrolysis results of the samples and their related graphical representation are shown in Table 1, Figures 5 to 11.

Results and discussion

All samples were processed under HAWK Pyrolysis to characterise the organic content, kerogen type, thermal maturity, generation potential, nature of hydrocarbons, depositional environment.

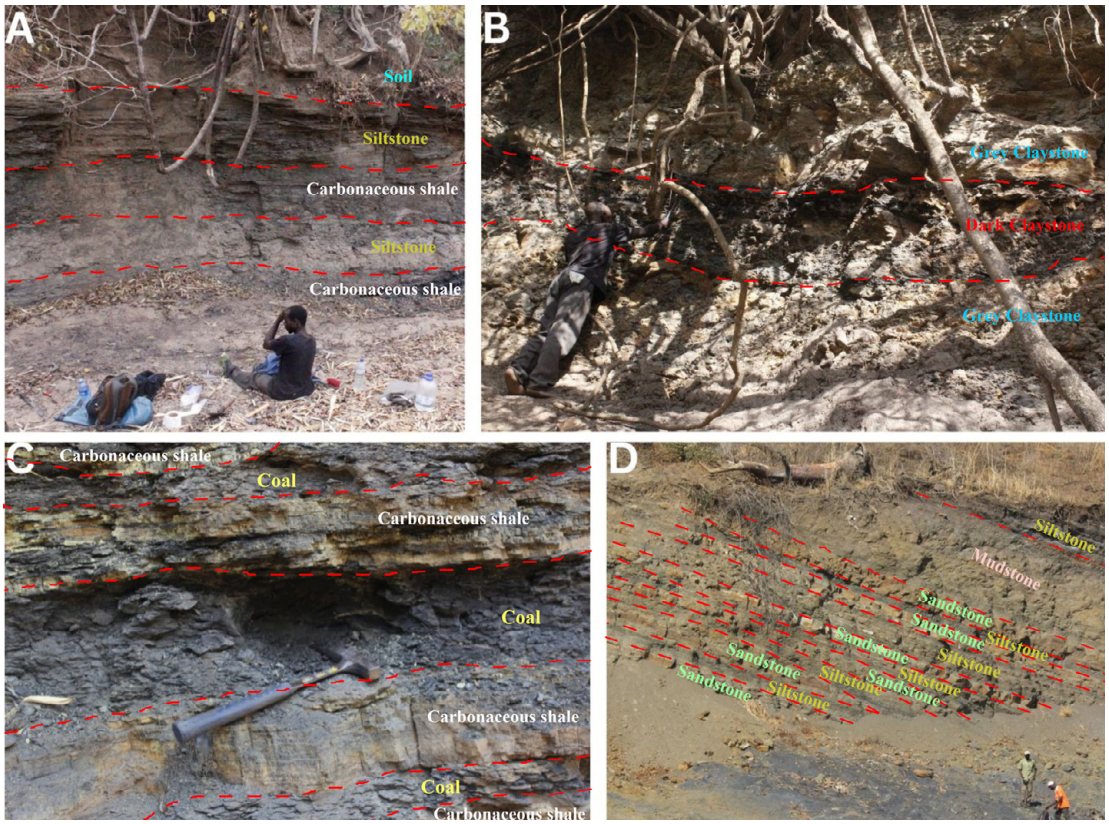


Figure 3. *Field illustrations of the studied outcrops showing organic rich units in black: (**A**) Luiga outcrop (KSh Formation, Early Triassic), (**B**) Nhamago outcrop (K4 Formation, Middle Permian), (**C**) Luchai outcrop (K4 Formation, Lower Permian), and (**D**) Michunwa outcrop (K5 Formation, Middle Permian). The geological age of the sediments from different outcrops in brackets are according to the information given by the geological map (Figure 1) adapted from Verniers et al. (1989).*

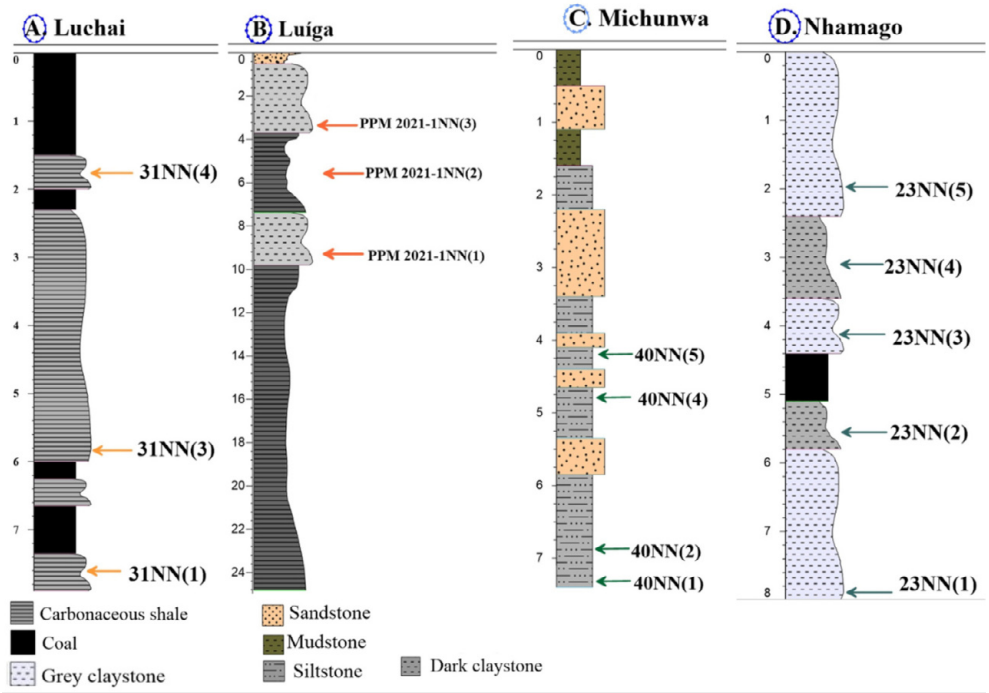


Figure 4. *Lithology and sample horizons for the four outcrops from the Maniamba Basin, Niassa, including the collected samples: (**A**) Luiga, (**B**) Nhamago, (**C**) Luchai, and (**D**) Michunwa.*

Organic richness and source rock quality

The TOC measures the organic richness of a rock and it is a qualitative tool to measure the petroleum potential (Peters and Cassa, 1994). Values of 1.0 wt% TOC are considered a minimum value for defining a petroleum source rock (Peters and Cassa, 1994). Additionally, measuring only organic carbon content is not enough for determining the potential of source rocks (Peters and Cassa, 1994). Thus, values of TOC should be regarded with caution because high organic carbon content is not always an indication of a potential oil source due to the fact that reworked OM from terrestrial sources within old marine sediments can display high TOC values (Sari and Aliyev, 2006). The results of TOC from the outcrops are presented in the Table 1.

The Nhamago outcrop (Figure 5) shows TOC values ranging from 1.1 to 4.8 wt%. This content points to excellent potential for hydrocarbon generation. The values for the Luchai outcrop (Figure 5) range from 1.4 to 7.3 wt%, also suggesting good to excellent organic richness according to Peters and Cassa (1994). In its turn the Michunwa (Figure 5) TOC values range from 1.6 to 4.7 wt% being regarded as good to excellent. The only exception are the samples from the Early Triassic Luiga outcrop (Figure 5), showing values ranging from 0.8 to 2.6 wt%, which are considered fair to very good for hydrocarbon generation. In summary, the variations in TOC content suggest that the carbonaceous shales, siltstones and studied claystone present a good potential for hydrocarbon generation. Further, the majority of TOC values from the studied outcrops are less than 2%.

Types of kerogen

The types of kerogen OM are defined by hydrogen and oxygen indices (HI and OI, respectively) (Tissot and Welte, 1978; Waples, 1985; Van Krevelen, 1993). Kerogen types with HI above 600 mg/g rock have an excellent potential for oil generation (Waples, 1985). HI between 150 and 300 mg/g indicates a mixture of kerogen Type III and II, suggesting that the rocks are capable of generating mixed gas and oil, but mainly gas. Kerogen with HI below 150 mg/g indicates mainly type III kerogen, regarded as potential source rock for gas generation. Most of the studied units display low HI values ranging from 1 to 36 (Table 1).

According to Geel et al. (2015), the oil released from kerogen might be adsorbed into the surface of the clay minerals thus lowering the HI values in the Karoo Basin. This fact would reduce the S2 peak and as a consequence reduce the HI values. Further, research performed by Geel et al., 2015 in the Lower Permian Whitehill Formation, Karoo Basin in South Africa indicated that the low HI values in this Karoo Formation has been linked to high clay content, high sulphur content and the presence of solid bitumen. This can be a likely explanation for the Maniamba Basin. In addition, the low HI values for the

Table 1. Total Organic Carbon (TOC) and Rock Eval pyrolysis results of the outcrop samples from Maniamba Basin.

Outcrops	Lithostratigraphy (Verniers et al., 1989)	Samples	S1 (mg HC/ g rock)	S2 (mg HC/ g rock)	S3 (mg CO_2/ g TOC)	PI	S3/S2	GP (ºC)	Tmax (wt%)	TOC	HI	OI
Luíga	KSb (Lower Triassic)	1NN (3)	0	0.04	0.7	0.30	17.5	0.04	537	0.87	4	81
		1NN (2)	0.01	0.47	1.16	0.04	2.46	0.48	452	2.21	21	52
		1NN (1)	0.41	3.83	0.24	0.10	0.06	4.24	434	2.67	143	9
Michunwa	K6 (Middle Permian)	40NN (5)	0.01	0.06	0.75	0.30	12.5	0.061	543	1.88	3	39
		40NN (3)	0.01	1.11	1.47	0.01	1.32	1.12	448	4.70	23	31
		40NN (2)	0	0.3	0.93	0.03	3.1	0.3	450	2.10	14	44
		40NN (1)	0.01	0.25	0.33	0.07	1.32	0.26	537	1.60	15	20
Nhamago	K4 (Lower Permian)	*23NN (5)	0.16	23.5	19.07	0.01	0.81	23.66	428	37.56	62	50
		23NN (4)	0.02	1.27	1.40	0.02	1.10	1.29	435	7.37	17	19
		23NN (3)	0	0.12	0.37	0.01	3.08	0.12	545	1.34	9	27
		23NN (2)	0	0.08	0.66	0.13	8.25	0.08	548	1.16	6	56
		23NN (1)	0.01	0.07	0.94	0.22	13.42	0.08	549	1.82	3	51
Luchai	K4 (Lower Permian)	31NN (4)	0.02	0.95	2.27	0.03	2.38	0.97	437	7.30	12	31
		31NN (3)	0.01	0.57	1.10	0.02	1.92	0.58	436	4.84	11	22
		31NN (1)	0.03	0.54	0.31	0.07	0.57	0.57	439	1.49	36	20

*Abbreviations S1=Free hydrocarbon content, mg HC/g rock; S2=Remaining hydrocarbon or generative potential, S3=the amount of CO_2 from breaking oxygen-containing compounds in kerogen at 300-3900 C, PI=Production Index; GP=Generator Potential; Tmax=Temperature at maximum of S2 peak (°C); TOC=Total organic carbon; HI=Hydrogen Index; OI=Oxygen Index. *Sample 23NN(5) is considered an outlier due to its high value of TOC reaching to 37.56wt%.

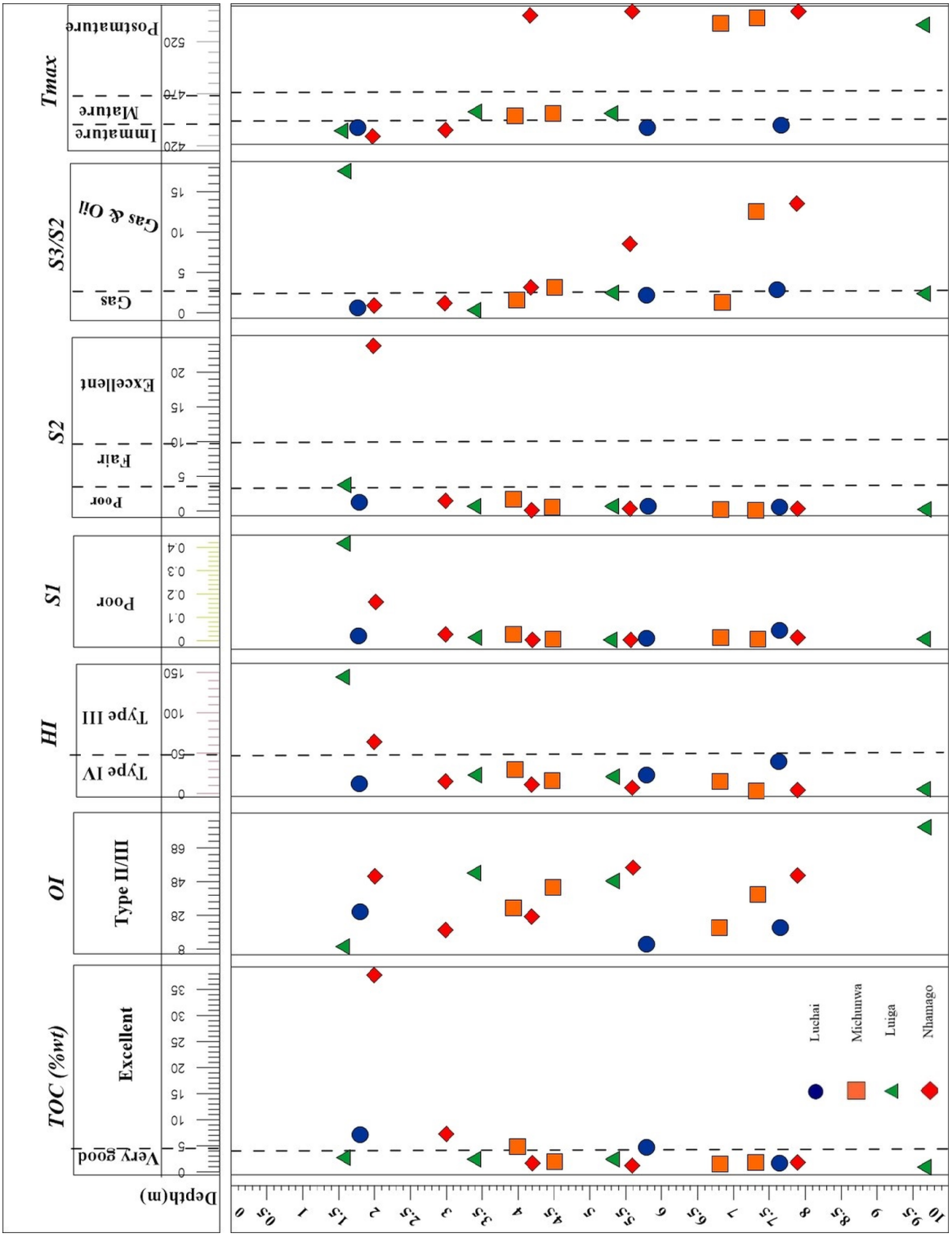


Figure 5. *Geochemical log of the four studied outcrops from the Maniamba Basin, Niassa, showing different parameters analysed through Rock Eval pyrolysis data.*

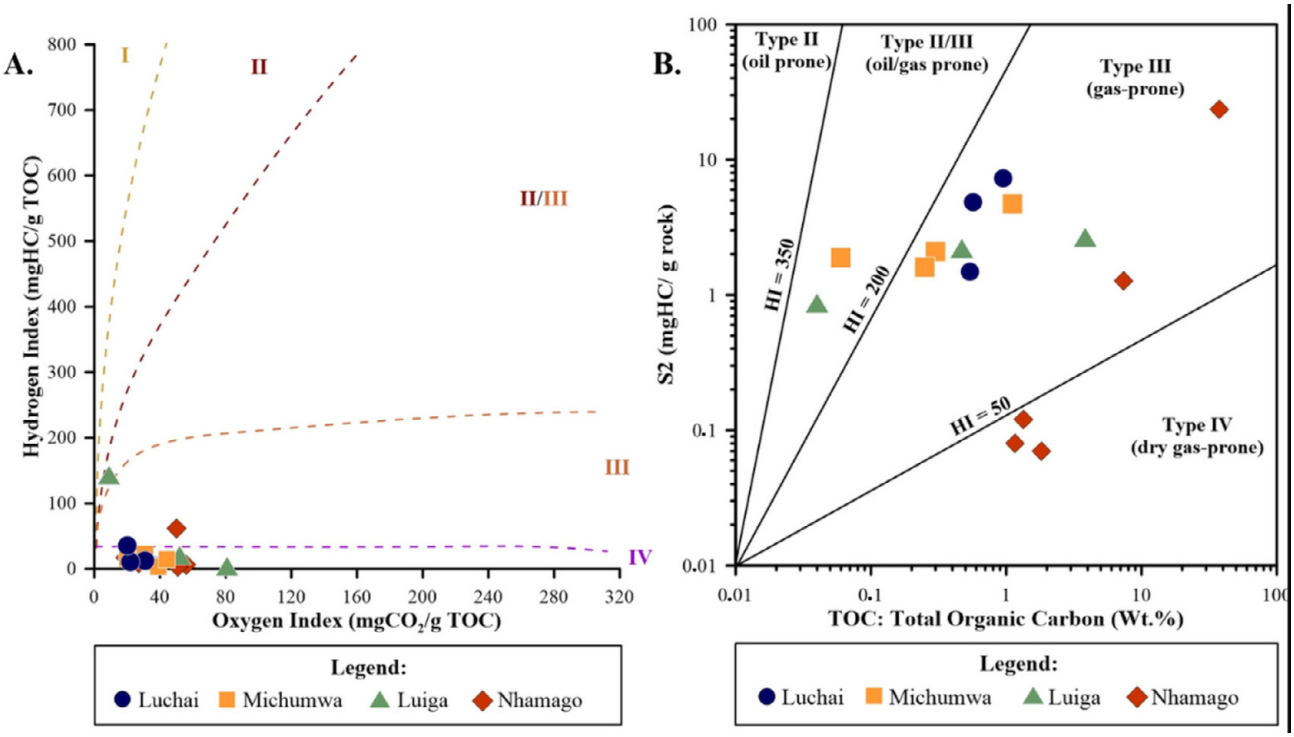


Figure 6. *Modified van Krevelen's diagrams illustrating kerogen types of source established from organic geochemical parameters (**A**) Hydrogen Index (HI) versus Oxygen Index (OI), (**B**) S2 versus Total Organic Carbon (TOC) plots showing the distribution of different types of kerogen in the outcrop samples modified after Espitalié et al. (1977).*

studied outcrops are indicative of absence of significant amounts of oil-generative lipid materials and the presence of kerogen that is mainly type III or type IV. Additionally, based on the HI versus OI and S2 versus TOC plot diagrams (Figure 6A and 6B), the results show a mix of kerogen type II/III, III and IV. However, the majority is classified as kerogen type III and IV and a few as kerogen type III and type II/III. In the studied area, carbonaceous shales, coal-bearing strata and terrigenous plant materials such as the Permian *Glossopteris* flora have been reported (Araújo et al., 2020) which is consistent with the obtained kerogen types. Moreover, low HI and higher OI values confirm the idea that OM is derived mainly from terrestrial sources with non-existent algal content as shown in the organic facies Figure 7.

Thermal maturation and influence of local geology

The composition of the OM changes its properties with increasing pressure and temperature. These conditions can generate either oil or gas. For oil generation a Tmax interval of 435°C to 465°C is necessary (Tissot and Welte, 1978). In regard to gas generation, a minimum Tmax value of 470°C is needed (Espitalie et al., 1997).

In the present study, the Tmax values for the Nhamago samples show immature to postmature rocks (Figure 8). Mature rocks for oil generation are found in the Luchai outcrop (Figure 8). The Michunwa data point to mature to supermature in these samples. Further, the data from the Luiga outcrop show early mature levels to postmature (Figure 8). The large variability of Tmax data can be associated with several effects such as intrusions, oxidation and reworking, alpha irradiation, natural impregnation or contamination by drilling fluids or due to the presence of faults (Peters and Cassa, 1994; Bordenave et al., 1993; Ade, 2000; Sydnes et al., 2019). Additionally, the lack of linear trend in the Tmax values can be associated with the clay mineral content as suggested by Gao et al., 2019. According to Gao et al. (2019), different clay minerals can have different effects on different types of kerogens thus influencing the Tmax values. For instance, with the ratio of kerogen/clay minerals changing, the Tmax can also be affected. The impact of mineral matrix on Rock Eval pyrolysis data has been documented by several researchers (Espitalié et al., 1977; Espitalié, 1986; Peters, 1986; Hazra et al., 2018; and others). Aside from Tmax, other thermal maturity parameter analysed is the PI. The PI has been used to interpret the thermal maturity of OM (Peters and Cassa, 1994; Nazir and Fazeelat, 2017a, 2017b). According to the aforementioned authors, samples with PI values less than 0.05 might be indicated as immature and as having generated little to no petroleum. Additionally, samples with PI values ranging from 0.05 and 0.10, can be assumed to have yielded very little oil and may have reached the wet gas zone. Finally, if PI values exceed 1.0, then the ability of the kerogen to yield hydrocarbons may have been depleted. For the studied material the Tmax corroborates with PI values indicating mature to postmature source rocks within oil and gas generating zone. Samples at postmature levels cannot generate liquid hydrocarbon, but can

act as a potential rock for dry gas (Khan et al., 2022). In the studied area different geological events may have contributed to the different level of maturation of the sediments in the Maniamba Basin. For instance, the reported kimberlite intrusions that represent the first or second stage of rifting of the Metangula graben (Verniers et al., 1989; Key et al., 2007) (Figure 9). The kimberlite dykes from the Maniamba Basin are reported from Micuela, Tulo and Nhamago sites (Figure 9). The aforementioned kimberlites pipes cut through lower and middle Karoo rocks and consolidated lower Karoo sandstones (Figure 9). In the studied outcrops, only Luchai and Nhamago sites are situated closer to the kimberlite intrusions. The Luchai area present Tmax values representatives of no influence by igneous intrusions. On the other hand, the Nhamago site display greater Tmax values which can represent an influence by the existing kimberlite intrusions in the area. However, further studies based on a large sample size and a systematic approach should be undertaken in order to differentiate reliably the effects of local burial and heating due to the emplacement of the intrusive in the area of study. Additional, should be hypothesised the contribution of the East African rift during the Late Tertiary. The East African rift affected the Metangula area forming the Niassa Lake and a small horst which runs along the Niassa Lake from Metangula over Messumba to near Likoma Island in Malawi (Verniers et al., 1989). The contribution of the rift system should be further investigated.

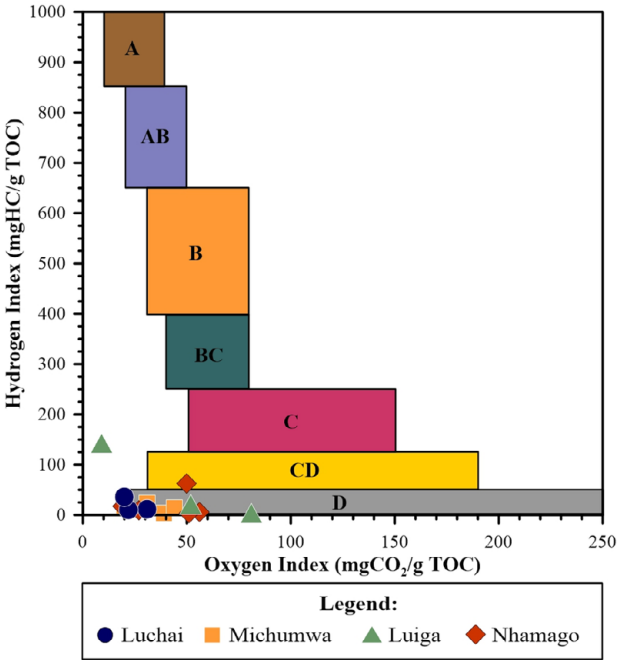


Figure 7. *Hydrogen Index (HI) versus Oxygen Index (OI) cross plot indicating the organic facies adapted from Jones (1987).*

Nature of hydrocarbons and its potential

Regarding migration, the variables S1 versus TOC pointed out to an indigenous nature to the studied samples (Figure 10). This fact can also be supported because all the source rocks contain an expected level of S1 hydrocarbons for their given TOC, and hence, are predominantly indigenous as suggested by Hunt, 1995. Moreover, the low values of the S1 yield compared to S2 also suggest the indigenous nature of the hydrocarbon present. On the other hand, the potential for oil production capacity has been plotted using the plot of S1 versus TOC. For the studied samples, only one sample from Luiga (as pointed out above) indicates an oil producible potential as shown in Figure 11. However, more samples will be needed to confirm the oil-generation potential for the studied sites.

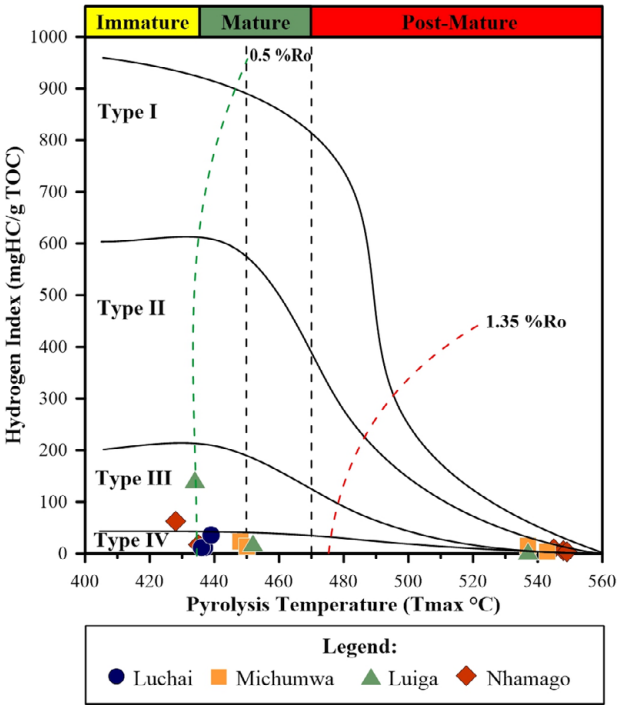


Figure 8. *Hydrogen Index (HI) versus Tmax cross plot showing the maturity and type of kerogen in the outcrop samples adapted from Van Krevelen (1993).*

Karoo-aged basins with similar organic geochemistry properties

Similar patterns regarding the organic content observed in the studied outcrop are observed in some Gondwana units of similar ages (Figure 12 and Table 2). The first obvious example occurs in the Moatize-Minjova Basin (Karoo Basin of Central Mozambique). In the aforementioned Basin, the target outcrops are from the Lower Permian Vúzi Formation and Moatize Formation. The OM of the Lower Permian Vúzi Formation is classified as Type IV Kerogen with low HI suggesting very little potential for gas generation. Some samples from the present study display this scenario. In the same basin, the Moatize Formation (Lower to Middle Permian) according to Fernandes et al., 2014, is

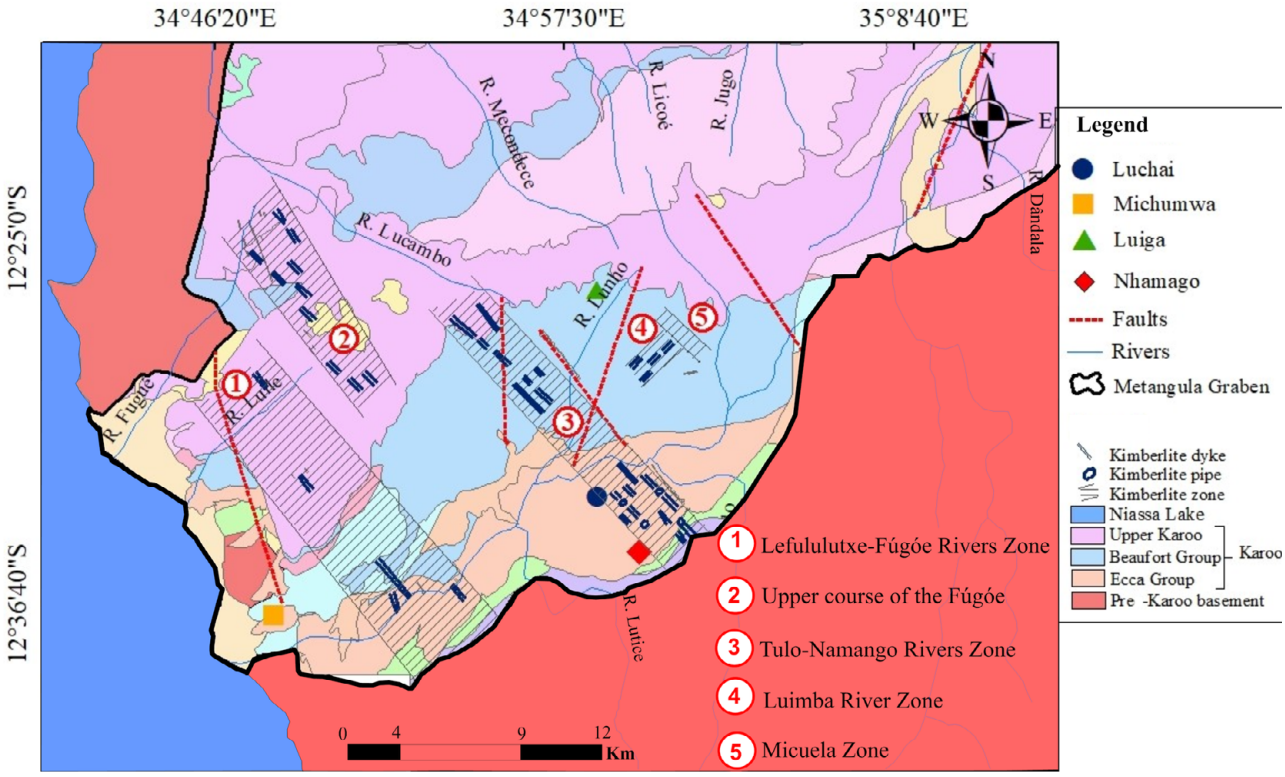


Figure 9. *Map showing the influence of kimberlite intrusions in the maturation of the studied samples adapted from Key et al. (2007).*

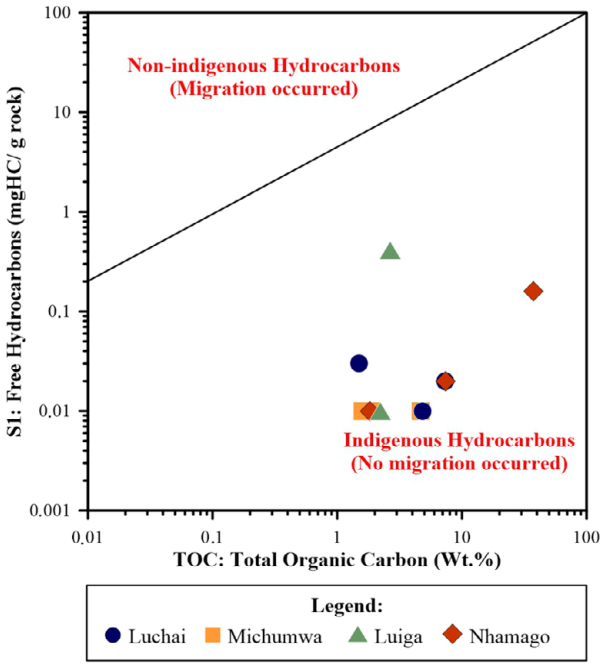


Figure 10. *Cross plot S1 versus Total Organic Carbon (TOC) shows the nature of the hydrocarbons within the outcrops adapted from Hunt (1995).*

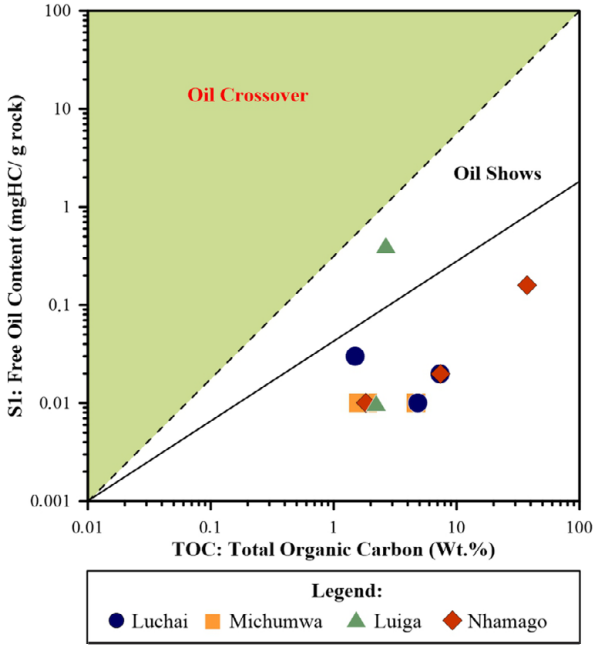


Figure 11. *Free Oil content versus Total Organic Carbon (TOC) showing oil crossover effect from the outcrop samples obtained from Mussa et al. (2018).*

characterised by having a mixed kerogen type II-III and type III with high TOC values (>4 wt%), moderate values of HI indicating a potential for thermogenic gas generation. The maturation values indicate the end of oil generation and onset of gas generation (Fernandes et al., 2014). The OM content in this Formation is similar to some units from the studied sites. All the studied outcrops show a mixed type II-III kerogen. The type II kerogen is only restricted to the Nhamago and Luiga outcrops.

Another surveyed basin, which occurs in the Tete province is the Sanangoé Mefidezi Basin which, according to Mahabeer (2017), shows samples with potential for oil generation, wet gas and dry gas based on the colour of selected sporomorphs. Mahabeer result suggests the occurrence of OM type II, mixed type II-III, type III and IV. These results are comparable with the data obtained from the outcrops described herein, however, no type II kerogen is identified for the sites. Regionally, ten Karoo-aged basins have also been surveyed in terms of the organic matter properties, the Ruhuhu and Tenga basins in Tanzania, the Main Karoo and Tuli Basins in from South Africa, the Moatize Minjova and Sanangoé-Mefidezi Basin in Mozambique, the Cahora Bassa and Mid-Zambezi basins in Zimbabwe and the Luangwa Basin in Zambia. The Lower Permian sedimentary rocks from the Ruhuhu Basin in Tanzania display moderate source rock properties (Kreuser et al., 1988). These rocks are mature and placed within the oil window. Kerogen type III is typical for the Ruhuhu Basin. Interestingly, this pattern is observed for the sediments from the Upper Permian in the same basin (Kreuser et al., 1988.). The studied sections in the Ruhuhu Basin display close similarities to those observed from Nhamago and Luiga outcrops. The Karoo sedimentary rocks from the Tenga Basin in Tanzania display type III and mixed type II/III kerogen which is correlatable with the sediments of the studied outcrops because all of the studied show this type of kerogen. Additionally, the black shales of Whitehill Formation in South Africa contain bisaccate pollen of terrestrial origin. An average of 4.5 weight TOC was also observed suggesting that it contains type II kerogen reflecting high level of maturity. The source of OM is of mixed origin (both type II and type III kerogen). The Whitehill Formation (Main Karoo Basin) and the Tuli Basin are rich in TOC being suitable for gas exploration (Geel et al., 2015; Akintola et al., 2023). Because these formations showed a mixed type II and type III kerogen can be correlated with two outcrops of the studied material, Nhamago and Luiga respectively. Other analysed

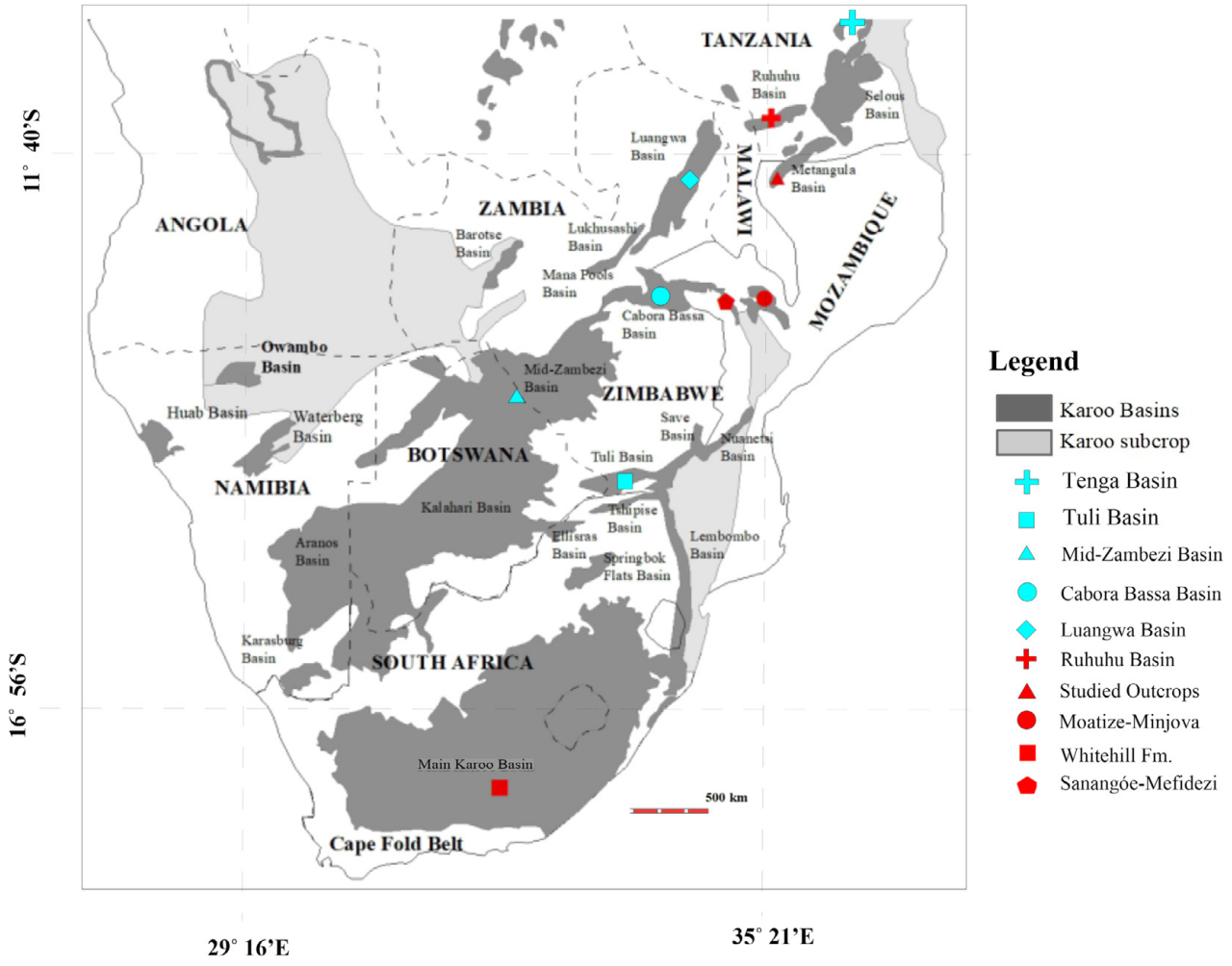


Figure 12. *Karoo Basin map illustrating the comparable Karoo sites based on the organic matter properties used in the present study.*

Table 2. The Maniamba Permian outcrops compared with other Karoo sites in terms of organic geochemistry properties.

Organic Matter Content	Whitehill Formation (Lower Permian shale, Karoo Basin) Geel et al., 2015	Tuli Basin, South Main Karoo Basin, Akintola et al., 2023	Vúzi Formation, (Lower Permian), Moatize-Minjova Basin, Fernandes et al., 2015	Moatize Formation, (Lower-Middle Permian), Moatize-Minjova Basin, Fernandes et al., 2015	Sanangoé Mifedezi Basin, Mahabeer, 2017	Ruhuhu Basin, (Lower and Upper Permian), Kreuser et al., 1988	Cahora Bassa Basin, Zimbabwé, Hiller and Shoko, 1996	Mid Zambezi Basin, Zimbabwe, Hiller and Shoko, 1996	Luangwa Basin, Zâmbia, Utting and Wielens, 1992	Tenga Basin, Tanzânia, Mallah and Sanga, 2022	Outcrops, (Maniamba Basin), In this paper
Vitrinite reflectance (%Ro)	4	1.19-1.30	1.3-1.69	1.3-1.69	No data	0.5-0.8	<0.5-1.0	<0.5-1.0	0.60-0.94	No data	No data
Tmax (ºC)	≥563	464-470	≤440	≤436	No data	No data	430-450??	430-450	No data	No data	428-549
TOC (%t)	07. to 8.15	47	0.9 to 2.4	<4.0	No data	No data	>0.5	>0.5	No data	No data	0.87 to 4.84
Kerogen Types	Mixed of type II and type III	Type III and Mixed type II/III	Type IV kerogen	Mixed of type II-III and type III	Mixed type II-III, type III	Type III kerogen	Mixed type II-III, type I and type III	Type II, Mixed type II/III and type III	Type II, III and IV	Type III and mixed type II/III	Mixed type II-III, type III and type IV

Karoo-age basins such as Cahora Bassa Basin, Mid Zambezi Basin in Zimbabwe, and Luangwa Basin in Zambia have demonstrated close affinities with the studied outcrops, however an exception is observed in the Cahora Bassa Basin (Table 2). In the Cahora Bassa Basin, a type I kerogen is observed and is associated with high latitude lake deposit capable of generating oil (Hiller and Shoko, 1996) (Table 2). In summary, a good correlation within the Karoo Basin can be extrapolated, however more data from some unexplored basins are still needed.

Conclusions

Rock Eval analysis coupled with TOC and kerogen analysis from four outcrops of Permian and Early Triassic ages in the Maniamba Basin were investigated herein. This research was carried out in order to evaluate its source rock potential of the sampled sediments. The main conclusions are as follows:

- The OM within the four outcrops is mainly dominated by kerogen type III, IV with minor mixed II/III kerogen.
- Low values of HI are observed at almost all outcrops.
- The observed kerogen is thermally mature to postmature due to proximity to igneous intrusions (e.g., kimberlite dykes).
- The lower HI and higher OI of OM indicates three organofacies C, CD and D and a kerogen dominated by terrestrial OM within an oxic environment.
- The studied sections revealed to be good to excellent source rocks with regard to organic richness.
- No marine source rock has been identified for the Karoo basins. The Moatize Minjova (Mozambique), Sanangoé-Mefidezi (Mozambique), Ruhuhu Basin, Cahora Bassa Basin (Zimbabwé), Luangwa Basin (Zambia) and Main Karoo Basin (South Africa) have demonstrated close similarities with the sediments from four outcrops of the Maniamba Basin in terms of their organic geochemistry properties. However, an exception is the occurrence of type I kerogen in the Cahora Bassa Basin (Zimbabwe) which is interpreted as high latitude lake deposit capable of generating oil.

All in all, it has been demonstrated herein that the rocks from the Maniamba outcrops possess suitable organic richness and source rock potential, and therefore in the future these sections might be of more interest in terms of hydrocarbon prospectivity. However, more studies are needed in this Basin using other proxies such as vitrinite reflectance, palynofacies, elemental analysis, x-ray diffraction, isotopes and biomarkers in order to improve the data presented herein regarding the determination of the potential for hydrocarbon generation and the contribution of igneous intrusions to the maturation of the studied OM.

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