Multi-analytical Approach (FTIR, XRF, XRD, GC-MS) Characterization of Source Rocks from the Anza Basin, Kenya

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Abstract: Potential source rocks from three wells (Chalbi-3, Sirius-1, and Ndovu-1) in the Anza Basin of northeastern Kenya were analyzed using elemental carbon-hydrogen-nitrogen analysis, and mineralogical characterization by X-ray diffraction (XRD), X-ray fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM-EDX)). A Gas Chromatography-Mass Spectrometry (GC-MS) analysis of the saturated aliphatic biomarkers was carried out to illuminate the organic matter source. The analytical results revealed that the source rocks have moderate to high total organic carbon (%TOC) content, suggesting conditions in the Basin favor organic production and preservation. The Hydrogen Indices (HI: 0.19–0.60 atomic ratios) typify a predominance of mixed type II/III (oil/gas-prone) with more type III (gas-prone) and less II (oil-prone) kerogens. The FTIR, XRF, and XRD results reveal that the studied source rock samples comprised mainly of quartz, followed by silicate-clay minerals and calcite minerals. The solvent-extractable organic matter investigation revealed biomarker distributions of n-alkanes and isoprenoids (pristane/ phytane ratios), suggesting that source rocks were derived from algae and bacteria deposited under weakly anoxic and low oxic environmental conditions, with minimal contribution from terrestrial organic matter sources. Consequently, all three wells have hydrocarbon generation potential, particularly Ndovu-1, which displays good organic matter content to produce oil and gas. The hydrocarbon potential is excellent and capable of making expulsions of oil and/or gas from the wells at sufficient depths.

Keywords: Hydrocarbons; Inorganic matter; Petroleum; Sedimentary rocks; Source rocks.

Introduction

The depletion of conventional petroleum sources and increased oil prices have led to widespread efforts to search for alternative energy sources [1-3]. Hence, unconventional energy sources like oil shale, shale oil, oil sand, organic-rich shales, coal bed methane, shale gas, tight reservoir, and source rocks [4], have taken center stage to satisfy our present and future oil and gas needs [5]. Some source rocks have become excellent reservoirs for generation and accumulation. A petroleum source rock is an organic-rich sedimentary rock with a high capacity for generating hydrocarbons (oil and gas) in sufficient quantities under suitable thermal maturation conditions [6]. The petroleum-generating potential of the source rock is directly related to its volume, organic richness (Total Organic Carbon), and thermal maturity [7]. Alongside organic richness (kerogen and bitumen), understanding the mineralogical composition of source rocks is significant in optimizing hydrocarbon recovery because the mineral phases in a rock determine a reservoir's physical and chemical properties.

Kenya has a history of oil exploration dating back to the 1950s [8]. However, most of the wells drilled in the past had no traces of hydrocarbons [9]. After decades of disappointing results, investments in hydrocarbon exploration decreased until 2010, when offshore gas finds in Mozambique and Tanzania, and onshore oil finds in Uganda attracted investors back to Kenya [10]. Kenya is under-explored and has enormous potential, making it attractive to investors [11]. In the entire history of Kenya, only 50 wells have been drilled. In Texas, similar in the geographical area to Kenya, 500,000 wells have been drilled since 1960 [12]. This comparison indicates that Kenya may be harboring large oil deposits which are yet to be trapped. The quantity of organic matter in Kenya's oil shales has not been studied.

The Anza basin is the termination of the Central African Rift System in the Chalbi sub-basins in Northern Kenya and an extension of the Melut and Muglad Rift basins in

South Sudan (Fig. 1), where working petroleum systems exist. After evaluating organic matter (OM) content as Total Organic Carbon (TOC), Gilbert et al. [13] demonstrated that the organic-rich sedimentary rocks of the Anza Basin could produce gas and oil. Gilbert et al. (2021) [13] and Rop's (2013) [14] contributions have focussed on the source rock characteristics and their relative importance for hydrocarbon generation. Organic matter and mineral matter represent a missing link that highlights the origin and source of the organic matter as well as their environment of deposition. However, investigations of various types of minerals and their importance in source rocks of the Anza basin are scarce. This provided an impetus for the current study, whose emphasis is mainly on investigating the source rock samples of the Anza basin in the North

Eastern part of Kenya.

The objectives of this study are to (i) determine the total organic matter (TOC), (ii) the hydrocarbon generating potentiality, and (iii) the mineral composition of source rocks using various laboratory analytical techniques. The study also examined the n-alkanes and isoprenoid biomarkers in the aliphatic hydrocarbon fraction samples derived from the source rock extracts. Typically, chemical and microscopic analyses of source rock samples are used in laboratories to assess the kind, quantity, and maturity of organic materials in the source rocks [15]. Determining the mineralogical composition of the source rocks is crucial since it will augment hydrocarbon (gas and oil) recovery. X-ray diffraction (XRD) tends to be supported by data from infrared spectroscopy, chemical analysis, and electron microscopy [16]. The results have provided information on the source rocks' functional groups and mineral matter.
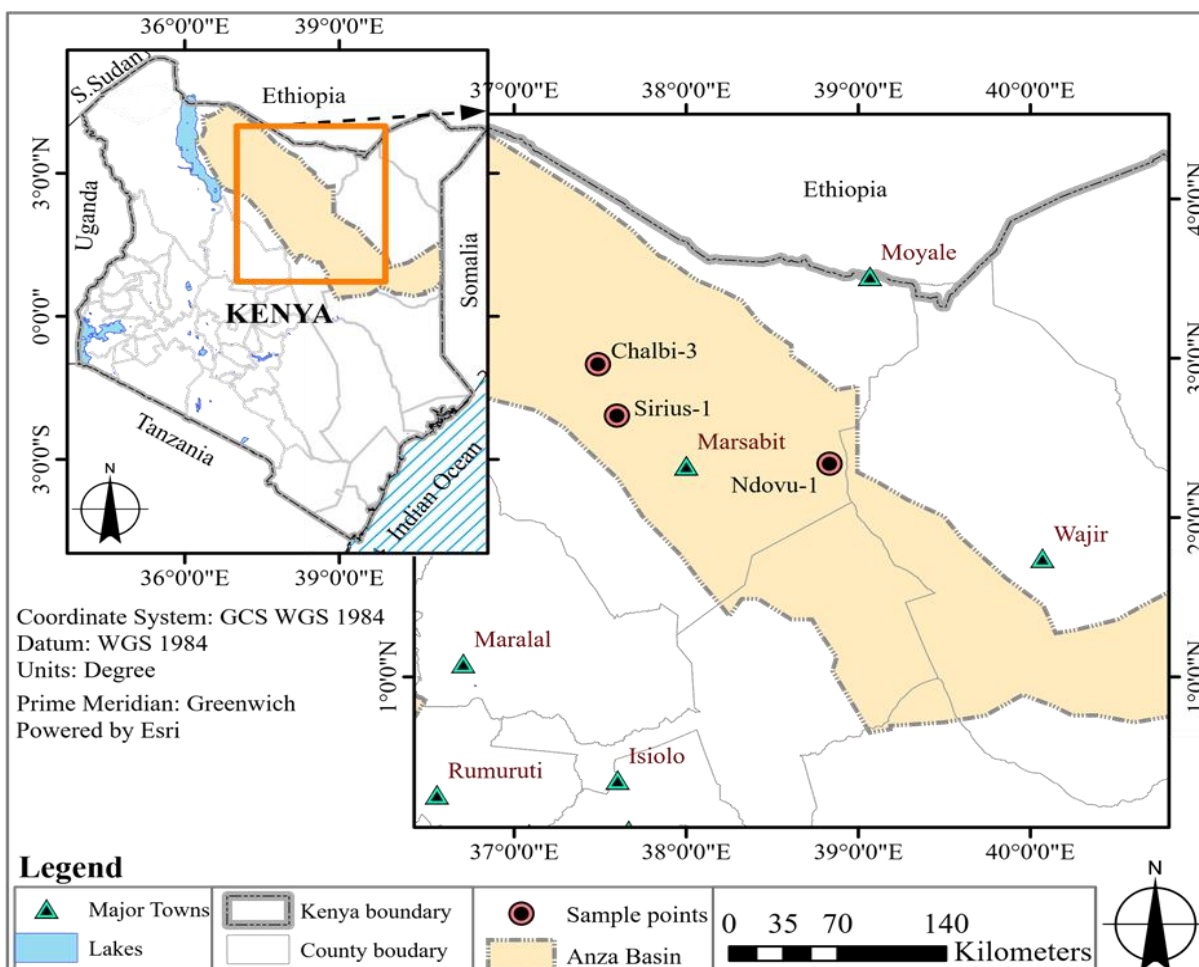
Figure 1. The geological map of Kenya shows the AnzaBasin, including the location of the studied exploratory wells; Chalbi-3, Sirius-1, and Ndovu-1 (Modified and adapted from Gilbert et al., 2021) [13]

Materials and Methods

Samples

A total of four potential source rock samples (obtained at longitudes 37°05'E and 38°47'E and latitudes 2°22'N and 3°20'N in the Anza basin) were provided by the National Oil Corporation of Kenya (NOCK) laboratories in Nairobi. The rock samples were collected from three wells at different depths: 3100 m for Chalbi-3, 2082 and 2316 m for Sirius-1, and 1066 m for Ndovu-1 well. Organic and inorganic geochemistry was performed on four samples. The samples were crushed to < 250 μm mesh and stored in black polythene bags.

The chemical composition of the organic matter (OM) of the source rock samples, expressed as weight percentage (wt. %) of C, H, N, and S elements, was carried out after the removal of oxidized inorganic carbon (carbonate ions) with 2M HC1. The analysis was performed using a Thermo Scientific CHN Flash 2000 Spectrometer at the University of KwaZulu-Natal (UKZN) in South Africa. Most sulfates were eliminated in the acid medium, and elemental sulfur (S) was not detected in the samples after the analyses.

Methodology

X-Ray Diffraction (XRD) is an analytical technique for identifying minerals and other crystalline phases in sedimentary rocks. The diffractograms follow Bragg's law for calculating the resulting angle, which is crystalline phase dependent [17]. The X-ray source was a 2.2 kW Cu X-ray tube (Cu Kα radiation of wavelength (λ) of approximately 0.15406 nm). The diffractograms were obtained by continuous scan from 8° to 90° at low 2θ angles at 0.02° intervals for good accuracy and precision. The source rock samples were analyzed using a Brucker D8 Advanced XRD instrument with Cu Kα radiation source at the University of KwaZulu-Natal, South Africa.

The FTIR analysis was conducted to identify organic matter and the minerals in the source rocks. The infrared absorption spectra were obtained using a Jasco-4700 ATR spectrophotometer. The source rock powder was mixed with pre-dehydrated KBr. The infrared spectra were acquired from 4000 to 500 cm^{-1}.

Scanning Electron microscopy (SEM) analysis of the source rocks of the oil shale samples was performed at the University of KwaZulu-Natal, South Africa. A high magnification Field Emission Scanning Electron Microscope (Model: JOEL/JSM-7500F) was used to scan the surface morphology of the original samples.

The chemical composition was determined by the X-ray fluorescence method. First, the mineral content and their emitted energies in keV for all the samples were determined using Bruker (energy dispersive XRF) spectrometer at UKZN in South Africa. Then, the proportions of the major elements in the samples, expressed as oxides, were calculated using the instrument *Bruker AXS S1CAL* Process software.

A gas chromatograph (GC) combined with a mass spectrometer (GC–MS; model: HP5975B MSD) was used to separate and detect the aliphatic hydrocarbons. For each analysis, 1 g of powdered source rock was extracted three times with 15 ml of dichloromethane and methanol (4:1 by vol.) by Soxhlet extraction for 24 h. The extracted solutions were combined, concentrated under reduced pressure, and applied to a silica gel column (130 mm x 10 mm i.d.; Keiselgel-60, Merck). Aliphatic hydrocarbons were obtained by eluting with hexane (10 ml). This hexane solution was concentrated to 50 μl under nitrogen flow to analyze individual aliphatic hydrocarbons.

Results and Discussion

Elemental Analysis (CHN)
Source rock potential

Total organic carbon (TOC) concentration is a measure of organic matter richness that aids in determining the potential of source rock for the generation of petroleum during maturation [18]. The results of elemental analysis for carbon (% TOC), hydrogen, and nitrogen; and the corresponding atomic H/C and H/N ratios of the studied source rocks are provided in Table 1. The TOC values of the analyzed source rock samples ranged from 0.54 to 1.99%, with a mean value of 1.38% TOC. All the source rock samples had TOC values > 0.5%, signifying moderate (0.5% wt.) to good (2.0% wt.) productive potential. According to Zhang and Hascakir [19], profitable oil extraction from a source rock can be accomplished if the organic content of the source rock exceeds 2.5%. However, there is no standard lower limit of organic matter content for oil shale/ source rock. Therefore, the studied values are sufficient to justify the examined rocks as potential petroleum-generative source rocks [18,20]. However, the composition and quality of the source rocks may vary within the limits of one deposit. About 90 % of the organic matter preserved in sedimentary rocks is usually in two forms: high molecular weight polymeric material (kerogen, insoluble in usual organic solvents) and the rest is free hydrocarbons (bitumen, soluble in usual organic solvents) [21].

The enrichment of organic matter in the analyzed source rock samples from the Anza basin may suggest organic matter preservation due to low oxygen conditions during the deposition. Biomarker results (discussed below) demonstrate the conservation of organic matter under reduced oxygen supplies. In addition, The present study yielded atomic hydrogen-to-carbon (HI = H/C) as well as nitrogen-to-carbon (N/C) ratios, ranging between 0.19 and 0.60 and 0.08 to 0.40, respectively (Table 1). The HI and N/C results are employed to recognize the bulk kerogen types and environmental

safety. These samples can be classified as type III/IV kerogen based on the HI values because initial H/C ratios are less than 1.0 [22]. Moreover, N/C values were also evaluated and are low (0.08–0.40), suggesting the quality of petroleum products generated from these source rocks of the Anza Basin have higher environmental safety.

Table 1. Different organic elemental parameters for 4 core samples of Anza Basin.

Sample	Depth, m	% Elemental composition (Mean ± SE for n = 3)				
		C (TOC)	H	N	H/C ratio	N/C ratio
Ndovu-1 (H)	1066	1.99 ± 0.150	0.74 ± 0.030	0.19 ± 0.004	0.37	0.10
Chalbi-3 (B)	3100	1.54 ± 0.053	0.38 ± 0.023	0.06 ± 0.004	0.25	0.40
Sirius-1 (D)	2316	1.46 ± 0.105	0.27 ± 0.044	0.05 ± 0.007	0.19	0.08
Sirius-1 (F)	2082	0.54 ± 0.056	0.32 ± 0.040	0.04 ± 0.006	0.60	0.08

Quality of source rock and Organic matter type(s)

The quality term of organic matter refers to whether the source rock organic matter is oil-prone or gas prone since different types of organic matter have different hydrocarbon-generating potentials or quality. The abundance of organic matter is an important aspect of evaluating source rock quality and is evaluated by the TOC wt. %, hydrogen index (H/C), and N/C ratios. The organic richness (TOC wt. %) ranges from 0.54 to 1.99 wt. %, while H/C and N/C ratios ranged from 0.19 to 0.60 and 0.08 to 0.40, respectively (Table 1). The low N/C values suggest that the quality of petroleum products generated from these source rocks of the Anza Basin will have higher environmental safety. The organic matter type(s) is determined by the hydrogen index (HI = H/C). The H/C ratios of the studied source rock samples are low, indicating that the organic matter in these source rocks is oxidized and/or highly mature. This indicates that source rocks are rich in type III/IV kerogen [22].
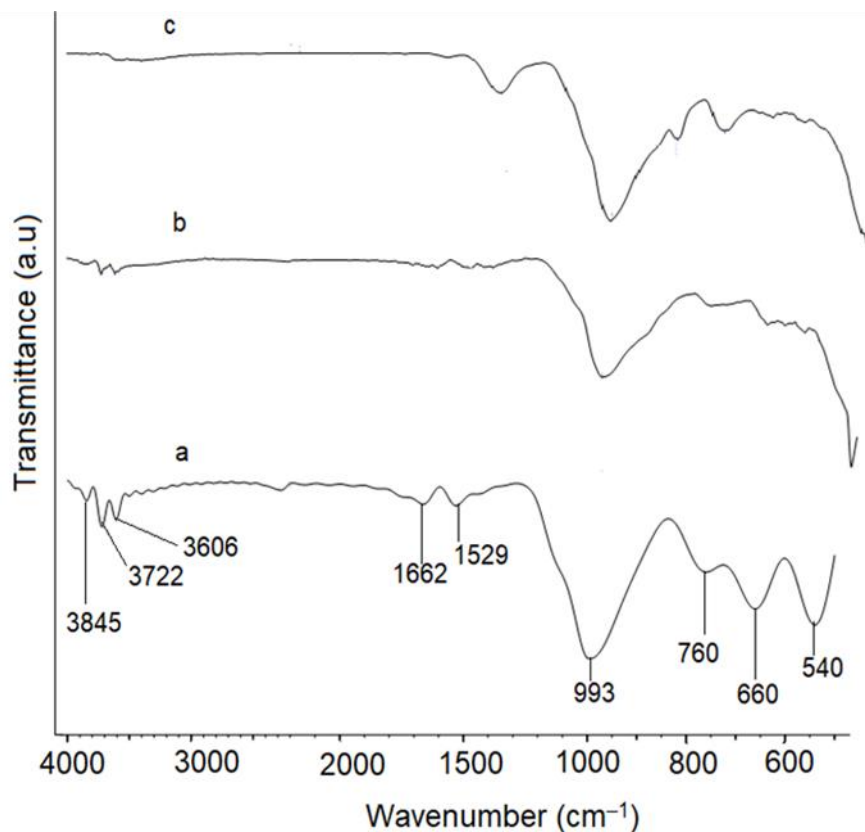
Figure 2. FTIR spectra of acid-treated source rocks: **a**=Chalbi-3 (B), **b**=Sirius-1 (F), **c**=Sirius-1(D)

Fourier Transform Infrared Spectra Analysis (FTIR)

Source rocks are heterogeneous and have a complex multicomponent composition. Fig. 2 shows the spectra of the studied samples. The spectra represent molecular absorption transitions of the different chemical bonds belonging to both organic compounds and the mineral matrices in the source rocks. All the source rocks exhibited peaks beyond 3500 cm^{-1}. The bands at 3845, 3722, and 3608 cm^{-1} are attributed to –OH groups associated with Al and Si of clay minerals present. An intense band at 1200–900 cm^{-1} has been detected in all samples and is assigned to asymmetric vibrations of Si–O groups of clay and quartz. This broad peak contains several vibration modes due to the Si–O–Si stretch, Si–O–Al (Mg), and (Al, Mg) ≡ O–H stretches in quartz, silica, and clay minerals. The Si–O bond, arising from silicates (SiO_4^{2-}), supports the presence of quartz in all the samples [23-25]. The peaks at 760, 660, 540, and 511 cm^{-1} are attributed to symmetric and asymmetric Si–O–Si vibrations that are typical of silicates such as quartz and silica [25]. After carbonate ion elimination using 2M HCl, the peak due to the carbonate (CO_3^{2-}) at 1431 cm^{-1} and asymmetric stretching at 871 cm^{-1} are missing in all the samples, except the Sirius-1 (D) sample, where the FTIR peaks due to CO_3^{2-} are observed. The Sirius-1 (D) sample probably contains acid-resistant carbonate rock whose origin is the Precambrian basement rocks overlain by Upper Jurassic rock with minor outcrops of Limestone with the Anza rift system [13]

The C-H bands in the FTIR spectra' 3000 to 2800 cm^{-1} region are also absent. Their absence may be consistent with organic matter levels being near the detection limit of the FTIR spectrometer or due to the likelihood of removal of aliphatic hydrocarbons from the samples. Similar results have been reported by Tanykova et al.

[23]where the samples had TOC lower than 3 wt. %. Some of the main characteristic absorption bands due to aliphatic and aromatic bonds are obscured and overlapped by strong absorption bands of inorganic minerals. The bands at 1660–1529 cm^{-1} are due to aromatic C=C bond stretches and N-H groups; and probably due to the C–C– skeletal vibration of polynuclear aromatic hydrocarbons. The contributions seen at approximately 660 cm^{-1} could also be ascribed to the vibrations of a linear skeletal chain of CH_2 groups comprising more than four CH_2 groups. The wavelengths in all the samples lying between 784.89 and 757.8 cm^{-1} indicate aromatic compounds, particularly mono- and poly-nuclear aromatics, while those peaks lying in the range 1660–1430 cm^{-1} could constitute alkenes and N-H groups [24]. This demonstrates that some organic bands are partially overlapped by the strong absorbance of minerals in the range 1500–500 cm^{-1}. Also, the bands could be associated with organic OH due to OM and the bending modes of water [24]. The characteristic peaks at 540 cm^{-1} could also signify C—X (X = Cl, Br, I) bonds in chloroalkanes, bromoalkanes, or iodoalkanes.

X-ray Florescence (XRF) Analysis

The XRF analysis results of the source rocks from the three wells are presented in Table 2. The identified oxides are SiO_2, Al_2O_3, Fe_2O_3, K_2O, CaO, MgO, TiO_2 Na_2O MnO; BaO, CuO, C, and SO_3. SiO_2 is the most abundant component (between 12.06 and 36.53 wt. %), followed by Al_2O_3 (4.36–8.06 wt. %). Fe_2O_3 was the third most abundant oxide. The higher concentrations of SiO_2 and Al_2O_3 are consistent with the occurrence of quartz and clay minerals in the studied samples. This slightly high concentration of SiO_2 and Al_2O_3 elements could be due to the input of detrital matter during the sediments' deposition supported by TiO_2 (0.2–3.1).

Table 2. Oxide distribution within the shale samples identified through XRF.

Sample/Depth m	Chemical composition (% wt.)													
	SiO$_2$	Fe$_2$O$_3$	Al$_2$O$_3$	CaO	MgO	Na$_2$O	K$_2$O	TiO$_2$	MnO	Cu	Ba	C	S	Al$_2$O$_3$/TiO$_2$
Chalbi-3 **C1** 3100	17.6	3.6	7.1	6.3	1.7	3.3	0.9	0.4	*	0.1	0.5	2.7	4.3	17.75
Sirius-1 **S2** 2317	12.1	3.1	4.4	11.7	1.3	0.9	*	0.2	0.4	*	*	12.4	*	22
Ndovu-1 **D1** 1298	24.0	20.3	8.1	1.2	0.9	1.3	2.3	3.1	*	*	*	*	*	2.61

* not detected

**X-ray Diffraction (XRD) Characterization**

Representative XRD diffractograms are shown in Fig. 3. Different minerals were identified by comparing their *d* values with those found in literature and 2-theta (2θ) values previously reported by Niu et al. [26]; Labus [27]. The *d* values (Table 3) are unique fingerprints

of each mineral. In addition, the minerals were further confirmed by FTIR analyses. Quartz (SiO_4) was found to be the dominant mineral, and calcite (calcium carbonate), calcium silicate, aluminum silicate, albite ($NaAlSi_3O_8$), haematite (Fe_2O_3), and anhydrite ($CaSO_4$) identified from the XRD spectral patterns of these source rocks.

Table 3. d Values of selected minerals.

Possible minerals	d (Å) of single peaks
Quartz	4.23, 3.36, 1.81, 1.53, 1.37
Calcite	3.12, 1.95,
Anhydrite	3.40, 2.01
Albite	3.96, 3.16
Calcium Silicate	2.09, 2.11, 2.98
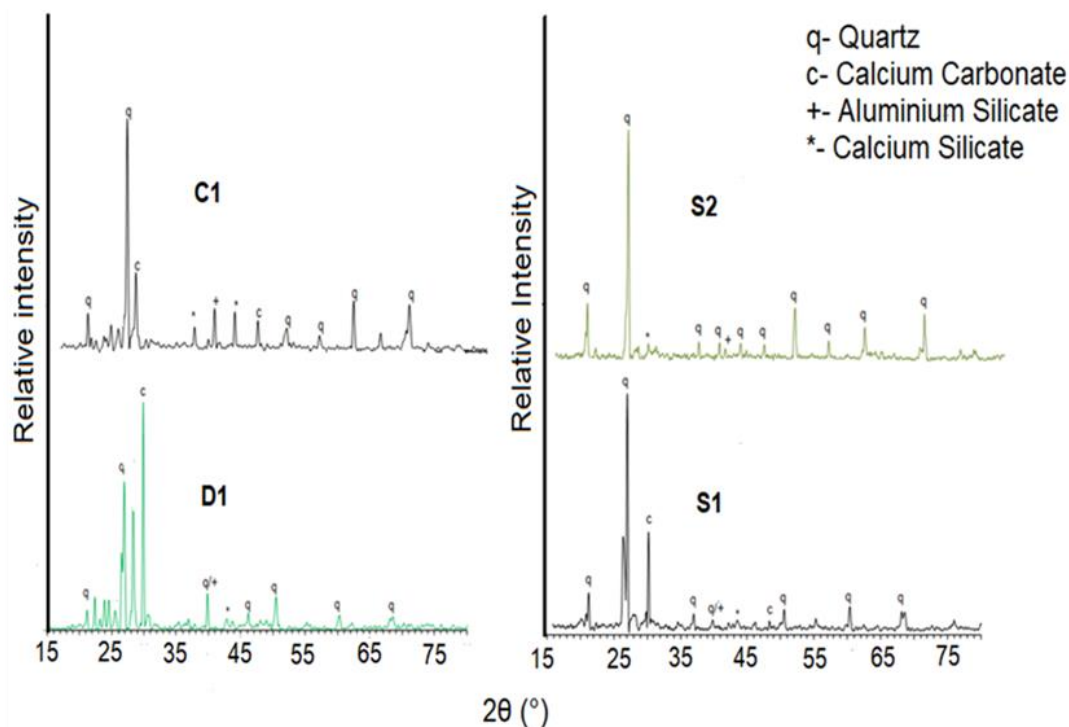
Figure 3. XRD patterns of source rock samples: c_1=Chalbi-3 (B); s_1=Sirius-1 (F); s_2=Sirius-1 (D); d_1=Ndovu-1 (H) of Anza Basin
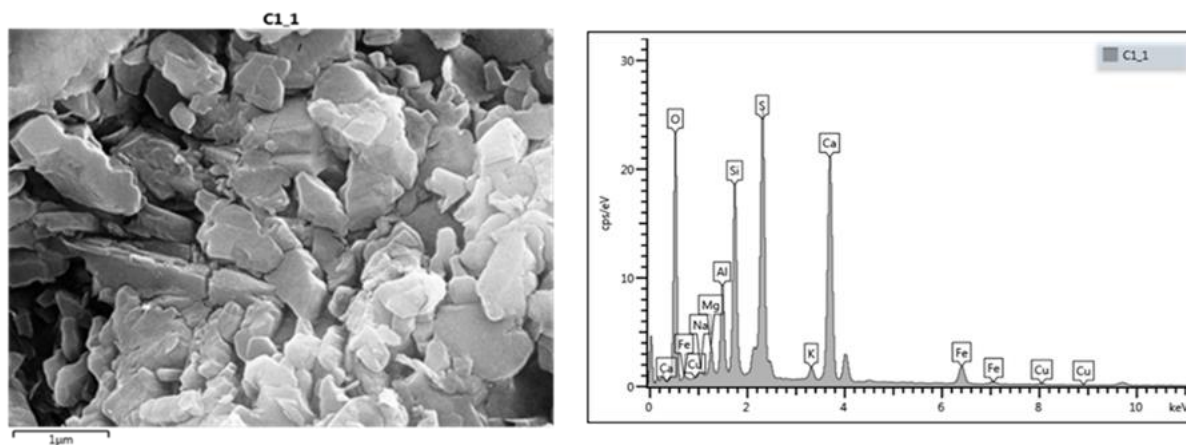
Figure 4. Scanning Electron Microscopy for selected samples of oil shale

SEM Analysis

The microstructure of the examined sample(C1.1) is illustrated in Fig. 4. The microstructure is characterized by intergranular pores developed among the mineral aggregates. The microanalysis EDX (inset graph in Fig. 4) reveals that quartz and clay minerals are the

major phases by previously determined XRF, XRD, and FTIR results. The observed pores and their connectivity are essential for the storage and flow of hydrocarbons that the conversion of OM could generate.

Saturated Hydrocarbon Biomarkers

The present study examined organic matter characteristics based on normal alkanes and isoprenoids (Figs. 5 and 6). The biomarker groups present from the saturated fraction include n-alkanes, acyclic isoprenoids

(shown as an inset in Fig. 5), and maybe sesquiterpenoids identified based on mass spectra fragmentation patterns. The mass spectrum peak of the n-alkanes and acyclic isoprenoids starts from m/z 57 as the base peak, followed by successive increments of 14 units due to the extension of the ethylene group (-CH_2-), with the base peak at m/z 57 being due to the release of the butyl group (-C_4H_9) [28]. The data at m/z 252 suggests the presence of n-cosine ($C_{20}H_{42}$), an n-alkane typically found in the source rocks [29].
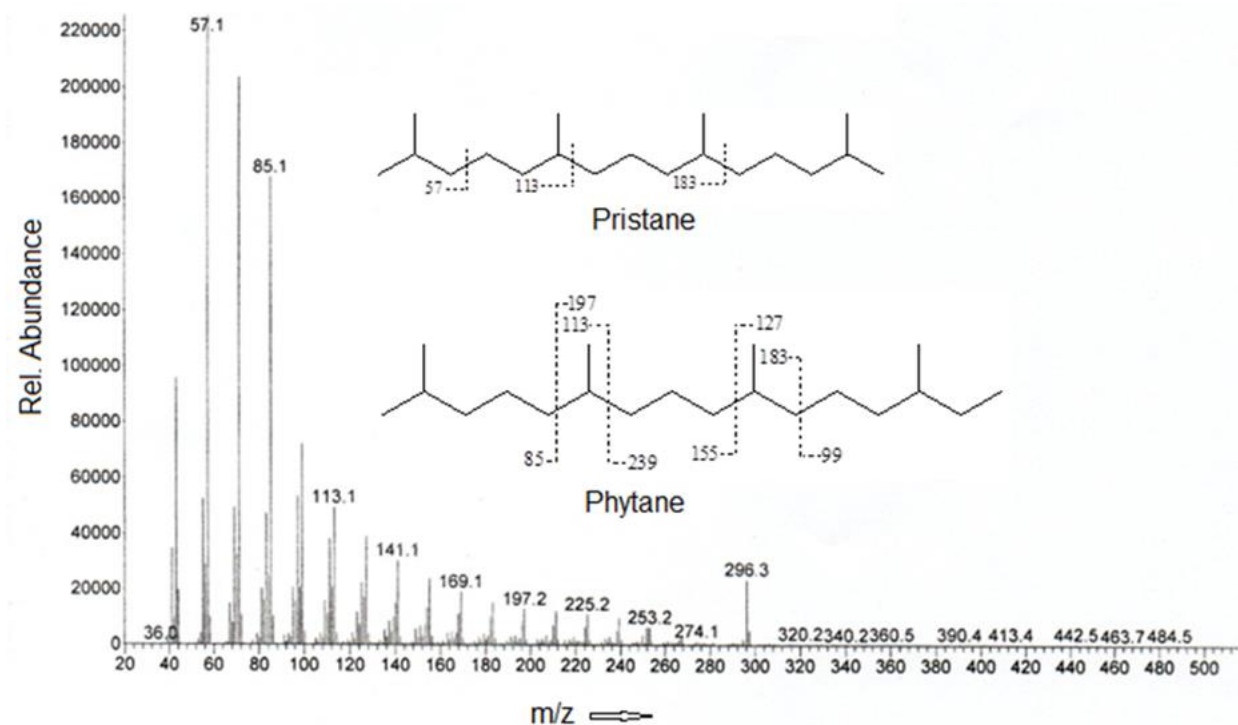
Figure 5. Fragmentograms of n-alkane (Inset shows structures of isoprenoids, pristine, and phytane)

Gas chromatograms for all the samples indicate that normal alkanes and isoprenoids are characterized by a unimodal distribution of n-C14 to n-C23 *n*-alkanes present (Fig. 6). The *n*-alkane profiles are dominated by short (nC14–nC20) or medium (C21–C23)- chain *n*-alkanes. The chromatograms also indicate the presence of acyclic isoprenoids such as pristane (Pr) and phytane (Ph) (Fig. 6). Pr/Ph ratios are relatively low,

ranging from 0.40 to 1.20 (unpublished data).. In addition, these isoprenoids are compared with their associated *n*-alkane concentrations (C17–C18). The isoprenoids/n-alkane (Pr/n-C17 and Ph/n-C18) ratios range from 0.63 to 0.86 and provide important information about the paleodepositional environment and offer a guide for redox settings and organic matter input [18].
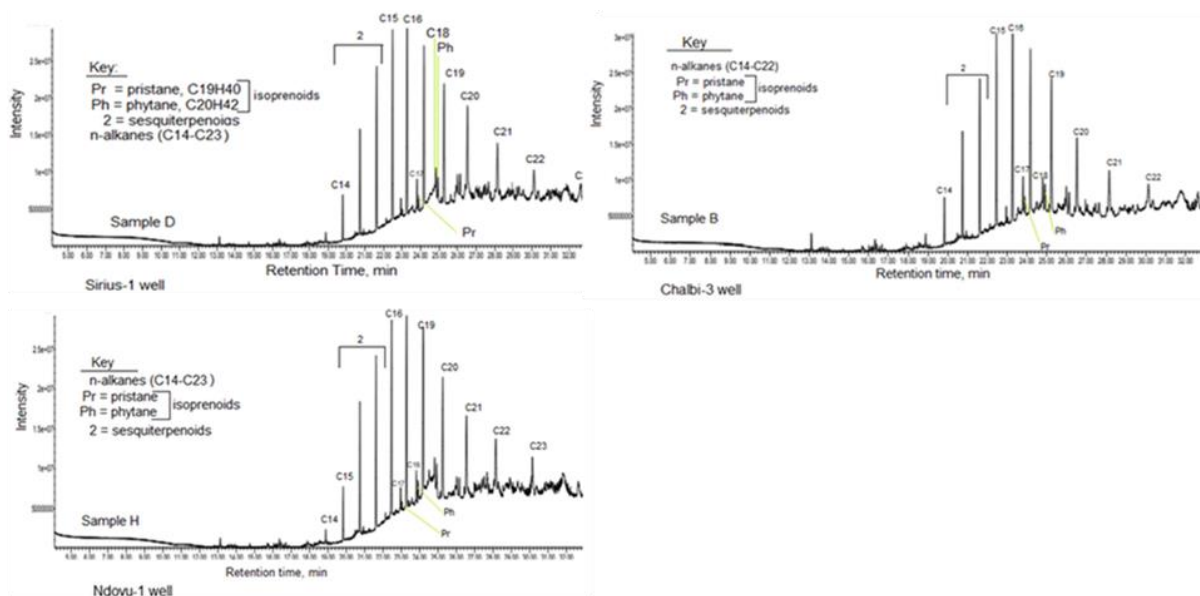
Figure 6. Gas chromatograms (TICs) of n-alkanes and isoprenoid hydrocarbons distribution in the selected source rock samples (with TOC > 1.5%) from Chalbi-3, Sirius-1 and Ndovu-1 well, respectively, determined via the total ion counts (TIC) by GC-MS

Discussion

Organic matter quantity (Richness) and Implications on source rock effectiveness

The organic richness of the sediments and their generative potential are gauged through TOC measurements [18,20]. The total organic carbon (TOC) ranges for all four source rock samples (Table 1) match the generally accepted criteria for fair to good potential to generate petroleum. The Ndovu-1 well, drilled from the South Anza sub-basin (Fig. 1) had the highest value of 1.99% %TOC at 1066 m, which contrasts all the values reported by Gilbert et al. [13] for the Ndovu-1 well that was below 0.50 wt % TOC threshold at the depth interval between 880 and 1350 m. The TOC contents reveal varying degrees of richness, which can be attributed to the environmental and burial depth's combined impacts. Our results' high %TOC value may be statistically insignificant, considering the small number of the analyzed samples. However, %TOC (wt.) cannot satisfy all the effective source rock evaluation requirements. One of the reasons is that thermal maturity affects the organic matter and reduces the original TOC by transforming the organic matter into petroleum and a residual [18]. Compared to the oil shale samples of Indian origin (which had carbon 6.1%, nitrogen 0.08%, and hydrogen 1.2%) and Tanzania (40% TOC) [30], our source rocks contain moderate amounts of carbon, hydrogen, and a comparatively low amount of nitrogen. The low content of nitrogen plays a vital role in improving the quality and stability of the extracted oil, particularly during refining and storage.

The organic matter type(s) is determined by the hydrogen index (HI = H/C atomic ratio). Tissot et al. (1974) [31] introduced a more straightforward nomenclature: Type I kerogen has a high H/C atomic ratio (*ca*. 1.5 and more; Type II kerogen is characterized by a relatively high H/C (1.2 to 1.5), and Type III has a H/C ratio of less than 1.0. The H/C ratios (0.19 to 0.60) of the studied source rock samples are low, indicating that the organic matter in these source rocks is oxidized and/or highly mature and is rich in type III/IV kerogen and mostly gas-prone kerogen [22].

Source of organic matter inputs and their paleoenvironmental conditions

In the present study, the distribution of normal alkanes and isoprenoids in the saturated HC fraction is described by a unimodal distribution. They are dominated by short-chain (< n-C20) alkanes characteristic of marine OM [32-34]. The long-chain hydrocarbons (>C20) in the examined source rocks also reflect the continental contribution of the organic matter from higher terrestrial plants [29]. Similar results have been reported where the homologous hydrocarbons of n-C14–n-C24 were derived from terrestrial environments and microorganisms during the formation process of petroleum organic compounds [13,14,23,33,34]. The higher contributions from the marine organic matter and some terrestrial source inputs into these source rock sediments are confirmed. The results indicate that the organic matter in the source rocks of the Anza basin is from both algal and terrestrial higher plant sources, which could be at an advanced stage of maturity. The other striking

molecular features of the extracted hydrocarbon oils are uniform in distribution patterns, which suggests that the hydrocarbon oils present are related and have undergone similar histories.

The contribution of the different organic matter types and their depositional circumstances can also be deduced using pristane and phytane ratios (e.g., Pr/Ph, Pr/n-C17, and Ph/n-C18) [18,35]. The lower Pr concentrations than Ph reveal a higher contribution of aquatic organic matter, such as algae, deposited under reducing conditions [13,32,35]. Hence, the studied samples showed relatively low Pr/Ph ranging from 0.40 to 1.20 (unpublished data), indicating that these source rock samples were deposited under suboxic to anoxic environmental settings. This shows all the samples contain a mixture of marine- and land-derived organic matter, though the Pr/Ph < 1 (i.e., 0.63–0.86) suggests the hydrocarbons in the oil extracts originated from marine organic sources under anoxic environmental conditions.

Mineralogy

XRF and XRD analyses indicate that the CaO content is relatively high compared to the low amount of MgO, reflecting the presence of calcite. The low percentage of Mg indicates the presence of dolomite in these samples, albeit in negligible amounts. The seminal work of Aliyev and Abbasov [36] recognized that sandstones characterized by high quartz content and SiO_2:Al_2O_3 ratios have a greater potential reservoir of quality petroleum. The SiO_2/Al_2O_3 ratios obtained from the present study were: Chalbi-3: {**C1** = 2.48; **C2** = 7.44}; Sirius-1: **S2** = 2.76; and Ndovu-1: **D1** = 2.98, respectively. These values (SiO_2/Al_2O_3) show that studied source rocks from the Anza Basin contain great potential reservoir quality for hydrocarbons in agreement with determined organic matter (0.5% ≤ TOC ≥2%) content. The FTIR, XRF, and XRD results also show that the studied source rocks contain organic matter (OM) and sandy-clay minerals. A mixture of clay and mineral components in organically carbon-enriched source rocks plays a fundamental role in the selective preservation of organic matter (OM) owing to their strong adsorption and catalytic properties during deposition and burial [27,37]. Thus, the viability of each field depends on its source rock. Alongside kerogen, the inorganic content of the oil shale/source rocks is an important ingredient in generating oil.

Implications for hydrocarbons exploration and development

Generally, the total organic carbon (TOC) ranges for all four source rock samples match the generally accepted criteria for fair to good potential for petroleum generation. The three wells have potentially extractable oil from 1066 - 3100 m. This makes them effective source rock candidates for generating commercial amounts of oil/gas in the Anza Basin. In addition, the accumulation of good source rocks within the sampled depths indicates the presence of an active petroleum system, as Gilbert et al. (2021) reported [13]. This conclusion will offer an excellent scientific base for potential prospects and exploration in the Anza basin.

Conclusions

This study was geared toward unraveling the hydrocarbon potential and mineralogy of the Anza basin and reached the following conclusions.

- The study has shown that the three exploratory wells source rocks from the Anza basin have high TOC content and low HI indices, indicating fair to good TOC content, suggesting that conditions in the Basin might favor organic matter production and preservation and also good petroleum-generating potential. The Ndovu-1 sample exhibited the highest TOC (1.99 ± 0.1502%) content and Sirius-1 samples [(D, 1.45 ± 0.1051%; F, 0.54 ± 0.0559%)] had mixed values. The source rocks' petroleum-generating potential varied with the wells' location and depths.

- The organic matter classifies these source rocks as containing mixed Type II/III kerogens, which may be oil/gas-prone if optimum maturity stages are reached. These are indicated by low to medium hydrogen index values (0.6–0.8 atomic ratios).

- The mineral part of the source rock samples mainly consists of quartz and silicate-clay components found in oil shales. The SEM, XRF, and XRD analysis results confirmed the presence of quartz and silicate–clay minerals. However, FTIR shows the aliphatic (C–H) groups in the region 3000-2800 cm^{-1} are absent, probably due to the dominance of the complex mineral composition interfering with the absorption of aliphatic and aromatic C–H groups owing to the low %TOC (< 2.0%).

- The composition and distribution of n-alkanes and isoprenoid biomarkers indicate a mixture of marine algal/bacterial and land-derived organic matter source input for the source rocks of the Anza basin. This is characterized by the abundance of short-chain n-alkanes, n < 20, and some long-chain n-alkanes, n > 20, and low Pr/Ph ratios.

- The N/C values of the organic matter are low, suggesting that the petroleum products from these source rocks have a high probability of higher environmental safety.

Acknowledgment

Conflicts of Interest

No potential conflict of interest or competing interest is foreseen.

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