New insights on Muglad’s Cretaceous source rocks: a paleogeographic review & organic geochemical characterization, Muglad basin, Sudan

I M, Omer Fadul Abul Gebbayin*1 & 2, N, Zhong*1, Q, Luo*1, E, Abu Elgasim*2 & S, Shi*1
1 State key laboratory of Petroleum Resources and prospecting, China University of Petroleum, Beijing-102249, China
2 Greater Nile petroleum Operating Company (GNPOC), Khartoum, Sudan
*Corresponding author E-mail: Omerabul_gebbayin@hotmail.com

Abstract. Pyrolysis, chromatographic, and isotopic techniques were applied to study a suite of (174) rock cuttings from Muglad’s block 2 & 4, aiming at identifying and fully characterizing the potential source rock/s in the basin. Two source rock units were recognized and described as good-very good for hydrocarbon generation in the study area. These include the middle Early Cretaceous Abu Gabra and the top Late Cretaceous Baraka formations. The former consists of a good-very good organic rich shales (TOC= 1.0-4.0 %, S 2 >20 mg HC/g TOC), of mixed kerogens dominated primarily by the oil prone type-I (HI= 600 mg/g) in association with few type-III, and is currently thermally mature for hydrocarbon generation in the basin peripheries and over mature in the centre. The Baraka displays a wide hydrocarbon generative potential ranging from fair to very good (TOC= (0.5-4.0%) and S 2 yield of (2.0-20 mg HC/g TOC), of mainly type-II oil and gas prone kerogen (HI= 450 mg/g), and thermally mature for hydrocarbon generation in the basin centre only.

Biomarker characteristics of the analyzed samples reveal three main organofacies units; a (I) fresh-water oxic to sub-oxic clay-rich Early Cretaceous distal lacustrine, (II) a highly anoxic, and clay-poor Late Cretaceousdistal marine, and a (III) proximal lacustrine and/marine of both E. and L. Cretaceous. Organofacies-I shows relatively high ratios of: [Pr/Ph (1.2-3.02), C 26/C25 tricyclic terpanes (1.11-3.12), Ts/Tm (0.95-1.33), gammacerane indices (0.14-0.50), and diasterane/regular steranes] with low: [tri- and tetracyclic terpanes, C 17/C25 n-alkanes (1.0-1.5), C29/C30 hopanes (0.55-1.14), and pregnanes & homopregnanes]. Organofacies-II inversely, is characterized by very low [Pr/Ph ratios (0.37-1.0) suggesting extreme anoxic conditions, C29/C25 tricyclic terpanes between (0.50-1.0), Ts/Tm (0.21-0.50), Gammacerane indices (0.05-0.22), and low diasterane/regular steranes (0.34-0.66)] with high: [tricyclic terpanes content dominated by the C 23 variety, C24 tetracyclic terpanes, C17/C25 n-alkanes ratios (3.7-5.12), C29/C30 hopanes (0.4-1.11), and abundant pregnanes and homopregnanes]. Organofacies-III is merely proximal sub-facies of the former two differentiated basically on the basis of the redox conditions of their corresponding depositional environments and amount of terrigenous organic matter supply. The isotopic data is fairly consistent with the biomarkers in delineating the same three organofacies units. We relate the marine input into Muglad basin during the L. Cretaceous to the global L. Cretaceous sea transgressions in Africa and thus foresee a booming new exploration opportunity in the basin.

1. Introduction

1.1. Background & study objectives
Muglad basin is a major member of the petroliferous Western and Central African Rifts System (WCARS) with estimated reserves of 2,053 mm bbl. The basin has been under intensive oil exploration and production activities since the early seventies when Chevron overseas first initiated the hunt for oil and gas in the area. Significant achievements have been made up to date with the discovery of giant oil fields such as Unity, Heglig, Toma South, Hamra, El Toor, and Bamboo, Munga, and Neem fields. The central part of the basin, known as the Kaikang trough however remained less explored due to several reasons. The area remotely lies within a rugged, swampy terrain, water-flooded nearly all the year round, and with scarce human activities restricted mainly to wild fishing and animal husbandry. Security issues have also been a challenge for quite long as the area has been...
devastated by the everlasting civil war since the independence of Sudan from the British colonialism in the early fifties. The area witnessed only a short unwavering peace period with the accomplishment of the Comprehensive Peace Agreement (CPA) signed between the Sudanese government and the South Sudanese rebellions in 2005. However, with the cessation of the Southern Sudan as of late 2011, situations were back again to escalating instability especially along the border lines between the two sister states.

Geology likewise, has its immense imprints on the complexity of the area as the basin is known to have witnessed three rifting episodes; Early Cretaceous, Late Cretaceous, and early–middle Tertiary, respectively [2]. Of these, the third cycle has the most spectacular impact on the petroleum system of the study area. During this period, the area is believed to have undergone vigorous restructuration in which old Cretaceous oil pools were breached and oil re-migrated up-dip into the newly formed traps of Tertiary age. In general, the complex geology and logistical constrains which collectively contributed to the current G&G data inadequacy, had led to the reality that very little is known on the nature of the petroleum system/s in the study area. Issues such as the active source rock/s that is/are actually charging the reservoirs in the area need to be investigated.

In spite of several exploration drillings in the Kaikang Trough, nevertheless, the overall achievement was such disappointing that the various operating companies opted to lower down their exploration activities in the area to the minimum. Out of around twenty wells drilled since Chevron times (early seventies), oil was found at four locations only; Kaikang, El Mahafir, Sunut, & Lol. Unlike the norm in the basin, the first two wells tapped oil in unusually young reservoirs of (Early Miocene-Oligocene) and (Early Oligocene-Eocene) ages respectively, whereas the later two have their oils in Cretaceous reservoirs. The oil in El Mahafir is believed to have been generated from the Abu Gabra source rock between 92-45 Ma and re-migrated later to a Tertiary trap during the Tertiary tectonism [3]. Such a complex geology and very low exploration success rate inspired the authors to investigate on the nature of the Cretaceous rocks in the Kaikang Trough, study their potentiality for hydrocarbon generation, and to foresee the overall future HC prospectivity of the area.

1.2. Location of the study area
The study area occupies the central part of the Muglad basin, also known as the Kaikang Trough, represents the bulk exploration area of GNPOC’s block-4 exploration lease with an area of 15,609 sqKm (Fig.1.2.1). GNPOC is a consortium of the China National Petroleum Company (CNPC), Petronas Carigali Overseas SdnBhd (PCSOB), Indian ONGC Videsh Ltd (OVL) who inherited Talisman Energy Inc.’s stake after withdrawal from the consortium in March 2003, and the Sudanese Petroleum Corporation (Sudapet) at an equity share of 40%, 30%, 25%, & 5% respectively. As a part of block-4 which used to be operated by GNPOC together with blocks 1 & 2, the area has recently been partially relinquished to the government of Sudan as stipulated by the current EPSA (Exploration & Production Sharing Agreement).
Fig.1.2.1 Location of the study area within the Sudanese framework of sedimentary basins, from Giedt, 1990[4](top) and GNPOC’s blocks 1, 2, & 4 concession map showing the outlines of the study area in red colour (bottom).

1.3. Tectonic evolution of the Muglad basin

Study of the tectonic history of sedimentary basins is crucial in the sense of understanding their hydrocarbon prospectivity. Tectonically, Sudan is part of the “Saharan Metacraton” which is believed to have witnessed several tectonic events during its life history[5-6]. It’s evident that a Neo-Proterozoic Pan-African tectono-thermal event has deformed an earlier active Pre-Neo-Proterozoic both oceanic and continental crusts in various forms such as metamorphism and emplacement of igneous bodies that eventually created what is presently known as Sudan’s “Pre-Cambrian Basement Complex” which represent the oldest rock units that today floor all Sudanese basins[6].

For the tectonic evolution of the Muglad basin, both a “Pull-apart” and rifting models have been suggested by earlier workers. Tim R. McHargue et al, ((1992) from Chevron Overseas developed a model for the tectono-stratigraphic history of the rift basins of the Southern Sudan. They have identified three rifting episodes, concomitant subsidence, and non-marine/non-volcanic sedimentation[2]. The Chinese Research Institute for Petroleum Exploration and Development (RIPED) disclosed in 1999 the rifting model judging from the depositional system styles, the tectonic cycle and the formation and distribution of oil pools. RIPED furthermore (in the same report), still suggest a “Pull-apart” model for the basin development based on the distribution pattern of highs and lows, the shift of the basin depo-centre with time, and the formation of traps as characteristics for such basins[7].

Recently,Fairhead, J. D. et. al., (2013)summarized the tectonic evolution of the Muglad basin as: a Neocomian-Barremian first syn-rift stage (142-120 Ma), followed by a second Aptian-Cenomanian (119-101 Ma) rift that was terminated by a regional unconformity, a Late Santonian-Baesian basin inversion event (84 Ma), a Late Senonian rifting (83-66 Ma), End Cretaceous Tectonics (65 Ma) which was associated with minor folding and faulting, Paleocene to Middle Eocene Quiescence or Rifting (57-38 Ma), and eventually an Early Late Eocene transpression (37 Ma)[8].It’s during the Late Senonian-Maastrichian rifting episode (83-66 Ma)that the authors believe the basin started receiving intermittent marine inundations that resulted in the marine signatures observed in this study which are detailed in the following sections.
1.4. Geology of the Muglad basin

Basic geology of the Muglad basin essentially comprises a group of rocks and sediments that vary in age from the Precambrian to the Quaternary. Literally, we can classify these rocks and sediments into two main categories:

1.4.1. Basement rocks

As the well-known Sudan’s Basement Complex, these are the oldest rock units in the basin, of Precambrian age that furnish the base of the basin\(^9\), and on top of which a group of sediments and sedimentary rock sequences unconformably rest. Distinct basement outcrops engulf the country from both the western and eastern boundaries shown in pink (Fig. 1.4.1).

In general, the Basement Complex of Sudan includes: high-grade metasediments such as Quartzites and marbles that are found in association with Amphibolite-facies gneisses and metasediments within a low-grade volcanogenic ophiolite assemblages such as in the Red Sea Hills of Eastern Sudan\(^5\), and high-grade granitoid gneisses that are associated with either inliers of high-grade metasediments (e.g. Bayuda, Nubian desert, North Kordofan belt, Darfur belt, and Nuba Mountains) or a low-grade volcanogenic ophiolite assemblages (e.g. Bayuda, Nubian desert, and Nuba mountains).

In the Muglad, the basement has been encountered in the peripheral parts of the basin at different locations. Granitic gneisses were penetrated at several wells throughout the basin, while marble has recently been hit by GNPOC at nearly 3,500 m in one well in block-2 area. Muglad’s basement was proven to be oil bearing (e.g. Block-17) however, no major commercial discovery is made so far.

![Geological map of Sudan (modified after the Ministry of Energy & Mines, Geological & Mineral Resources Department, Khartoum, 1981).](image)

1.4.2. Sedimentary cover & chronostratigraphy

A group of sediments and sedimentary rocks of ages ranging from the Late Jurassic??/Early Cretaceous to the Quaternary period that were unconformably lain on top of the Pre-Cambrian basement rocks (Fig. 1.4.1). They are all of elastic and continental origin in the study area except for the Late Cretaceous sequence whose organic geochemical and stable carbon isotope data show strong evidence for a marine origin as discussed by the authors in this paper. Sedimentation in the basin took place as a result of three rifting episodes: (I) end Jurassic??/Early Cretaceous, (II) L.Cretaceous, and (III) Tertiary (Fig. 1.4.2). The first rift ended with the accumulation of a thick non-marine sandstones and organic-rich shales and mudstones of the Abu Gabra formation (Neocomian-Barremian) representing the major source rock in the basin. Widespread fluvial sandstone of the Bentiu formation...
(Aptian-Cenomanian) was uncomformably deposited on top of the Abu Gabra and is considered the major reservoir in the basin. A thick reddish-brown flood plain mudstone of the Aradeiba formation (Santonian) represent the top seal of the E. Cretaceous petroleum system. The formation comprises some good intra-formational sandstones reservoirs. A progradational sequence of intercalated sand-shale units within the Darfur group uncomformably overlie the Bentiu shales and provide good reservoirs for the system. The topmost portion of this sequence provide a good quality source rock rich in algal type-II marine kerogen i.e. Baraka and Ghazal formations (Campanian-Maastrichian) which was followed by a thermal sag phase resulting in the deposition of thick massive fluvial sandstones of the Paleocene Amal formation. The basin again witnessed fluvio-lacustrine conditions during the Tertiary rifting that resulted in thick shales of the Nayil and Tendi formations which represent good top seals to the Amal, Nayil, and Tendi sandstone reservoirs (Fig. 1.4.2).

![Fig. 1.4.2 Muglad’s Chrono-stratigraphic chart based on Palynological data modified after [9; 10]](image)

### 1.5. Previous work

Chevron Overseas Petroleum exploration initiated the early systematic work on Muglad Basin’s source rock and oils characterization in the early seventies. From nearly fifty wells, Chevron worked on some Vitrinite reflectance (VRo), Spore Colour Indices (SCI), Kerogen typing, Pyrolysis Tmax, and Borehole Temperature (BHT) data. Depending on GC & GCMS data of some Muglad oils, Chevron concluded that they (oils) originated from one family and further noted four subdivisions that they attributed to variations within source rock facies[11;12].

Several other workers also studied Muglad’s data including Robertson Research Inc. (RRI), 1984; Paul Gunther (1995, 1996); Waples, (1997); Graham Dolby, (1998); Moffat et al., (2000); Omer Ibrahim & Ahmed Mahgoub, (2007); Wellstrat Services Limited, (2007); CNPC-IRC, (2010)[13-21]. The source potential and lacustrine origin of the Early Cretaceous Abu Gabra source rock as the major source responsible for the generation of Muglad oils has widely been agreed on by all workers. Other potential source rocks included the Campanian-Maastrichian Baraka shales plus the Tertiary Tendi and Nayil shales[11;12].

Much of the research on Muglad’s petroleum system has previously been focusing basically on the basin’s E. Cretaceous as it represents the main exploration target and thus very little is known about the L. Cretaceous. In order to understand the L. Cretaceous geology of the basin, it’s necessary to view it in the context of the global tectonic and climatic changes that prevailed during this important geologic period. The events that took place towards the end of the Cretaceous have well been documented by several workers e.g. (Haq et al, 1987; Jenkyns
et al, 2004; Miller et al, 2004, 2005; Miller and Pekar, 2005; Guiraud et al, 2005; Müller et al, 2008). The development of numerous mantle plumes through the then widening mid-oceanic ridges in association with intense volcanic activity have provoked greenhouse conditions due to the emanation of huge CO₂ quantities into the atmosphere. Temperatures consequently increased resulting eventually in rising sea levels which inundated nearly one third of the globe and created a number of epi-continental seas such as the Trans Saharan Seaway (TSS) in Africa and the Western Interior Seaway (WIS) in North America, as characteristic features of the L. Cretaceous paleogeography. Muglad basin was within the midst of these situations and thus, must have been affected by these transgressions (Fig. 1.5.1).

Fig.1.5.1 Late Cretaceous paleogeography of the globe and location of the Muglad basin with respect to the TSS and Tythes seas, modified from Greg Neyman, Old Earth Ministries online.

Based on Maarten de Witt’s, (2007) topographic model of Africa during the greenhouse world, it seems Muglad basin as well as most WCARS basins has extensively been inundated by the vast marine invasion (Fig.1.5.2).

Fig. 1.5.2 Mesozoic topographic model of Africa normalized to the high sea level of the ice-free Cretaceous greenhouse world and location of the Muglad & other WCARS basins, modified from.
Anoxia during the L. Cretaceous Africa and Mediterranean has previously been reported by Mücke who described the regionally extended belt of ooidal ironstone deposits from Nigeria to Egypt through Sudan\cite{31}. These deposits are rich in pyrite and siderite which readily form in highly anoxic environments. Very good source rocks were deposited over the globe during this time at shallow marine seas and 85% of global oil has been generated from black shales that belong to this period\cite{32-33}(Fig.1.5.3). Our current source rock investigation proves the existence of organic-rich shales within Baraka and Ghazal formations in the study area that indicate highly anoxic depositional environments.

For the Cretaceous geology of Sudan, Klitzsch&Wycisk were the pioneers who reported on the L. Cretaceous marine incursions in some Sudanese interior basins. Investigating the outcrop geology of areas such as Wadi Howar, Jabal Abyad, and Dongola in NW Sudan, they noted shallow marine deposits within the Campanian-Maastrichtian Kababish formation which they attributed to the Campanian-Maastrichtian Tethyan marine transgression\cite{34}. In their work they did not rule out the possibility of the extension of this transgression further southwards beyond their study area, a thing that has already been proven later by several works such as Barazi& Fiedler, (1993), Mücke, (2000), and this study (Fig.1.5.4).
Working on marine ichnofossils and marine fauna (e.g. Thalassinoides and Deplocriterion), Barazi & Fiedler (1993) were able to extend the Campanian-Maastrichtian Tethyan transgression up to Hamrat el Wuz locality, few kilometers NW of Khartoum[35]. Mücke, (2000) discussed the Late Cretaceous Kaolinitic and Chemositic ooidal ironstone deposits belt that extends from Nigeria to Egypt through Sudan. He correlated the oolites of Shendi formation (Ahra basin) with those of Wadi Howar which was once considered the southernmost limit of the Late Cretaceous Tethyan transgression in Sudan by Klitzsch & Wycisk[31]. A Campanian-Maastrichtian age has been assigned to the subsurface Shendi Formation by Eisawi based on miospores data from two shallow water wells in the area[36].

Based on a notion from a literature review as part of a sedimentological work on ~800 m core data, Evoy, et al., 1999) highlighted information on the presence of submarine fan deposition within the Aradeiba formation of the Muglad basin (Santonian). They further inferred that such a model only fits with a transgressive surface at the Bentiu-Aradeiba contact, a maximum flooding surface within lower Aradeiba, and the whole Darfur Group (Aradeiba-Ghazal) as a single progradational sequence (i.e. HSST)[37]. Recently Yousef M. Makeen, et al, (2015) reported that the source rocks for some 15 Fula oils (Muglad basin) is not pure lacustrine but it rather shows strong marine influence[39]. Most recently, An, K. et al, (2017) reviewed the stratigraphy and sedimentary data of
22 north Africa continental basins and they concluded that extensive marine facies dominated the L. Cretaceous of these basins including Khartoum basin which witnessed the deposition of subordinate limestone during the Maastrichian[40](Fig. 1.5.4).

Luckily, a lithological prove for the marine input in the basin comes from Tmr-1 wild cat where around four hundred meters section of the topmost L. Cretaceous Baraka formation, was reported to be a calcareous and “chalky” lithology (Fig.1.5.6). We tend to explain the emplacement of such a lithology within a known continental setting through a sea transgression event. A strong biostratigraphic evidence also stems from the reporting of two dinoflagellates species; xochosphaeridium/Downiesphaeridium group and Spicadinium sp. cf. S. nenjiangense(Fig.1.5.7) that have been identified at the base L. Cretaceous in the Muglad basin from Kng W-1 well (Fig. 2.1) by Omer Babiker (Unpublished PhD thesis at the University Technology Malaya & personal communications with him).

Fig. 1.5.6 Part of the Mud log covering the upper section of the Baraka formation (Maastrichian) at Tmr-1 well showing nearly 400 m chalky lithology.

Fig. 1.5.7 Two Dinoflagellates species noted at the base L. Cretaceous of the Muglad basin from Kng W-1 well (Omer Babiker, personal communication)
2. Samples and analytical methods applied

A source rock characterization is conducted with the objective of analyzing and highlighting the main potential source rocks that could charge the reservoirs in the study area. For this, a total of 174 cuttings samples covering the whole stratigraphic section from as old as the Early Cretaceous to as young as the Pliocene sediments were collected and analyzed at the State Key Lab of Petroleum Resources & Prospecting (SKLPRP) of China University of Petroleum in Beijing. Samples were precisely chosen from eight wells such that the whole study area (i.e. Kaikang Trough) is thoroughly covered (Fig. 2.1). Analysis results were augmented with analysis data from some other four wells (Elm-1, Elg-1, Elf AG-1, and ET-6) that was previously acquired by GNPOC in the past years for a better constraint.

Fig. 2.1 Sampling locations of the studied wells shown on a top basement depth map of GNPOC’s blocks 1, 2, & 4 (smiley=discovery wells and crosses= dry holes).

Analytical techniques included: Rock-eval Pyrolysis using OGE-II workstation, determination of Total Organic Carbon (TOC) using Leco CS-230 machine, and stable Carbon isotopes measurements using EA-MAT 253 IRMS machine. Due to the fact that the samples quantities obtained from GNPOC were not sufficient enough to carry further analysis such as Vitrinite reflectance (Ro), earlier acquired Ro data was used for thermal maturity determinations of the organic matter in combination with Pyrolysis T_{max}. All data show high consistency and integrity despite the fact that they were acquired through different labs and at different times.
3. Discussion of results

3.1. Source rocks organic geochemical characterization from Pyrolysis results

This is basically a screening test that involved aspects such as the organic richness, kerogen quality and thermal maturity of the different source rocks in order to determine their hydrocarbon generation potential. Total Organic Carbon content (TOC) and Pyrolysis S2 yield were used as tools for the assessment of hydrocarbon generation potential. The TOC-determined generative potential of the rocks in this study is as per the classification by (Tissot & Welt, 1984) and (Hunt, 1996)[41-42]. While the S2-determined generative potential is following the classification by (Peters & Cassa, 1994) and (Peters, 1986)[43-44]. Likewise, Kerogen quality and types were deduced using Tissot & Welte’s (1984) HI vs. T\textsubscript{max} cross-plot[41]. Thermal maturity of the analyzed rocks are determined using pyrolysis Tmax and Ro data following (Peters and Cassa, 1994)[43](Table.3.1). Obtained results are discussed in the following section:

| Stage of maturity for oil | Maturation | Ro (%) | Tmax (°C) |
|-------------------------|------------|--------|-----------|
| Immature                |            | 0.2-0.6| <435      |
| Mature:                 |            |        |           |
| Early                   |            | 0.6-0.65| 435-445  |
| Peak                    |            | 0.65-0.9| 445-450  |
| Late                    |            | 0.9-1.35| 450-470  |
| Post mature             |            | >1.35  | >470      |

3.1.1. Tertiary rocks sequence (Paleocene-Pliocene)

TOC content and S2 yield show organically rich shale units within this sequence (e.g. Adock, Tendi, and Nayil formations in wells such as Elg-1, Tmr-1, and Lo-1 (Figs. 3.1.2a &b). In general, TOC and S2 contents shown by these shales fall within the “fair- excellent” category with values in the range of (0.5->4 % TOC) and (2.5<S2> 20 mg HC/g TOC) respectively. This is a good indication for a high generation potential of the Tertiary sequence within the study area (Fig. 3.1.1).

Fig.3.1.1 Characterization of the organic richness of the Tertiary shales in the Kaikang Trough expressed by plotting S2 versus TOC% data.

Geochemical logs showing organic richness variations within the study wells are displayed in the following figures (Fig.3.1.2a and b). Some wells show very rich Tertiary sections e.g. Elg-1, Tmr-1, and Lo-1 whereas wells like Elm-1, Tim-1, & Lwk-1 show poor organic richness.
Fig. 3.1.2a Organic richness of the Tertiary shales sequence in the Eastern Kaikang Trough expressed by TOC, S2, & HI variation with depth, red arrows point to rich intervals.

Fig. 3.1.2b Organic richness of the Tertiary shale sequence in the Western Kaikang Trough expressed by TOC, S2, & HI variations with depth, red arrows point to rich intervals.

Kerogen types deduced from the Pyrolysis Hydrogen Indices (HI)Vs. T\text{max} cross-plot (Fig. 3.1.3) show values in excess of 600 mg HC/g TOC which represent type-I oil-prone kerogens, with others showing HI between (75-200 mg HC/g TOC) indicating kerogen type-III variety that is capable of generating gas\cite{41}. There is an indication for free hydrocarbons within the Tertiary section (Fig. 3.1.3).
Thermal maturity determined using Vitrinite reflectance (Ro) and Pyrolysis $T_{\text{max}}$ data is shown in the following chart (Fig. 3.1.4). In general, both parameters show fairly consistent maturation profiles for the Tertiary rock sequence placing it in the immature window at nearly all locations. $T_{\text{max}}$ partially, shows a slightly higher maturity to the stage of early oil generation in some wells. However, $T_{\text{max}}$ is known to be easily affected by several factors including variations in the types of organic matter and mineral matrix \cite{44-45}.

3.1.2. Late Cretaceous sequence (Santonian-Maastrichtian)
This section includes a group of rock units that were deposited during Muglad’s second rift phase (Santonian-Maastrichtian). Evaluation of the hydrocarbon generation potential of this sequence is based on data from seven wells in the study area; four from the western flank of the trough namely; Tim-1, Zna-1, Lwk-1, and Lo-1) plus another three from the eastern flank; Elm-1, Elg-1, and Tmr-1(Fig.2.1). In general, this sequence falls below around 2,000 m depth in the study area.
The organic matter of these rocks could be ranked as fair-very good with TOC values between (0.5-4.0%) and S2 yield of (2.5-20 mg HC/g TOC). These values reveal a good hydrocarbon generative potential for this sequence (Fig. 3.1.5).

Fig. 3.1.5 Organic richness of the L. Cretaceous shale units in the studied wells as expressed by the TOC versus Pyrolysis S2 cross-plot.

The L. Cretaceous shales show distinct lateral variations as far as their organic richness is concerned. It’s quite noticeable that the sequence is much richer in the eastern trend than the western (Fig. 3.1.6a and b). Proximity to the sediment supply sources could be the reason for these lateral facies variations. The analyzed samples show non-source intervals presumably due to intensive reworking particularly in the western flank wells such as Lol, Zna-1, and to a lesser degree, in Tim-1 (Fig. 3.1.5). This could be attributed to sub-aerial exposure of the sediments at the western flank (i.e. more proximal), while a better preservation could be noted in the more distal eastern flank (Fig. 3.1.6a & b).

Fig. 3.1.6a Organic richness of the L. Cretaceous shale sequence in the Kaikang Trough as expressed by TOC, S2, & HI against depths for eastern flank wells. Red arrows point to the rich intervals.
Unlike for the Tertiary section, the quality of the organic matter of the L. Cretaceous shales as revealed by the Pyrolysis $T_{\text{max}}$ and Hydrogen Indices (HI) cross-plot interestingly shows a mixture of mainly, types-II, -III, and some reworked type-IV kerogens at the bottom of the graph (Fig.3.1.7). Predomination of type-II kerogen in the organic matter of these extracts was the starting point that invoked the authors to look into the possibility of a marine tint in these rocks as it’s well known that Kerogen type-II is mainly of marine origin [46-47]. Biomarker, C-isotopes, lithological, paleogeographical, and recently acquired biostratigraphical data all conclusively support this hypothesis as discussed in the following sections (3.2- 3.4).

Fig.3.1.7 Pyrolysis $T_{\text{max}}$ versus HI cross-plots illustrating the kerogen types of the Muglad’s L. Cretaceous rocks sequence in the study wells.
The thermal maturation of the L.Cretaceous rocks is similarly investigated using Vitrinite reflectance and Pyrolysis T\textsubscript{max} data. Both parameters are consistent showing the sequence as mature and well within the oil window (Fig.3.1.8). Ro data for wells like Tim-1 and Zna-1 indicate they even entered late generation stages (Ro = 0.9-1.35 %).

3.1.3. Early Cretaceous (Barremian-Neocomian), Abu Gabra Shales
Cutting samples from five wells were collected and analyzed in order to characterize the Abu Gabra shales in the study area; four wells located along the Eastern flank of the trough (i.e. Nm K-1, -2, Nm D-1, and Elf AG-1) plus one from the western (i.e. Lwk-1)(Fig.2.1). Currently there is no Abu Gabra penetration in the centre of the trough due to the greater burial depths, information on the likely presence and characteristics of this formation could therefore only be inferred from seismic and/or oils discovered in the trough.

With the exception of Lwk-1, the Abu Gabra shales in the study area show fair-very good organic richness with TOC values between (0.5-4.0 %) and S\textsubscript{2} between (2.5-30 mg TOC/g rocks). Few samples lie within the poor/non-source category with TOC <0.5 and S\textsubscript{2} yield <2.5 mg TOC/g rock), see (Fig.3.1.9). Abu Gabra is therefore, of high generative power where penetrated in the study area.

An obvious vertical variation in organic richness of the Abu Gabra formation could be observed with a top and bottom organic lean sections as seen in Nm D-1 and Nm K-1 and a middle organic rich interval in the three wells (Fig.3.1.10).This is fairly consistent with what has been noted by several workers previously\cite{48-49}. The upper section is missing in both NmK-1 & 2 due to erosion as top Abu Gabra is an unconformity in the basin, while it’s preserved in Nm D-1 because it’s located more basin-wards. Results of Lwk-1 are highly inconclusive due to incomplete sampling coverage. Analyses have covered only the top 165 m section of the nearly 2,000 m penetrated Abu Gabra in this well, which is completely organic lean and non-source. It shows very poor organic
richness with TOC < 0.5% and S2 yield < 0.2 mg TOC/g rock (off-scale) and therefore, used here just for reference. More analysis is needed to cover the remaining deeper section of the Abu Gabra for a better evaluation (Fig.3.1.10).

Fig.3.1.10 Organic richness of the E. Cretaceous Abu Gabra shales in Kaikang Trough as expressed by TOC, S2, & HI against depths for the study wells.

Qualitatively, the Abu Gabra formation shows a very good kerogen quality made up almost exclusively of the type-I kerogen (HI= 600-750) in association with few humic type-III (HI <150), (Fig.3.1.11). The formation is thus characterized by a mixed kerogen quality and shows high potential for oil generation. This is typical for an open lake system that could accumulate both sapropelic as well as humic organic matter from the surroundings as was the case for the basin during the E. Cretaceous times.
Fig. 3.1.11 Pyrolysis $T_{\text{max}}$ versus HI cross-plots illustrating the kerogen types of the Abu Gabra Formation in the study wells.

The kerogen quality of the Abu Gabra penetrated section in Lwk-1 (not shown in Fig. 3.1.11 above) is very poor as it is comprised entirely from inertenic type-IV kerogen (HI < 50) that is not capable of generating any hydrocarbons upon maturation. However, as mentioned above, this should not be taken to rule out the potentiality of the Abu Gabra in the western Kaikang flank since the penetrated interval in this well is not fully analyzed. Further investigation on the deeper section must be carried for a decisive conclusion (Fig.3.1.12).

Thermal maturity analysis using Vitrinite reflectance ($R_o$) and Pyrolysis $T_{\text{max}}$ data is carried in order to determine the thermal maturation status of the Abu Gabra source rock at the trough’s margins. In general, both parameters show fairly consistent maturation profiles for both the eastern and western flanks wells placing the formation well within the peak oil generation window ($R_o=0.7-1.2\%$ & $T_{\text{max}}=435-465^\circ\text{C}$ roughly below 2,500 m and at a wet gas generation ($R_o>1.2\%$ & $T_{\text{max}}>465^\circ\text{C}$) at around (3,900 m) at all well locations (Fig.3.1.12).

Fig. 3.1.12 Thermal maturity of the E. Cretaceous Abu Gabra shales as indicated by $R_o$ and Pyrolysis $T_{\text{max}}$ parameters against depth for the study wells.
An important observation is that, Ro in Nm K-1 & Nm K-2 shows immaturity for the formation in these two wells, indicating an obvious Ro suppression case (Fig.3.1.13). This is believed to be due to contamination with migrated hydrocarbons judging from the cross-plot of Pyrolysis Tmax vs. PI of (Fig. 3.1.13) which clearly indicates migrated hydrocarbons in these two wells only. As discussed in Peters, (1986), Mukhopadhyay & Dow, (1994) and Jose Iglesias et al., (2001), impregnation with migrating hydrocarbons leads to suppression in Ro values \[44; 48-49\].

3.2. Source rocks biomarker characterization:

Rocks that successfully passed the screening test (section 3.1 above) are considered hydrocarbon sources that further required detailed geochemical analysis in order to understand more details on their organochemical characteristics. Only two source intervals were qualified for this in this study namely; the E. and L. Cretaceous Abu Gabra and Baraka formations respectively. Both rocks units have shown high ranks as far as the organic richness, kerogen quality, and thermal maturity are concerned. Although the Tertiary sequence has shown excellent organic richness and kerogen quality, nevertheless they are excluded due to immaturity.

Biomarkers are complex molecular fossils derived from biochemical, particularly lipids, in once-living organisms \[50\]. Similarly, they could also be defined as any of a suite of complex organic compounds composed of carbon, hydrogen and other elements such as oxygen, nitrogen and sulphur, which are found in crude oils, bitumen, petroleum source rocks and eventually show simplification in molecular structure from the present organic molecules found in all living organisms \[51\]. Numerous biomarker applications are currently widely used by the geochemists in the course of hydrocarbon exploration, development, and production. Most commonly, they are used in the determinations of the organic facies, depositional environments, and thermal maturity of the organic matter contained in source rocks, crude oils and bitumen.

The "organic facies" concept was first introduced by Rogers in 1980 in his famous article: "application of organic facies concepts to hydrocarbon source rock evaluation" \[52\]. Several workers discussed the concept afterwards \[43; 53-54\], and a number of definitions were set to describe the term. Tyson (1995) defined it as: a "group of sediments having a distinctive set of organic constituents that can be recognized by microscopy or be associated to a characteristic organochemical composition". A proposal by Jones and Demaison (1982) defines it as: a detectable subdivision of a certain stratigraphic unit which can be discriminated by the characteristics of the organic constituents without considering the aspects of the inorganic component of the sediments \[55\].

Organic petrography and geochemistry parameters have also been in use to characterize an association of sediments as "organic facies" defined by the virtue of the organic matter content, its source, and depositional environment \[53\]. Application of the "organic facies" concept can assist in identifying both small and large scale cycles associated with transgressive-regressive events in a basin \[54\]. The ultimate objective of the organic facies studies is the prediction of the likely occurrence of hydrocarbon source potential as a function of depositional environment \[54\]. In this study and using Conford, 1980’s definition of "organic facies" we managed to identify three major organofacies subdivisions within Muglad’s Cretaceous rocks sequence namely; I-distal lacustrine, II-
distal marine, and III-marginal lacustrine & marine. We were able also to identify a marine transgressive cycle into the basin during Campanian-Maastrichtian time.

Out of the one hundred seventy four (174) rocks samples analyzed for organic geochemical characterization in this study, nineteen (19) samples have passed the initial screening test with good-very good organic richness (TOC 1.0-4.0 %) and thus qualified for detailed biomarker and isotopes chemistry analysis. The organic matter in these rocks was solvent extracted, undergone Thin Layer Chromatography (TLC) in order to obtain the hydrocarbon fractions (i.e. Saturates, Aromatics, and polars). The saturate fractions were then analyzed for Gas Chromatography (GC) and Gas Chromatography-Mass Spectrometry (GC-MS) analysis in order to study the biomarker compositions of these rocks as well as stable carbon isotopes. As will be discussed in the following section, this data, integrated with previously acquired biomarker and isotope data, is used to determine the organic facies and depositional environments plus the thermal maturities of the study rocks.

3.2.1. Organic facies & Depositional environments
Investigation on the organic facies and depositional environments of the rocks extracts in this study is carried using saturate GC and GC-MS biomarker and C-isotope data. Based on this, three organo-facies and their corresponding depositional environments were recognized: (I) a fresh-water oxic to sub-oxic clay-rich lacustrine, (II) a highly anoxic clay-poor marine, and (III) a proximal marine and lacustrine (Fig.3.2.1).

A. GC biomarker signatures:

N-alkanes and Mono-methyl branched alkanes (MMAs) distributions:
Characteristic biomarker types obtained from gas chromatograms include the widespread alkane group (i.e. n-alkanes, isoprenoids, Mono-methyl branched alkanes (MMAs), cyclic alkanes, etc.). N-alkanes represent major constituent of the organic matter in oils and rock extracts. A group of Mono-methyl branched alkanes (MMAs), which originate either from plant waxes (C25-C31) or cyanobacteria (C13-C19) are also a common feature. Generally, gas chromatograms are correlated by comparing the shapes of the n-alkanes distributions, the unresolved complex mixtures (UCMs), and some individual specific compound peak intensities. It has been found that relative distribution of some n-alkanes hydrocarbons could be used to predict the organic matter source and depositional environment. For instance, C27-C33 long-chain n-alkanes enrichment in rock extracts and oil samples is attributed to stronger input of higher plants (e.g. lipids) and terrestrial material. Submerged/ floating aquatic plants show enriched mid-chain n-alkanes in the range of C21-C25. N-alkane distribution with abundant short-chain C15-C19 suggest marine input from algal and bacterial biomass. Concentration of the high molecular weight (HMW) n-alkanes beyond the n-C20, generally decrease with increasing Carbon number in rocks and oils of a typical marine origin. Predominance of n-C17 over n-C25 n-alkanes suggest strong marine organic matter input in the sediments and could similarly relate to maturity.

The chromatograms (GC & TIC traces) of the analyzed samples show two main shape patterns for n-alkanes distribution indicating two major organo-facies groups; a sharply-headed bell-shaped and a widely-headed one (Fig.3.2.1). The later, seen in the extracts of the E. Cretaceous Abu Gabra source (represented for in (Fig.3.2.1) by ET-6-Ag-3020 & NmK-1-Ag-3030 samples), is characterized by a wide and more or less flat UCM humps and a predominance of a mixture of short-, mid-, and long-chain-alkanes in the(C12-C15) range associated with Mono-methyl branched alkanes (MMAs) in the same range. This indicates a strong contribution of both higher and submerged/floating plants as well as algae and Cyanobacteria input representing unrestricted system typical of some lacustrine environments. Two sub-facies units could clearly be noted in this group; one with less prominent MMAs and clear C25-C29 odd/even preference as indication for a proximal facies with more terrestrial input (ET-6-Ag-3020) typical of marginal lacustrine environments (e.g. deltaic/fluvio-deltaic), and another with rich MMAs and no carbon preference (NmK-1-Ag-3030) indicating a more distal facies with minimum terrestrial input typical of deep lacustrine settings (Fig.3.2.1). This is enormously consistent with the geographical locations of the two subunits with respect to the basin and represents a clear manifestation of the control of the sediments supply source proximity on lateral facies variation in a given source rock depositional environment.

The sharply-headed group shows pronounced spiky UCM humps, abundant low molecular weight (LMW)/short n-alkanes, and MMAs in the range of C15-C20 as an indication for a strong algal and cyanobacterial input and is specifically shown by the extracts of the L. Cretaceous(Fig.3.2.1).Based on the n-alkanes distribution that shows three conspicuous marine OM input signatures (e.g. abundant short-chain n-alkanes in the C15-C19 range, the n-alkanes greater than C20 gradually decrease with increasing Carbon number, and a clear predomination of the n-C17 over n-25 n-alkanes in all samples of this group), we judge a marine origin for this group(Fig. 3.2.1).This might incredibly look weird considering the known geology of this continental basin however, various biomarker, isotopic, and paleogeographic data discussed in this work all consistently support our conclusion.
Like the E. Cretaceous lacustrine facies, the marine L. Cretaceous facies could similarly be subdivided based on the types of their organic matter input into two sub-facies; a distal Baraka and Ghazal formations (Late Campanian-Maastrichtian) and a proximal Zarqa formation (Early Campanian). The former is composed almost exclusively of algal and bacterial content (dominant short-chain n-alkanes) with very minimal terrestrial input typical to the conditions in some marine environments such as estuaries and bays. The later sub-facies inversely shows less algal and bacterial input with relatively more terrestrial input indicating a more open system such as deltaic and coastal plains (Fig.3.2.1). It could easily be noted that facies variation within the marine group is temporal rather than lateral indicating exotic events that affected the basin at different times during the L. Cretaceous. We tend to relate these to the sporadic marine incursions that characterized vast African territories during the L. Cretaceous.

**Fig.3.2.1** Saturates’ TIC traces showing: A- similar sharply-headed n-alkanes envelopes with humped baselines for the L. Cretaceous (a marine facies) correlated to B- widely-headed envelopes with flat-humped baselines for the E. Cretaceous Abu Gabra source rock (lacustrine). Red arrows show relative nC17/nC25 ratios and dotted lines show MMAs.

Degree of waxiness as an environmental parameter is frequently used in organic geochemical characterization of source rocks and oils. It’s expressed by the summation of \( (nC_{21}-nC_{31}) \) divided by the summation of \( (nC_{15}-nC_{20}) \), and it reflects the amount of land derived versus aquatic organic matter in sediments and oils \[71\]. The classification of oils based on source input is related with waxiness as an environmental source input parameter \[72\]. Based on this, Muglad’s Cretaceous rock sequence could be differentiated into a waxier E. Cretaceous Abu Gabra with a degree of waxiness between (1.21-1.69) and a less waxy L. Cretaceous (degree of waxiness: 0.4-0.76) (Table3.2 and Fig.3.2.2). This is a clear indication that the former has much more terrigenous organic matter input than the later which is largely consistent with the results of the n-alkanes distribution above.
Fig. 3.2.2: Distinct differentiation between the two Muglad’s Cretaceous source rocks units based on their degree of waxiness and Pr/Ph ratios cross-plot.

Table 3.2.1: Summary of the GC parameters of Muglad’s Cretaceous rock extracts.

| Well name | Sample Type | Formation       | Depth (m) | Pr/Ph | Pr/nC17 | Ph/nC18 | nC25/nC18 | nC17/nC25 | Waxiness |
|-----------|-------------|----------------|-----------|-------|---------|---------|-----------|-----------|----------|
| Lo-1      | Cutting     | Ghazal          | 3210      | 0.98  | 0.34    | 0.28    | 0.12      | 6.80      | 0.40     |
| Zna-1     | Cutting     | Baraka          | 3277      | 0.85  | 0.82    | 0.96    | 0.20      | 5.12      | 0.43     |
| Tim-1     | Cutting     | Baraka          | 2810      | 0.54  | 0.20    | 0.29    | 0.21      | 3.80      | 0.61     |
| Lo-1      | Cutting     | Amal/Baraka     | 2045      | 1.10  | 0.57    | 0.45    | 0.21      | 4.20      | 0.63     |
| Lo-1      | Cutting     | Zarqa           | 3370      | 0.81  | 0.71    | 0.64    | 0.24      | 3.10      | 0.71     |
| Lo-1      | Cutting     | Zarqa           | 3720      | 1.02  | 0.62    | 0.67    | 0.29      | 3.70      | 0.76     |
| ET-6      | Cutting     | Abu Gabra       | 2690      | 3.02  | 0.63    | 0.30    | -         | -         | -        |
| ET-6      | Cutting     | Abu Gabra       | 3020      | 2.15  | 0.39    | 0.21    | -         | -         | -        |
| Nm K-2    | Cutting     | Abu Gabra       | 2740      | 1.71  | 0.28    | 0.19    | 0.74      | 1.50      | 1.26     |
| Nm K-2    | Cutting     | Abu Gabra       | 2890      | 1.94  | 0.23    | 0.13    | 0.79      | 1.50      | 1.27     |
| Nm D-1    | Cutting     | Abu Gabra       | 3570      | 1.17  | 0.08    | 0.06    | 0.79      | 1.22      | 1.21     |
| Nm D-1    | Cutting     | Abu Gabra       | 3040      | 1.32  | 0.26    | 0.22    | 0.82      | 1.30      | 1.25     |
| Nm K-1    | Cutting     | Abu Gabra       | 3030      | 1.44  | 0.23    | 0.15    | 0.88      | 1.00      | 1.54     |
| Nm K-1    | Cutting     | Abu Gabra       | 2650      | 1.74  | 0.37    | 0.22    | 0.97      | 1.06      | 1.69     |

Isoprenoids distribution (i.e. Pristane/Phytane ratios):

Pristane/Phytane ratio (Pr/Ph) is used as an indicator for the redox conditions during the processes of sedimentation and diagenesis\(^{[73-74]}\) as well as a proxy for the organic matter source and hence the depositional environment in which the OM accumulated\(^{[75; 73; 41;76]}\). Reducing/hypersaline conditions would always give values less than unity accumulating mainly marine OM (e.g. carbonates/evaporites) whereas values >3.0 represent oxidizing conditions typical of terrestrial environments (e.g. coal and peat swamps) which are rich in land plants\(^{[68]}\). Pr/Ph ratios in the range between 1 and 3 reflect intermediate conditions (oxic-suboxic) depositional
environments \[42-77\]. As noted in some Chinese basins, source rocks deposited in a fresh-water environment are characterized by Pr/Ph ratios from 1.2 to 2.2 \[78\]. A Pr/Ph ratio > 1.5 is usually ascribed for terrigenous organic matter input under sub-oxic to oxic conditions while ratios less than 0.6 are taken to represent anoxic, often hypersaline conditions \[60; 61; 79\].

Unlike for Muglad’s E. Cretaceous which is characterized by fresh-brackish oxic-suboxic depositional conditions as shown by Pr/Ph values between (1.2-3.02) and associated with terrigenous OM accumulation typical of lacustrine settings, highly anoxic conditions seem to have dominated the L. Cretaceous displayed by the very low Pr/Ph ratios between (0.54-1.1) and the accumulation of marine OM (Table3.2.1 & Fig. 3.2.1). This is pretty well consistent with the degree of waxiness results and the n-alkane distribution discussed above. Anoxia was a global phenomenon in the Cretaceous during which sporadic anoxic oceanic events (AOEs) has been globally well documented in the stratigraphic records (e.g. Schlanger and Jenkyns, 1976; Ryan and Cita, 1977 and Jenkyns, 1980) \[80-82\]. Mello et al., (1989) studied pelitic Cenomanian-Maastrichtian sediments from a number of Brazilian continental margin basins and noted intermittent anoxic events that produced organic rich marine sediments during Cenomanian to Santonian \[83\]. These anoxic events have been attributed to the major global sea-level rises during this period \[84-87\]. In the Muglad we noted the increase of anoxia and marine input during the Campanian-Maastrichtian which indicates a marine incursion event into the basin during this period.

\textbf{Pr/nC17 versus Phytane/nC18 cross-plot}

A cross plot of the ratios of the isoprenoids such as the pristane and phytane over their corresponding n-alkanes (n-C\textsubscript{17} & n-C\textsubscript{18} respectively) has widely been used to describe the depositional environments of the organic source and type of the organic matter accumulated in an area \[88\]. Used here to characterize the analyzed samples, this plot shows the Abu Gabra source rock to fall basically within the “mixed type-II–III” area typical of lacustrine settings, while the L. Cretaceous rocks predominantly lie in the “type-II, algal, marine, and strongly reducing” zone (Fig.3.2.3 and Table3.2.1). This conclusion is very much in line with the results shown by the n-alkanes and isoprenoids distribution in the study rocks discussed above and also with the Pyrolysis results discussed in (section 3.1).

![Fig. 3.2.3 Three facies subdivisions (I, II, & III) of Muglad’s E. Cretaceous Abu Gabra source rock ([solid triangles=Neem area] & [solid circles=El Toor area]), and L. Cretaceous, Baraka Formation (open squires), L. Cretaceous Ghazal-Zarqa Formations (colour squares) \[88\]. The same facies subdivisions noted in Fig. 3.2.1 are also obviously noted in the cross-plots of (Figs. 3.2.3 & 3.2.4). Both groups show distal as well as proximal sub-facies; a distal lacustrine (Neem area), a proximal lacustrine (ET-6 area), a distal marine (Baraka-Ghazal formations), and a proximal marine (Zarqa formation).](image-url)
B. Source rocks GCMS biomarkers signatures

Gas chromatography Mass Spectrometry (GCMS) was applied quite often by geochemists in the course of certain biomarkers characterization of source rocks and crude oils (e.g. Terpanes and Steranes). GCMS parameters applied in this study are shown in Appendix-I.

i. Triterpanes:

Triterpanes are derived mainly from bacteria and are frequently used as indicators for depositional and digenetic conditions [89]. For this group of biomarkers always refer to (Fig.3.2.5), appendix-I and (Table3.2.2) for compound identification.
Fig. 3.2.5 Saturates’ GCMS 191 fragmentogram showing the tri-terpanes distribution in Muglad’s L. Cretaceous (A=Marine) and the E. Cretaceous Abu Gabra rocks (B=Lacustrine). Note the distinctly elevated C23 tricyclic (compound #5) in the Baraka Formation at both Tim-1 and Kng-1 wells as indication for a marine origin.

Table 3.2.2 Tri-terpane compounds identification for the Saturated GCMS m/z 191 fragmentogram.

| No. | Compound name |
|-----|--------------|
| 1   | 13β(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 2   | 12αβ(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 3   | 13β(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 4   | 12αβ(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 5   | 13β(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 6   | 12αβ(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 7   | 13β(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 8   | 12αβ(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 9   | 13β(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 10  | 13β(H)1,4αβ(H)-C_{23} tricyclic diastere 
| 11  | 15αβ(H)-22,29-trimethopane(Tm) 
| 12  | 17β(H)22,29-trimethopane(Tm) 
| 13  | 17β(H)22,29-trimethopane(Tm) 
| 14  | 15αβ(H)-22,29-trimethopane(Tm) 
| 15  | 17β(H)-30-homohopane(32R) 
| 16  | 17αβ(H)-21αβ(H)-homohopane(32R) 
| 17  | 17αβ(H)-21αβ(H)-homohopane(32R) 
| 18  | 17αβ(H)-21αβ(H)-homohopane(22R) 
| 19  | 17αβ(H)-21αβ(H)-homohopane(22R) 
| 20  | Gammacerane |
i.a Tricyclic & Tetracyclic terpanes (TT& Tet.):
These were first noted in the Green River Shales [90-91] and were since then, frequently used in oil-source rocks correlations, source rocks characterizations, and determinations of maturity and biodegradation [92-94; 68]. Mainly, they are of algal and bacterial origin and are found in rocks deposited in both lacustrine and marine environments [95; 59; 96]. Abundance of certain tricycles such as the C_{23} in oils or rock extracts has always been attributed to deposition in marine environments [95], while C_{19} and C_{20} members are ubiquitous in terrestrial sources [68]. Some tricyclic terpanes’ ratios are sensitive source indicators for marine versus non-marine depositional environments, e.g. C_{26}/C_{25}[97-98; 50]. Tetracyclic terpanes, particularly the C_{24} member is believed to originate from carbonate and evaporite sources [99-103]. Peters and others worked on some five hundred oil samples from around the globe (Fig. 3.2.5) and showed that C_{26}/C_{25} tricyclic ratios > 1.0 are typical of lacustrine oils while carbonates, marls, and marine shales display values < 1.0[50].

![Diagnostic Vs Tricyclic Terpane Ratios](image)

Fig. 3.2.6 C_{26}/C_{25} tricyclic terpane versus C_{31} 22R/C_{30} hopane cross-plot for more than 500 worldwide crude oil samples used as a database to predict source-rock depositional environments, (modified from) [50].

Based on the tricyclic terpane contents, the analyzed Muglad rocks extracts show two distinct groups; a generally highly enriched L. Cretaceous versus a relatively less-enriched E. Cretaceous (Fig. 3.2.6). This is an indication for a more algal and bacterial input in the former which is very well correlated with the fact that their paraffins’ content is primarily dominated by the LMW varieties which are derived from the same biological sources (Fig. 3.2.1).

Of the tricyclic terpane members, the C_{23}TT is the most dominant component in the L. Cretaceous extracts (e.g. Kng-1, KA2 Bka & Tim-1, Bka-2810 samples), which is a clear indication for a marine input in this unit [95] (Fig.3.2.4). This is fairly consistent with both the Pyrolysis results of these extracts (i.e. predominantly type-II kerogens), as well as their chromatographic data (i.e. dominant LMW n-alkanes in the n-C_{15} to n-C_{20} range, Pr/Ph ratio <1.0, and the Pr/nC_{17} and Ph/nC_{18} cross-plots). In (Fig. 3.2.7) with few exceptions, the majority of the L. Cretaceous extracts obviously plot in the marine environment area with a C_{26}/C_{25} tricyclic ratio less than one. However, the E. Cretaceous Abu Gabra source rock displays a C_{26}/C_{25} tricyclic ratio that is greater than one indicating its lacustrine origin.
i.b Tm/Ts

A commonly applied biomarker fingerprinting parameter that is used in correlation studies and is expressed as either Tm/Ts, Ts/Tm, or Ts/(Ts/Tm). Mello et. al. (1988a) differentiated lacustrine saline, marine evaporitic, or marine carbonate depositional environments (Ts/Tm <1) from lacustrine fresh-water or marine deltaic (Ts/Tm >1). The parameter could also be used as a maturity indicator although Waples & Machihara suggested that this should not be used quantitatively due to the fact that it could be affected by facies. High Tm/Ts ratios are high in terrestrial (fluvio-deltaic) oils, medium in marine oils, and low in lacustrine oils. High Tm/Ts ratios have been reported in some oils from Carbonates.

A cross-plot of the Ts/Tm and C26/C25 tricyclic terpane ratios (Fig. 3.2.7) of the analyzed Muglad’s extracts confirms the previously identified organo-facies subdivisions discussed in section (3.2.1); a distal marine (I) for the top L. Cretaceous (i.e. Baraka-Ghazal Fms.) with Ts/Tm and C26/C25TT< 1.0, a distal lacustrine E. Cretaceous (II) with Ts/Tm >0.5 and C26/C25TTbetween (1.8-4.0) in Neem area, and a marginal marine (III) for both Zarqa Fm, and E. Cretaceous Abu Gabra from ET-6 with Ts/Tm >0.5 and C26/C25TTbetween (1.0-1.5).

Fig. 3.2.8 C26/C25 tricyclic terpane versus Ts/Tm cross-plot for Muglad’s Cretaceous source rocks showing the top L. Cretaceous (Baraka) as marine while the E. Cretaceous as lacustrine facies. Open squires=Baraka samples, solid squires=Ghazal-Zarqa, and solid black triangles and circles= E. Cretaceous Abu Gabra.
Due to the expected bias by the facies effect (marine vs. lacustrine) \cite{89}, Ts/Tm ratio does not show clear maturity trends for the studied extracts hence, it’s not used to constrain maturity in this study.

\textbf{i.c} C29/C30 17α (H)-hopane

The ratio is characteristic source indicator used to differentiate between clastics and carbonates \cite{108-109}. In general, the ratio is high (> 1) in oils sourced from anoxic organic rich carbonates and evaporate \cite{89-100}. Clastic lithologies however, usually display high C30 hopane concentrations and hence, low C29/C30 hopane ratio less than unity \cite{110-111}. Consistent with the Ts/Tm versus C26/C25 TT cross-plot (Fig. 3.2.8), a cross-plot of C26/C25 TT versus C29/C30 hopane clearly reveal the same three organo-facies; a distal marine (I) top L. Cretaceous Baraka and Ghazal with C26/C25 TT < 1.0 and C29/C30 hopane between (0.5-1.3), a marginal marine and lacustrine (III) both L. & E. Cretaceous (i.e. Abu Gabra from ET-6 and Zarqa respectively) with C26/C25 TT between (1.0-2.5) and C29/C30 hopane < 1.0, and finally a distal lacustrine (II) E. Cretaceous with C26/C25 TT > 2.5 and C29/C30 hopane < 1.0 (Fig. 3.2.9).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.2.9.png}
\caption{A cross-plot of the C28/C30 hopanes against the Pr/Ph ratios for the E. Cretaceous Abu Gabra (solid black circles and triangles) versus the L. Cretaceous rocks (open & solid squire).}
\end{figure}

\textbf{i.d} Gammacerane index:

Gammacerane is a triterpane associated usually with environments of increasing salinity, both marine and lacustrine \cite{50;110-112}. High values could also indicate stratified water column during source deposition \cite{113}. Gammacerane is derived from a triterpenoid known as “Tetrahymanol” which occurs in a protozoan of the genus Tetrahymena \cite{43}. Moldwan et al. (1985) reported an index of 8.0 for a Green River oil form the Altamont-Bluebell field \cite{110}.

Gammacerane indices observed in the studied rocks are variable with the E. Cretaceous Abu Gabra showing relatively higher values in the range of (0.14-0.50), (Fig.3.2.4 and Appendix-i). While the L. Cretaceous rocks display far lower values in the range of (0.05-0.22). As there is no evidence for any abnormal salinities during the Abu Gabra time (fresh-water oxic environment, Pr/Ph >1), the authors would rather attribute this higher Gammacerane values in the Abu Gabra probably to water column stratification effect.

\textbf{i.e} Rearranged hopanes:

The rearranged hopanes C30 17α (H)-diahopane (C30D) and C29 18α (H)-30-norneohopane (C29Ts) or compounds 14 & 15 respectively (see Fig.3.2.4 and Table-3.2.2 for identification) are formed by rearrangement of hopanoid precursor in oxic, clay rich sediments \cite{48, 50}. Abundant C29Ts hopanes indicate terrigenous input in the source material of these sediments and oils \cite{89}. In this study, the Abu Gabra shales show high enrichment of rearranged
hopanes (C29Ts and C30D) as indication for the oxic nature of its depositional environment and hence a higher clay content. The L. Cretaceous samples in the other hand (Tim, Kng and Lo), are much depleted in these compounds as indication for a more anoxic depositional setting which is in favor of very low clay contents (Fig. 3.2.4).

ii. Steranes:
Steranes are saturated biomarkers built up from six isoprene structural units which are derived from the steroids of eukaryotic membranes and hormones through diagenetic and catagenetic degradation and saturation. Most frequently, they are used to infer depositional environments and organic matter type [114-116; 79]. Sterane distribution of the analyzed rocks are shown in (Fig. 3.2.10) below and for steranes biomarker parameters refer to Appendix-I. 

Fig. 3.2.10 Saturates’ GCMS 218 fragmentograms showing the steranes distribution in Muglad’s Cretaceous source rocks. Two main organic facies: A-Marine (L. Cretaceous) and B-lacustrine (E. Cretaceous Abu Gabra).

ii.a (C27-C29) Regular Steranes:
Relative abundances of the C27-C29 regular steranes have always been used to constrain the types of organisms contained by the organic matter. Although C29 sterane is considered a terrestrial marker [116-50], some blue-green and brown algae and marine diatoms were also known to be possible sources [117]. Higher C27 regular sterane concentrations are indicative of marine organic matter input [56]. Elevated C28 sterane imply strong lacustrine algae and phytoplankton content [116-118] and could likewise indicate marine sources [110; 119; 68].

In general, sterane distribution of the analyzed Muglad rock extracts show prominent C27 homologs in the distal facies of both marine and lacustrine (I & II) as indication for strong algal input with the proximal facies show elevated C29 instead (Fig. 3.2.10). On the famous Sterane triangular diagram developed by Huang and Meinschein, (1979), the regular steranes distribution consistently indicate the same three sets of organic facies noted above by the other biomarker groups such as the alkanes, isoprenoids, and terpanes. These are; a distal lacustrine (I) facies displayed by the E. Cretaceous Abu Gabra extracts in Neem area (solid black triangles), a
distal marine (II) (e.g. estuarine/bay) in the case of the top L. Cretaceous Baraka extracts (open squares), and a proximal marine&/lacustrine (III) as shown by both the Abu Gabra from El Toor area and Zarqa in several wells, respectively(Fig. 3.2.11).

Fig. 3.2.11 Regular steranes distribution for the study rocks, solid black triangles are E. Cretaceous Abu Gabra from Neem area, solid black circles represent the E. Cretaceous Abu Gabra from El Toor area, while squires (open & solid) represent the different L. Cretaceous rocks (modified [116; 118])

Following Waseda & Nishita’s (1998) Pr/Ph against the regular steranes (C27/(C27+C29) cross-plot[120], Muglad’s Cretaceous sequence could be classified into two major facies units: a pelagic-oxic and a pelagic-anoxic which respectively correspond to the same lacustrine and marine facies discussed in the previous sections (Fig. 3.2.12). Although much has been written on pelagic depositional environments and pelagic sediments in the literature [121-122], nevertheless, a precise definition has not yet been adopted. Jenkyns, (1978) used the term for “open sea”, continental margin facies, and deposits of epeiric seas [122]. In the Wikipedia, pelagic waters are: “any water in the sea or lake that is neither close to the bottom nor near the shore” [51].

In the Muglad, the E. Cretaceous extracts plot in the pelagic-oxic zone and subdivides, based on the environment’s degree of oxicity (Pr/Ph) and the amount of terrigenous input (C27/(C27+C29) into two sub-facies: a (I) distal lacustrine in Neem versus a (III) proximal lacustrine (i.e. fluvial-fluvio-deltaic) at El Toor areas respectively(Fig. 3.2.12). The pelagic-anoxic facies however, is restricted to all the L. Cretaceous extracts and similarly subdivides, depending on the oxicity and terrigenous material supply into: a (II) distal marine sub-facies (Baraka & some Ghazal extracts) with less terrestrial input and a (III) proximal marine i.e. deltaic/coastal plain (Zarqa & some Ghazal extracts) with strong terrestrial input.
Fig. 3.2.12 A cross-plot of Pr/Ph ratios versus regular steranes (C27/(C27+C29) for Muglad’s L. Cretaceous (squires) and E. Cretaceous Abu Gabra (triangles=Neem and circles=El Toor). (Modified after [120]). I=deep lacustrine, II=marine III=marginal lacustrine & marine.

ii.b Diasteranes:
These are re-arranged steranes that are generally associated with clay-rich sediments (e.g. shales) typical of oxic environments resulting from clay-catalyzed re-arrangement of regular steranes [123; 89] and references there. The ratio between diasteranes and regular steranes is controlled by facies, maturity, and the redox conditions in the depositional environment [124; 89; 43]. It has been observed that some carbonates show high diasterane contents suggesting mechanisms other than clay catalysis for their formation [125]. From (Fig.3.2.9) above, the E. Cretaceous Abu Gabra extracts show relatively higher diasterane content suggesting more clay enrichment and more clastic facies, while the L. Cretaceous rocks are extremely depleted in the diasteranes as an indication for very low clay content in these rocks. Vertical facies variation within the L. Cretaceous sequence is obvious from (Fig. 3.2.9) where abrupt decrease of diasterane content is notable from the bottom of the sequence (e.g. Zarqa formation) towards the top (i.e. Baraka formation), implying a shift from marginal marine to distal marine facies.

ii.c Pregnanes:
Pregnanes are believed to be typical of higher salinities in the depositional environments [126-127]. Guangli and others suggested that these compounds are geological products originating from steroid precursors with carbonaceous material and sulphur as catalysts [128]. Usually, low pregnanes are associated with high diasteranes in oxic environments having significant terrigenous input in clay-rich source rocks. A high pregnane/low diasterane combination indicates restricted, sulfur-rich anoxic carbonates [128]. In the study area, it’s quite obvious to note comparable pregnanes and regular steranes contents for the E. Cretaceous/Abu Gabra and some L. Cretaceous (e.g. Ghazal-Zarqa formations) that are associated with elevated diasteranes compositions (m/z 218, Fig.3.2.9). This is a clear indication that these shales are rich in terrigenous input and have accumulated in oxic and clay-rich environments typical of both marginal lacustrine and/or marine environments. The Baraka formation however, shows abundant pregnane content relative to the regular steranes with very low diasteranes as an indication for marine input (Fig.3.2.9).

A summary of all marine diagnostic biomarkers and references there about which were discussed in the previous sections is shown in Table 4.4 below.
Table 4.4 Table of diagnostic biomarkers in favor of marine hypothesis used in this study.

| No. | Biomarker          | Published limits/Cut-offs | Muglad's Cretaceous, data | LITERATURE INTERPRETATION | References |
|-----|--------------------|---------------------------|---------------------------|---------------------------|------------|
| 1   | C17/C25 n-alkanes  | High                      | High                      | Marine                    | [59, 62-70]|
| 2   | Pr/Ph              | < 1.0                     | (0.37-1.0)                | Marine/hypersaline        | [42, 50]   |
| 3   | C15-C20            | Abundant                  | Abundant                  | Marine                    | [68]       |
| 4   | Ts/Tm              | < 0.5                     | (0.21-0.50)               | Marine                    | [42, 61]   |
| 5   | C29/C30 hopane     | > 0.6                     | (0.55-1.14)               | Marine                    | [50, 100]  |
| 6   | Tricyclic terpanes | Abundant                  | Abundant                  | Marine                    | [50, 115]  |
| 7   | C23 Tricyclic      | Dominant                  | Dominant                  | Marine                    | [95]       |
| 8   | C25/C26 Tricyclics | < 0.9                     | (0.31-0.56)               | Marine                    | [50]       |
| 9   | C25 Tetracyclics   | High                      | High                      | Marine                    | [61, 99]   |
| 10  | Pregnanes & homopregnanes | Abundant            | Abundant                  | Marine                    | [111]      |

3.2.2. Source rocks Biomarkers’ maturity:
The biomarker maturity of the analyzed rock extracts in this study is investigated using triterpane and sterane isomerization parameters: 22S/(22S+22R) of the C32 homohopane and 20S/(20S+20R) of the C29 sterane respectively. Biomarker maturity data indicate perfect consistency with those of the pyrolysis results placing the studied extracts at immaturity stage for all the Tertiary sequence and mature (early-peak) oil generation windows for the Cretaceous (Fig.3.2.13).

Terpanes maturity:

The 22S/(22S+22R) isomers of the C32 extended hopane has widely been used as an effective biomarker maturity indicator that were frequently used for correlation purposes [129]. During the maturation process the ratio increases from 0.0 to 0.60 (equilibrium stage = 0.62) with values from (0.5 to 0.54) indicate early oil generation and (0.57 to 0.62) represent an oil window maturation [130].

Based on the above, the Cretaceous extracts (both Early & Late) show similar 22S/(22S+22R) values between (0.57-0.63) which indicate maturity in the oil window while all the Tertiary extracts (Diamond shapes) show immaturity (Fig.3.2.13).

Steranes maturity:

The 20S/(20S+20R) of the C29 5αααα sterane is the most reliable and useful biomarker maturity parameter particularly for the immature-mature stages [50;79;113]. The ratio increases with thermal maturity from 0.0 at the immature stage to nearly 0.55 at peak oil generation with equilibrium at 0.52-0.55 [106;127]. Sterane and terpanes isomerization maturity of the analyzed extracts consistently with the Pyrolysis Tmax, and Ro maturity shows an immature Tertiary (Tendi & Nayil formations) and early-peak oil window stage for the Cretaceous extracts (Fig.3.2.13).
3.3. Source rocks C-isotopes composition:

Studies have shown that petroleum generation takes place whenever a metastable thermodynamic equilibrium between petroleum compounds, water, CO$_2$, and rock minerals is reached [131-137]. Strong stable carbon isotope fractionation takes place during carbon intake into the organic matter [138].

Sapropelic lacustrine organic matter shows light δ$^{13}$C‰ values (-25.2 to -35.5 ‰ PDB), while the humic is relatively heavier with values in the range of (-22.6 to -28.0 ‰ PDB) [139]. Carbon isotopic composition for the studied Muglad basin rock extracts shown in (Fig.3.3.1) indicate the E. Cretaceous Abu Gabra to be isotopically the lightest (-29.6 to -31.4 ‰) plotting in the mixed organic matter zone. In contrast, the L. Cretaceous rocks, are shown to be much heavier (-26.6 to -29.5 ‰) and showing distinct organic facies variation including mixed (Zarqa formation) as well as marine (Baraka & Ghazal formations) organic matter. This comes in total agreement with the numerous biomarker indications discussed above as a supportive proof for the marine input during Muglad’s L. Cretaceous. The same three organo-facies delineated above are again clearly noted in (Fig.3.3.1) below (I, II, and III).
4. Conclusions:
Based on results from this study and from Omer & Ahmed, 2007’s work, the organic geochemical characterization of Muglad’s Cretaceous source rocks reveal two major organo-facies units: a lacustrine and a marine. Based on the nature of their depositional environments and hence the accumulated organic matter type in each, the lacustrine facies could further be subdivided into two subunits, a distal (deep facies) and a proximal fluvial/fluvio-deltaic (shallow facies) lacustrine respectively. Similarly, the marine facies could also be categorized into: a distal (estuarine/shallow marine) and a proximal (deltaic/coastal plain) marine facies.

The Lacustrine organo-facies is the most dominant in the basin, prevailed almost all the time through the whole life history of the basin, and could be differentiated into: A deep lacustrine sub-facies, fresh-water, organic rich, mixed organic matter (kerogen types I, II & III), good-very good oil prone, deposited in an oxic clay-rich, more distal environment, and is thermally mature for oil generation at the present in the study area. This is found basically in the north-eastern corner of the study area (i.e. Neem field) and is anticipated to extend throughout the whole central trough.

A shallow-lacustrine, organic rich, constituted of mixed kerogens, good-very good oil and gas prone, derived from an oxic clay-rich, more proximal environment, thermally mature for hydrocarbon generation at present, and is basically represented by the E. Cretaceous Abu Gabra formation found essentially in the shallow sub-basins at both eastern and western flanks of the basin (e.g. El Toor area).

The Marine organo-facies: prevailed when the basin developed anoxic and strongly reducing conditions during the L. Cretaceous as indicated by several biomarkers discussed in this study. The paleogeography of the Muglad basin during the Campanian-Maastrichtian could be viewed as an epeiric sea occupying the central Kaikang trough resulting from the Tethyan transgression. Based on several biomarker characteristics, the marine organo-facies is here subdivided into two sub-facies: II- A distal (estuarine/shallow marine) sub-facies which is organic rich (average TOC 0.7-1.8%), oil and gas prone facies (kerogen type II & III), deposited in an anoxic clay-poor marine environment, and is mature for hydrocarbon generation at present in the central Kaikang trough. It is essentially noted in the Campanian-Maastrichtian Baraka & Ghazal shales at several well locations in the study area, and II- a Proximal (e.g. deltaic-coastal-plain), organic rich, constituted of mixed kerogens, good-very good oil and gas prone, derived from an anoxic clay-poor, deposited in a more proximal environment where interaction between both marine and continental settings were active (Fig.4.33), thermally mature for hydrocarbon generation at present, and is basically represented by the Zarqa shales.

5. Acknowledgements:
Sincere appreciation to the Greater Nile Petroleum Operating Company (GNPOC) and the Oil Exploration & Production Authority (OEPA) of the Sudanese ministry of oil and gas for providing the data and approving to conduct this work. We are also grateful to the State Key Laboratories for Petroleum Resources and Prospecting (SKLPRP) of China University of Petroleum in Beijing for using their lab facilities during the course of the study.

References

[1] SAVANNA HPETROLEUM ESTIMATES & ROBERTSON CGG-2014, cited in http://www.savannah-petroleum.com).
[2] McHargue T, Heidrick T, Livingstone J. 1992. Tectonostratigraphic development of the interior Sudan rifts, Central Africa. In Geodynamics of Rifting, Volume II. Case History Studies on Riffs: North and South America and Africa, Ziegler PA (ed.). Tectonophysics 213: 187-202.
[3] AbulGebbayin, Omer. I. M. et. al., 2018. Origin of a Tertiary oil from El Mahafir wildcat & geochemical correlation to some Muglad source rocks, Muglad basin, Sudan. Journal of African Earth Sciences 137 (2018), pp. 133-148.
[4] Giedt, Norman, R., 1990. Unity field-Sudan Muglad rift basin, Upper Nile province, in AAPG Treatise in Petroleum Geology, Structural traps III: Tectonic fold and fault traps, p. 177-197.
[5] Thomas schlutter, 2006. Geological Atlas of Africa, Springer-Verlag-Berlin Heidelberg (2006) 218-221
[6] Mohamed G. Abdelsalam et al, 2002. The Saharan Metacraton, Journal of African Earth Sciences 34 (2002) 119–136.
[7] Research Institute of Petroleum E and D. 1999. Final Report, Regional geology and tectonics project, blocks 1,2 and 4. GNPOC internal report, RIPED, pp.5-12.
[8] Fairhead, J.D., C.M. Green, S.M. Masterton, R. Guiraud, 2013. The role that plate tectonics, inferred stress changes and stratigraphic unconformities have on the evolution of the West and Central African Rift System and the Atlantic continental margins Tectonophysics, 594 (2013), pp. 118–127.
[9] Schull, T.J. 1988. Rift Basins of Interior Sudan: Petroleum Exploration and Discovery. American Association of Petroleum Geologists Bulletin 72: 1128-1142.
[10] Stead, D. T., & Awad, M. Z., (2005). Palynological zonation of Cenozoic non-marine sediments, Muglad basin, Sudan.
[11] Miles, J. 1984, Sudan Regional Geochemical study, Chevron Overseas Petroleum Inc, GNPOC internal report, 45pp.
[12] Hwang, R.J.: Ahmed, A.S.: Moldowan, J.M. 1994. Oil composition variation and reservoir continuity: Unity Field, Sudan. Organic Geochemistry 21: 171-188.
[13] Robertson Research, 1984. The Petroleum Geology of Southern, Central, and Eastern Sudan, volume 4, Geochemistry. Commercial GNPOC internal report.
[14] Gunther, P., 1995. Correlation study of oils from the Heglig-Unity areas, Muglad basin, The Sudan, Africa. GNPOC internal report
[15] Gunther, P., 1996b, Source rock evaluation of cuttings samples and an oil from SPC Toma South, The Sudan, Africa, State Petroleum Corporation report
[16] Waples, D.W., 1997, Oils of the Muglad Basin. (GNPOC internal report 33pp.).
[17] Dolby, G. 1998. Maturation Analyses of Twelve Wells in the Muglad basin, Sudan. GNPOC internal report 20pp.
[18] Moffat, I.W., 2000, Geochemical and basin modeling study, Central Muglad basin, Sudan, (GNPOC internal report), pp. 205-206.
[19] Omer, I.M. & Ahmed, M.M., 2007. Biomarker indications as evidence for organofacies variations within the Abu Gabra formation of the Muglad basin, Sudan, Taylor & Francis 2007, Chapter 5, p. 37-47.
[20] Wellstrat Services Limited, 2007, High Resolution Sequence Stratigraphic Studies in
[21] CNPC-IRC/RIPED, 2010. Tectonic Framework study, blocks 1, 2, & 4 of Sudan. GNPOC internal report.
[22] Miller K G, Sugarman P J, Browning J V, Kominz M A, Olsson R K, Feigenson M D, Hernández J C (2004). Upper Cretaceous sequences and sea-level history, New Jersey coastal plain. Geol Soc Am Bull, 116 (3) : 368-393
[23] Miller K G, Wright J D, Browning J V (2005). Visions of ice sheets in a greenhouse world. Mar Geol, 217(3–4): 215–231
[24] Miller K G, Pekar S F (2005). The Phanerozoic record of global sea-level change. Science, 310(5752): 368-393
[25] Miller K G, Wright J D, Browning J V (2005). Visions of ice sheets in a greenhouse world. Mar Geol, 217(3–4): 215–231
(1991) 1M3-1522
B. Spiro, 1991. Effects of minerals on rock-eval pyrolysis of Kerogen. Journal of Thermal Analysis, Pot 37 Bulletin, v. 70, p. 318-329.
Peters, K.E., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis, AAPG to trap. Am. Assoc. Pet. Geol. Mem., 60: 93-117.
Hunt, J.M., 1996, Petroleum Geochemistry and Geology, W.H. Freeman & Company.
Tissot, R.P. &Welte, D.H., 1984. Petroleum Formation and Occurrence. 2nd Ed. Springer, Berlin, Heidelberg, New York, 699 p.
Waples, D. W., 1985. Geochemistry in Petroleum Exploration, International Human Resources Development Corporation, Boston, 232 p.
Walters, C. C. (2007), The Origin of Petroleum. In: Practical Advances in Petroleum Processing (Eds. Chang S. H. and Paul R. R.), Springer Science and Business Media, New York. 1: p. 90.
Mukhopadhay, P.K., and W.G. Dow, eds., 1994, Vitrinite reflectance as a maturity parameter: applications and limitations: Washington, D.C., American Chemical Society Symposium Series 570, 294 p.
Jose Iglesias, et. al., 2001. The influence of impregnation by hydrocarbons on coal structure during its thermal evolution. Journal of Analytical and Applied Pyrolysis, pp. 58-59
Peters, K.E; Walters, C.C. and Moldowan, J.M., 2005. The Biomarker Guide Volume 2: Biomarkers and Isotopes in Petroleum Exploration and Earth History, 2nd Ed. Cambridge, 475-1155 p.
Wikipedia, (website)
Rogers, M. A., 1980. Application of organic facies concepts to hydrocarbon source rocks evaluation. In: Proceedings of the 10th World Petroleum Congress, Bucharest 1979, Heyden, London, 2, 23-30.
Cornford C., Rüllkötter J., Welte D., 1980. A synthesis of organic petrographic and geochemical results from DSDP sites in the eastern central North Atlantic. Phys. Chem. Earth, 12, 445-453.
Tyson, R.V., 1995. Sedimentary Organic Matter. Organic facies and palynofacies. Chapman and Hall, Londres, 615 pp.
Jones, R. W., Demaison, G. J., 1982. Organic Facies - stratigraphic concepts and exploration tool. In:
Saldivar-Sali, A. (Ed.). Proceedings of the Second ASCOPE Conference and Exhibition, Manilla, Asean Council on Petroleum, pp. 51-68.

[56] MendonçaFilho, J.G.; Menezes, T.R.; Mendonca, I.O.; Oliveira, A.D.; Silva, T.F.; Rondon, N.F.; Silva, F.S. 2012. Organic Facies: Palynofacies and Organic Geochemistry Approches. In: Dionisios Panagiotaras. (Org.). Geochemistry Earth and System Processes. 1ed. Patras: InTech, 2012, v. 1, p. 211-245.

[57] Shea J., Brassell S. C., and Ward D. M. (1990) Mid-chain branched mono- and dimethyl alkanes in hot spring cyanobacterial mats: a direct biogenic source for branched alkanes in ancient sediments? Org. Geochem. 15, 223–231.

[58] Robinson, Neil; Eglinton, Geoffrey (1990). Lipid chemistry of Icelandic hot spring microbial mats. Org. Geochem., 15(3), 291-8.

[59] Philp, R.P., 1985. Fossil fuel biomarkers. Applications and Spectra. Methods in Geochemistry and Geophysics, vol. 23. Elsevier, Amsterdam.

[60] González-Vila F. J. (1995). Alkane biomarkers, geochemical significance and application in Oil Shale geochemistry. In: Snape C. (eds) Composition, Geochemistry and Conversion of Oil Shales. NATO ASI Series (Series C: Mathematical and Physical Sciences), vol 455 Springer, Dordrecht.

[61] Mello, M.R., et al., 1988a, Geochemical and biological marker assessment of depositional environments using Brazilian offshore oils, Marine and Petroleum Geology, 5, pp. 205-223.

[62] Eglinton, G., and Hamilton, R., 1967, Leaf epicuticular waxes: Science, v. 156, p. 1322.

[63] Cranwell P A (1973). Chain-length distribution of n-alkanes from lake sediments in relation to post-glacial environmental change. Freshwater Biol, 1973, 3: 259–265

[64] Cranwell P A (1984). Lipid geochemistry of sediments from Upton Broad, a small productive lake. Org Geochem, 1984, 7: 25–37

[65] Ficken K J, Li B, Swain D L, et al. (2000). An n-alkane proxy for the sedimentary input of submerged/ floating freshwater aquatic macrophytes. Org Geochem, 2000, 31: 745–749

[66] Mead R, Xu Y P, Chong J, et al. (2005). Sediment and soil organic matter source assessment as revealed by the molecular distribution and carbon isotopic composition of n-alkanes. Org Geochem, 2005, 36: 363–370

[67] Collister J. W., Summons R. E., Lichtfouse E. and Hayes J. M. (1992). An isotopic biogeochemical study of the Green River oil shale. Org. Geochem. 19, 265-270.

[68] Peters, K.E., Moldowan, J.M., 1993. The Biomarker Guide. Interpreting Molecular Fossils in Petroleum and the Ancient Sediments. Prentice-Hall, Englewood Cliffs, New Jersey p. 363.

[69] Tissot, B., Califet-Debyser, Y., Deroo, G. and Oudin, J.L. (1971). Origin and evolution of hydrocarbons from the western desert, Egypt. JKAU: Earth Sci., V.20, No. 2, pp:97-125

[70] Connan, J. and Cassou, A.M. (1980) Properties of gases and petroleum liquids derived from terrestrial kerogen at various maturation levels. - Geochim. Cosmochim. Acta 44, 1 - 24.

[71] Eglinton, G., and Hamilton, R., 1967, Leaf epicuticular waxes: Science, v. 156, p. 1322.

[72] Didyk, B. M. et al, 1978. Organic geochemical indicators of paleoenvironmental conditions of sedimentation. Geochem. Cosmochim. Acta, 42, 727-738.

[73] Bakr, Mohamed, 2009. Molecular organic geochemistry of crude oil from Shushan and Abu Ghareid Basins, Western desert, Egypt. JKAC: Earth Sci., V.20, No. 2, pp:97-125

[74] Coull, D.J., and Gize AP (1996). Pristane/phytane ratios in the mineralized Kupferschiefer of the Fore-Sudetic Monocline, Southwest, Poland. Ore Geol Rev 11:89–103

[75] Amane, W., Hideki, N., 1997. Geochemical characteristics of terrigenous and marine sourced oils in Hokkaido, Japan. Organic Geochemistry 28, 27

[76] Wang, J.S., Huang, X.Z., Sui, J.C., Shao, H.S., Yan, C.F., Wang, S.Q., He, Z.R., 1997. Evolutional characteristics and their paleoclimate significance of trace elements in the Hetaoyuan Formation, Biyang depression. Acta Sedimentol. Sin. 15, 65-70 (in Chinese with English abstract).

[77] Volkman J K, Maxwell J R, 1986. Acyclic isoprenoids as biological markers [M]. Amsterdam: R B Johns, 1986, 1-42.

[78] Schlanger S. O. and Jenkyns H. C. (1976) Cretaceous oceanic anoxic events: causes and consequences Geol. Mijnbouw 55, 179-184.

[79] Ryan W. B. F. and Cita M. B., 1977. Ignorance concerning episodes of ocean-wide stagnation Mar. Geol. 23,
[82] Jenkyns H. C. (1980). Cretaceous anoxic events: from continents to oceans. J. Geol. Soc. London 137, 171-188.

[83] Mello, M. R., Koutsoukos, E. A. M., Hart, M. B., Brassell, S. C. & Maxwell, J. R., 1989. Late Cretaceous anoxic events in the Brazilian continental margin. Org. Geochem., 14 (5), 529 - 542.

[84] Arthur M. A., Schlanger S. O. and Jenkyns H. C. (1987). The Cenomanian-Turonian Oceanic Anoxic Event, 11. Palaeoceanographic controls on organic-matter production and preservation. In Marine Petroleum Source Rocks Geological Society Special Publication No. 26 (Edited by Brooks J. and Fleet A. J.), pp. 401-420, Blackwell Scientific Publications.

[85] Schlanger S. O., Arthur M. A., Jenkyns H. C. and Scholle P. A., 1987. The Cenomanian-Turonian oceanic anoxic event. I. Stratigraphy and distribution of organic-rich beds and the marine 6 13C excursion. In Marine Petroleum Source Rocks, Geological Society Special Publication (Edited by Brooks J. and Fleet A. J.) Vol 26. pp.371 400. Blackwell Scientific Publications.

[86] Graciansky de P. C., Brosse E., Deroo G., Herbin J. P., Montadert L., Muller C., Sigal J. and Schaaf A., 1987. Organic-rich sediments and paleoenvironmental reconstructions of the Cretaceous North Atlantic. In Marine Petroleum Source Rocks, Geological Society Special Publication (Edited by Brooks J. and Fleet A. J.), Vol. 26, pp. 317 344. Blackwell Scientific Publications.

[87] Bralower T. J. and Thierstein H. R. 1987. Organic-carbon and metal accumulation in Holocene and mid-Cretaceous marine sediments: palaeoceanographic significance. In Marine Petroleum Source Rocks, Geological Sociey, Special Publication No. 26 (Edited by Brooks J. and Fleet A. J.), pp. 345-370. Blackwell Scientific Publications.

[88] Shanmugam, G., 1985. Significance of coniferous rain forests and related organic matter in generating commercial quantities of oil, Gipps land Basin. Australia. Am. Assoc. Pet. Geol. Bull. 69, 1241–1254.

[89] Waples, D.W. and Machihara, T., 1991, Biomarkers for geologists- A Practical Guide to the Application of Steranes and Triterpanes in Petroleum Geology, AAPG, Methods in exploration, No. 9.

[90] Anders, D.E., Robinson, W.E., 1971. Cycloalkane constituents of the bitumen from Green River shale. Geochimica et Cosmochimica Acta 35, pp. 661-678.

[91] Gallegos, E.J., 1971. Identification of new steranes, terpanes, and branched paraffins in Green River shale by combined capillary gas chromatography and mass spectrometry. Analytical Chemistry 43, pp. 1151-1160.

[92] Seifert, W.K., Moldovan, J.M., Jones, R.W., 1980. Application of biological marker chemistry to petroleum exploration. Proceedings of the Tenth World Petroleum Congress. Bucharest, Romania. September, 1979. Paper SP8, Heyden, pp. 425-440.

[93] Seifert, W.K., and Moldovan, J.M., 1981, Paleoecosystemic analysis by biological marker, Geochimica et Cosmochimica Acta, v.45, pp.783-794. Seifert, W.K., Moldovan, J.M., 1979. The effect of biodegradation on steranes and terpanes in crude oils. Geochimica et Cosmochimica Acta 43, 11-126.

[94] Zumberge, J. E., 1987. Terpenoid biomarker distributions in low maturity crude oils. Organic Geochemistry 11:479-496.

[95] Aquino Neto, F.R., Trendel, J.M., Restle, A., Connan, J. and Albrecht, P.A., 1983. Occurrence and formation of tricyclic and tetracyclic terpanes in sediments and petroleum. In: M. BjorÔy, et al. (Editors), Advances in organic geochemistry 1981, Wiley, Chichester, pp.659-667.

[96] Philp, R. P. and Gilbert, T. D. (1986): “Biomarker distribution in Australian oils predominantly derived from terrigenous source material”, Org. Geochem. 10, 73 – 84

[97] Burwood R, Leplat P, Mycke B, Paulet J, 1992. Rifted margin source rock deposition: a carbon isotope and biomarker study of a West African Lower Cretaceous “lacustrine” section. Org. Geochem 19: pp. 41–52

[98] Hansson, A. D., et al. 2000. Molecular organic geochemistry of the Tarim basin, north-west China. AAPG Bull. 84:1109-1128.

[99] Palacas, J.G., Donald, E.A., King, J.D., 1984. South Florida Basin – a prime example of carbonate source rocks of petroleum. In: J.G. Palacas, (Ed.), Petroleum Geochemistry and Source Rock potential of Carbonate Rocks. American Association of Petroleum Geologists Studies in Geology 18, pp. 71 – 96.

[100] Connan, J., Bouroullec, J., Dessort, D., Albrecht, P., 1986. The microbial input in carbonate-anhydrite facies of a sabkha palaeoenvironment from Guatemala: a molecular approach. Org. Geochem. 10, 29-50.

[101] Connan J. and Dessort D. (1987) Novel family of hexacyclophanoid alkanes (C32-C35) occurring in sediments and oils from anoxic palaeoenvironments. Org. Geochem. 11, 103-113.

[102] Mann, A.L., Goodwin, N.S., Lowe, S., 1987. Geochemical characteristics of lacustrine source rocks: A combined palynological/molecular study of a Tertiary sequence from offshore China. In: Proceedings of the Indonesian petroleum Association, Sixteenth Annual Convention. Jakarta, Indonesian Petroleum Association, 1: 241-258.

[103] Clark, J.P., Philip, R.P., 1989. Geochemical characterization of evaporite and carbonate depositional
environments and correlation of associated crude oils in the Black Creek Basin. Canadian Petroleum Geologists Bulletin, 37: 401-416.

[104] Van Graas, G. W. (1990). Biomarker maturity parameters for high maturities: Calibration of the working range up to the oil/condensate threshold. Org. Geochem. 16, pp. 1025–1032.

[105] Robinson, 1987. An Overview of Source Rocks and Oils in Indonesia. Proceedings of the Indonesian Petroleum Association, 16th Annual Convention, vol. 1. Indonesian Petroleum Association, Jakarta, pp. 97–122.

[106] McKirdy, D. M. et al., 1984. Hydrocarbon genesis and organic facies in Cambrian carbonates of the Eastern offshore Basin, South Australia. Palaeas J G. Petroleum Geochemistry and Source Rock Potential of Carbonate Rocks. Tulsa: AAPG Bulletin.

[107] Mattavelli, L., and Novelli, L., 1990, Geochemistry and habitat of the oils in Italy: AAPG Bulletin, v. 74, no. 10, p. 1623-1639.

[108] Wang, Z.D., Fingas, M., Sergy, G., 1994c. Study of 22-year-old arrow oil samples using biomarker compounds by GC/MS. Environ. Sci. Technol. 28, pp. 1733–1746.

[109] Wang, Z., Yang, C., Yang, Z., Sun, J., Hollebone, B., Brown, C., Landriault, M., 2011. Forensic fingerprinting and source identification of the 2009 Sarnia (Ontario) oil spill. J. Environ. Monit. 13, pp. 3004–3017.

[110] Moldowan J.M., Seifert W.K., and Gallegos E.J., 1985, Relationship between Petroleum Composition and Depositional Environment of Petroleum Source Rocks, AAPG Bull., v. 69 No. 8, pp. 1255-1268.

[111] Ten Haven, H. L. & Rullkotter, J., (1988). The diagenetic fate of taraxer-14-ene and Oleanane isomers. Geochimica et Cosmochim Acta, 56, 2001-2024.

[112] Ten Haven, H. L. et al., 1989. Tetrahymanol, the most likely precursor of gammacerane, occurs ubiquitously in marine sediments. GeochimActa 53, 3073-3079.

[113] Damste J.S.S., et al., 1996. Evidence for Gammacerane as an Indicator of Water Column Stratification, Netherlands Institute for Sea Research and Indiana University (http://www.uic).

[114] Lijmbach, G., 1975. On the origin of petroleum: proceedings of the 9th world petroleum congress, Applied science publishers, London, Vol. 2, 357-369.

[115] SEIFERT, W.K. and MOLDOWAN, J.M., 1978. Applications of steranes, terpanes and mono-aromatics to the maturation, migration and source of crude oils. Geochem, Cosmochim Acta 42, pp. 77-95.

[116] Huang, W. Y. and Meinschein, W.G., 1979. Sterols as ecological indicators. Geochim Cosmochim Acta 43:739–745

[117] Nichols, P.D., Palmisano, A.C., Rayner, M.S., Smith, G.A., White, D.C., 1990. Occurrence of novel C30 sterols in Ant-arctic sea-ice diatom communities during a spring bloom. Organic Geochemistry 15, pp. 503-508.

[118] Fleck, S. et al. 2002. Sequence stratigraphic framework. The siliciclastic shelf environment of Cretaceous series, SE France. Organic Geochemistry 33(12):1533-1557.

[119] Grantham and Wake field, 1988, cited in Peters and Moldowan, 1993. Variations in the sterane carbon number distributions of marine source rock derived crude oils through geological time. Organic Geochemistry 12, 61–73.

[120] Waseda and Nishita, 1998. Geochemical characteristics of terrigenous- and marine-sourced oils in Hokkaido, Japan OrganicGeochemistry, 28 (1998), pp. 27–41

[121] Berger, W.H., and E.L. Winterer, 1974. Plate stratigraphy and the fluctuating carbonate line. In: Pelagic Sediments on Land and Under the Sea (K. J. Hs., and H. Jenkyns, Eds.). Spec. Publ. Intl. Assoc. Sediment., 1: 11-48.

[122] Jenkyns, H.C., 1978. Pelagic environments in sedimentary environments and facies, G. Reading ed, Elsevier Sci. Pub., New York, P. 342-396.

[123] Rubinstein, J., Sieskind, O., Albrecht, P., 1975. Rearranged sterenes in a shale: occurrence and simulated formation. Journal of the Chemical Society Perkin Transactions I 1833, 1833–1835.

[124] Moldowan, J.M., Sundaraman, P. & Schoell, M., 1986. Sensitivity of Biomarker Properties to Depositional Environment and/or Source Input in the Lower Toarcian of S.W. Germany. Organic Geochemistry, 10, pp. 915-926.

[125] Clark, J.P., Philp, R.P., 1989. Geochemical characterization of evaporite and carbonate depositional environments and correlation of associated crude oils in Black Creek Basin. Bulletin of Canadian Petroleum Geology 37, pp. 401-416.

[126] Mueller, E. et al., 1995, Geochemical characterization and relationship of oils and solid bitumins from SE Turkey, Journal of Petroleum geology, volume 18.

[127] Ten Haven, H. L. et al., 1986. Organic geochemical studies of a Messinian evaporitic basin, northern Apennines (Italy) II: Isoprenoid and n-alkyl Thiophenes and Thiolanes. in: Leythaeuser, D. & Rullkotter, J.
(eds), Advances in organic geochemistry, 1985, Pergamon Press, Oxford, 791-805.

[128] Guangli Wang, Xiangchun Chang, T. G. Wang, and Bernd Simonet, 2015. Pregnanes as molecular indicators for depositional environments of sediments and petroleum source rocks. Organic Geochemistry 78: DOI: 10.1016/j.orggeochem.2014.11.004

[129] Ensminger A., Albrecht P., Ourisson G. and Tissot B. 1977. Evolution of polycyclic alkanes under the effect of burial (Early Toarcian shales, Paris basin). In Advances in Organic Geochemistry1975 (Ed. Campos R. and Gotli J.) pp. 45-52. ENADIMSA, Madrid.

[130] Seifert, W.K. & Moldowan, J.M., 1986. Use of Biological Markers in Petroleum Exploration. In R.B. Johns (Ed.), Methods in Geochemistry and Geophysics, 24, 261-290.

[131] Hoering T. C., 1984. Thermal reactions of kerogen with added water, heavy water and pure organic substances, Org. Geochem. 5: pp. 267-278.

[132] Lewan, M. D. (1985). Evaluation of petroleum generation by hydrous pyrolysis experiments. Phil. Trans. of the Royal SOC., v. 315, pp. 123-134.

[133] Seewald, J.S., 1994. Evidence for metastable equilibrium between hydrocarbons under hydrothermal conditions. Nature 370, pp. 285-287.

[134] Stalker, L., Farrimond, E., Larter, S.R., 1994. Water as an oxygen source for the production of oxygenated compounds (including CO2 precursors) during kerogen maturation. Org. Geochem. 22, pp. 477-486.

[135] McCollom, T.M., Simonet, B.R.T., Shock, E.L., 1995. Metastable equilibrium among benzenoid derivatives in hydrothermal experiments and geological fluids. Geol. Soc. Am. - Abstr. Programs 26, p. 311 (abstr.).

[136] Helgeson, H.C., Knox, A.M., Owens, C. E., Shock, E.L., 1993. Petroleum, oil field waters, and authigenic mineral assemblages; are they in metastable equilibrium in hydrocarbon reservoirs? Geochim. Cosmochim. Acta 57, pp. 3295-3339.

[137] Shock, E.L., 1988, Organic acid metastability in sedimentary basins: Geology, v. 16, p. 886–890.

[138] Alian Perrodon, 1983. Dynamics of Oil and Gas Accumulations, Elf Aquitaine Edition

[139] Ahmed, Y.M., 1996, Organic matter Characterization and Environmental Control on Organic facies and Lithofacies of Early Cretaceous Lake Assalam, northwest Muglad Basin, Sudan. (PhD. Thesis).

[140] Rullkotter, J., and Marzi, R., 1988, Natural and artificial maturation of biological markers in a Toarcian shale from northern Germany: Organic Geochemistry, v. 13, p. 639-645.
| Well Name | Formation/Depth (m) | Pr/Ph | Tricyc. Terpanes C26/C25 | C29/C3017α (H) hopane | C32 Hop. 22S(22S+22R) | Ts/Tm | Tm/Ts | C31 22R/C30 Hop. | C29 20S/(20S+20R), Gmc | Gmc Ind. | % C27 | % C28 | % C29 | C27(C27+C29) | SAT | ARO |
|-----------|---------------------|-------|--------------------------|------------------------|-----------------------|-------|-------|-----------------|------------------------|----------|-------|-------|-------|-----------------|-----|------|
| ET-6      | Abu Gabra (2990-3020) | 3.02  | 1.25                     | 0.54                   | 0.61                  | 1.15  | 0.87  | 0.16            | 0.40                   | 21.10    | 33    | 26    | 42    | 0.44            |   - | -28.6 |
| ET-6      | Abu Gabra (2660-2690) | 2.15  | 1.00                     | 0.53                   | 0.60                  | 1.08  | 0.93  | 0.16            | 0.38                   | 18.80    | 39    | 21    | 40    | 0.49            |   - | -    |
| Nm D-1    | Abu Gabra (3040)     | 1.32  | 3.40                     | 0.45                   | 0.57                  | 1.33  | 0.75  | 0.16            | 0.43                   | 21.00    | 47    | 24    | 29    | 0.62            | -30.8| -29.7 |
| Faras-1   | Zarqa (2620)         | 0.67  | 1.00                     | 0.50                   | 0.59                  | 1.47  | 0.68  | 0.21            | 0.40                   | 17.10    | 31    | 32    | 37    | 0.46            |   - | -    |
| Garaad-1  | Zarqa (1540)         | 0.79  | 1.00                     | 0.55                   | 0.59                  | 0.93  | 1.08  | 0.18            | 0.33                   | 10.60    | 32    | 30    | 38    | 0.45            |   - | -    |
| Grintiya-1| Ghazal (2445)        | 0.90  | 0.50                     | 1.08                   | 0.59                  | 0.21  | 4.76  | 0.19            | 0.36                   | 9.40      | 31    | 32    | 37    | 0.45            | -27.5| -27.5 |
| Khairat-1 | Baraka (2525)        | 0.80  | 1.10                     | 0.51                   | 0.59                  | 1.25  | 0.80  | 0.16            | 0.40                   | 4.60      | 37    | 30    | 34    | 0.52            | -28.2| -28.6 |
| Elm-1     | Baraka (2340)        | 0.50  | 1.14                     | 0.60                   | 0.50                  | 2.00  | 0.31  | 0.35            | 4.80                   | 31       | 26    | 43    | 42    | 0.42            |   - | -    |
| Elm-1     | Zarqa (2390)         | 0.40  | 1.03                     | 0.61                   | 0.48                  | 2.08  | 0.31  | 0.37            | 7.70                   | 37       | 21    | 41    | 47    | 0.47            | -27.6| -26.3 |
| Tim-1     | Baraka (2240)        | 0.82  | 0.57                     | 0.95                   | 1.05                  | 0.41  | 18.58 | 34              | 35                     | 32       | 35    | 32    | 32    | 0.52            |   - | -    |
| Tim-1     | Baraka (2360)        | 0.37  | 0.50                     | 0.72                   | 0.63                  | 0.39  | 2.56  | 0.18            | 0.44                   | 11.25     | 35    | 27    | 38    | 0.48            | -27.5| -28.6 |
| Tim-1     | Baraka (2590)        | 0.56  | 0.50                     | 0.60                   | 0.63                  | 0.43  | 2.33  | 0.23            | 0.46                   | 13.95     | 32    | 29    | 39    | 0.45            | -27.8| -28.4 |
| Tim-1     | Baraka (2780)        | 0.71  | 0.63                     | 0.75                   | 1.33                  | 0.51  | 17.30 | 47              | 22                     | 31       | 0.60 | -    | -    | -              |   - | -    |
| Tim-1     | Ghazal (3065)        | 0.52  | 1.00                     | 0.50                   | 0.61                  | 0.64  | 1.56  | 0.22            | 0.28                   | 22.17     | 33    | 25    | 43    | 0.44            | -27.1| -27.8 |
| Zna-1     | Amal (2420)          | 1.00  | 2.20                     | 0.60                   | 0.60                  | 0.90  | 1.10  | 0.10            | 0.52                   | 0.19      | 40    | 26    | 34    | 0.54            | -29.1| -27.6 |
| Lo-1      | Ghazal (3210)        | 1.00  | 2.34                     | 0.60                   | 0.62                  | 1.20  | 0.83  | 0.30            | 0.53                   | 0.10      | 47    | 20    | 33    | 0.58            | -28.8| -27.7 |
| Zna-1     | Baraka (3277)        | 0.90  | 0.61                     | 1.10                   | 0.68                  | 0.40  | 2.50  | 0.30            | 0.34                   | 0.17      | 37    | 29    | 34    | 0.52            | -29.0| -26.9 |
| Tim-1     | Baraka (2810)        | 0.50  | 2.54                     | 0.70                   | 0.58                  | 0.70  | 1.43  | 0.10            | 0.37                   | 0.20      | 54    | 22    | 24    | 0.69            | -27.1| -27.4 |
| Lo-1      | Amal/Baraka (2045)   | 1.10  | 2.11                     | 0.40                   | 0.39                  | 0.50  | 2.00  | 0.10            | 0.39                   | 0.16      | 36    | 25    | 39    | 0.48            | -29.7| -28.9 |
| Lo-1      | Zarqa (3370)         | 0.80  | 2.27                     | 0.70                   | 0.58                  | 0.90  | 1.11  | 0.10            | 0.54                   | 0.09      | 40    | 25    | 35    | 0.53            | -28.7| -28.2 |
| Lo-1      | Zarqa (3720)         | 1.00  | 1.91                     | 1.10                   | 0.61                  | 0.40  | 2.50  | 0.30            | 0.54                   | 0.21      | 38    | 25    | 37    | 0.51            | -28.6| -27.3 |
| Nm D-1    | Abu Gabra (3570)     | 1.20  | 2.40                     | 1.00                   | 0.50                  | 1.00  | 1.00  | 2.10            | 0.50                   | 0.50      | 33    | 33    | 33    | 0.50            | -29.6| -29.0 |
| Sample          | Location Source | Tricyclic (m/z 191) | Gammacerane (m/z 217 & 218) |
|-----------------|-----------------|---------------------|-----------------------------|
| Nm K-2          | Abu Gabra (2740)| 1.70                | 0.60                        |
| Nm K-2          | Abu Gabra (2890)| 1.90                | 0.50                        |
| Nm K-1          | Abu Gabra (3030)| 1.40                | 0.50                        |
| Nm K-1          | Abu Gabra (2650)| 1.70                | 0.60                        |

**Appendix-I: Table-2:** Saturated GCMS biomarker parameters for both the Terpanes (from m/z 191) and Steranes (from m/z 217 & 218) groups for the study rocks and the oil indicating organic matter source, depositional environments, and maturity. TT: Tricyclic terpanes, Gmc Ind.: Gammacerane index (Gammacerane/C30 hopane*100, after Hunt, 1996).