Source Rock Evaluation of the Upper Cretaceous Sirte Formation in Eastern Sirte Basin, Libya

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Abstract: The present work discusses the geochemistry and maturation history of the Upper Cretaceous source rock of Sirte Formation in the Eastern side of Sirte Basin, Libya. The study involves details on the evaluation of the kerogen type and richness in relation to the prevailed depositional environment. Thirty three cuttings samples were collected from three wells abbreviated, hereafter, as A, B and C, respectively. According to the Rock-Eval results, the study sediments can be classified as very good to perfect source rocks for oil and gas generation. The TOC richness and anoxic condition propose adequate preservation conditions. Kerogenis determined to be of Type II or mixed Types II and III (oil and gas condensate). T_{max} and predication index evaluation indicate that maturity of the study source rocksoccur between immature or/and early mature oil zone and at the beginning of the oil-producing stage. The positive relationship between SiO_2 and Al_2O_3, besides the relatively low SiO_2/Al_2O_3, proposes their mutual association as alumino-silicates. However, the positive correlation between $Al_2O_3$and K_2O confirms the dominance of theillitic mode. The content of alumina is reversely related to the content of CaO, where the latter designates the marine carbonate sedimentation while alumina measures the clay admixture which is essentially allochthonous. From burial history study of the sampled wells, the Sirte Formation started to the onset of oil generation in wells through early Eocene to Oligocene, and reached the peak of oil generation during the Miocene time.

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Key words: Sirte, Libya, source rock, maturation, kerogen, geochemistry.

1. Introduction

The Sirte Basin (also referred to as Sirt Basin), is located on the northern margin of the African plate in the north central part of Libya between latitudes 14°00' - 20°00' E and longitudes 28°00' - 31°00' N (Fig. 1). It is the youngest sedimentary basin in Libyaandit covers an area of about 600km^2, extending offshore along the Mediterranean Sea. Sirte Basin is one of Africa's most productive petroleum basins and the world's 13thlargest petroleum province, with reserves estimated at 43 billion barrels of oil equivalent (recoverable) within 16 giant oil fields and 23 relatively large oil fields (Ahlbrandt, 2001). Central Sirte Basin Carbonates is an established unit and contains fields producing from carbonates of the Upper Cretaceous, Paleocene, and Eocene platforms, mostly onshore, with potential for production to water at depths of about 200m is in offshore areas. The basin is characterized by a fill which is entirely Mesozoic and Cenozoic in age, and by the presence of series of platforms and deep troughs (Hallett, 2002).

The present study is based on 33 cuttings samples collected from three wells, namely; "3M1-59", "5P1-59" and "3Y1-59", hereafter abbreviated as A, B and C, respectively. The TOC and Rock-Eval pyrolysis data provide important clues on the evaluation of the study source rock, thermal maturity, kerogen type and burial history. The inorganic analysis was done by the indicatively coupled plasma-mass spectrometry (ICP-MS) technique in the ACME Lab of Vancouver in Canada. The analysis involves the major elements and about 50 trace elements including the 14 rare earth elements (REE) and some very rare elements such as In, Re, Te and Tl.

Study Area

The study area belongs to "Blocks 59" in the Gialo oil field, which is located in eastern part of the Sirte Basin, between latitudes 28°03'6" and 28°51"N, and longitudes 21°30 and 19°42"E.The Gialo oil field is about 300 kilometers south of the Ajdabiya city and 30km south of Gialo city (Fig .1).

2. lithostratigraphy

The Sirte Basin is divided into three lithostratigraphic sequences, as illustrated in figure 2 (Barr and Weegar, 1972 and Hallett, 2002). The first is the**pre-riftsequence** which is represented by Hofra (Gargaf) Formation and Sarir (Nubian) Formation. The former is bound by unconformable boundaries, where it is overlain by Bahi Formation and underlain by Basement igneous rocks (Saheel, *et al*., 2010). It is separated from the basement by a major unconformity, and dominated by the pre-Lower Cretaceous sedimentary. **The second sequence (syn-rift)** represents the Late Cretaceous to Late Eocene sediments. The Cretaceous sediments unconformably overlay by the Hofra Formation. These sediments are represented by Sarir, Bahi, Maragh, Lidam, Etel, Argub, Rachmat, Tagrifat, Sirte, Kalash, Satal, Waha, Hagfa, Beda, Khalifa, Zelten, Harash, Kheir, Al Gir, Gialo and Awjilah formations, from base to top. **The third sequence (post-rift)** represents the Lower Eocene - Miocene sediments which are mainly shallow marine carbonates (tidal to supra-tidal environment) as result of regional lowering in the sea level (regression). These sediments are represented by Arida, Diba and Marada formations (Barr and Weegar, 1972 and Hallett, 2002).

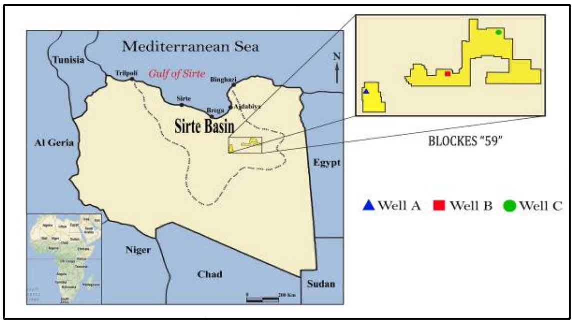


Fig (1): Location map of the study area and the location of the three wells; 3M1-59(A), 5P1-59 (B) and 3Y1-59(C), in Sirte Basin, Blocks 59,Gialo oil field.

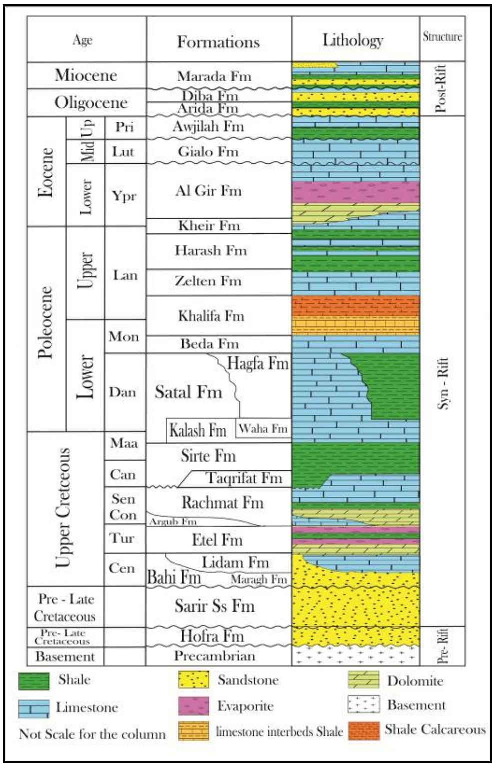


Fig (2) Stratigraphic section in Eastern Sirte Basin(modified after Barr and Weegar, 1972 and Hallett 2002).

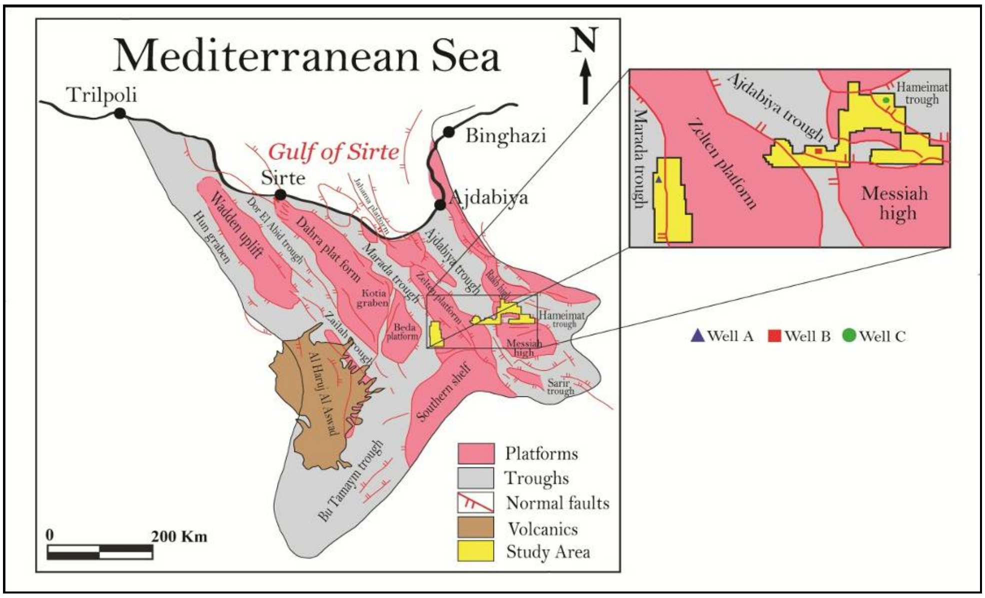


Fig (3) Major structural elements of the Sirte Basin and Study area (modified after Abadi 2002 and Saheel et al., 2010).

3. Geologic Setting

The basin has long been considered as part of the Tethys rift system (*e.g.*,Abadi, *et al.*, 2008; Capitanio,*et al.*, 2009; Abouessa,*et al.*, 2012). It reflects significant rifting in the Early Cretaceous and syn-rift sedimentary filling from Cretaceous to

Eocene, and post-rift deposition in the Oligocene and Miocene (Fig 3). Generally, Sirte Basin remained a positive element until nearly the end of Cretaceous at which movement and deformation (block faulting) took place. Then, the Sirte area was generally submerged, probably for the first time since the Early Paleozoic area. The period of the Late Mesozoic-Early Cenozoic appears to have been relatively more eventful from the view point of tectonic evolution and the attendant sedimentation history (Sinha and Mriheel, 1996; Abouessa, *et al*., 2012). Hydrocarbon is produced from reservoirs varying in age from Cambrian to Tertiary, from both horst and graben systems. Upper Cretaceous marine shales are the dominant source rocks. The basin's recoverable reserves are about 45 billion barrels of oil and 33 trillion cubic feet of gas (Abadi, *et al.*, 2008).**4. Sedimentological considerations:**

Sedimentologically, the Sirte Formation (Fm) is mainly composed of brown to dark brown, and gray to dark gray shale, commonly calcareous, pyritic but also silty and carbonaceous with interbeds of limestone, especially at its lower part. These facies are overlain and underlain by gray to dark gray calcareous and pyritic shales. In Marada area, Sirte Fm is subdivided into two members, the lower is limestone dominated while the upper ischiefly of shale. The former is characterized by limestone faces with argillaceous limestone interbeds, and it is well penetrated at well (A), with thickness of about 255m but it decreases towards the NE direction, and completely wedged out at well (B). The upper member is characterized by its shale to calcareous shale nature with sporadic limestone interbeds, but seldom with silt interbeds. This member is well penetrated by the three study wells. While in Hameimat trough, Sirte Fm is divided into three members; lower shale, middle limestone and upper shale. The lower member is characterized by its sandy, silty and argillaceous nature with limestone interbeds. The recorded maximum thickness of this member is 418m but it decreases towards the SW. The middle limestone member is characterized by its limestone to argillaceous limestone nature with shale interbeds. It is penetrated in well (C) with thickness of about 150m but decreases due SW.

However, Sirte Formation has been encountered in Marada trough (well A), Ajdabiya trough (well B) and Hameimat trough (well C), from SW to NE. The thickness and lithology of the Sirte Formation are variable in each of the boreholes under consideration. The thickness is estimated to be up to 783m at well (C) duenorth-east**,** at Hameimat rough, but decreases towards south-west to 255m at the well (A) (Marada trough). Clearly the variation in the thickness of the Sirte Formation might have been related to tectonic activities of Sirte Basin. These activities have triggered variation in the rate of subsidence which, in turn, affected variation in thickness of this formation (Fig. 4).

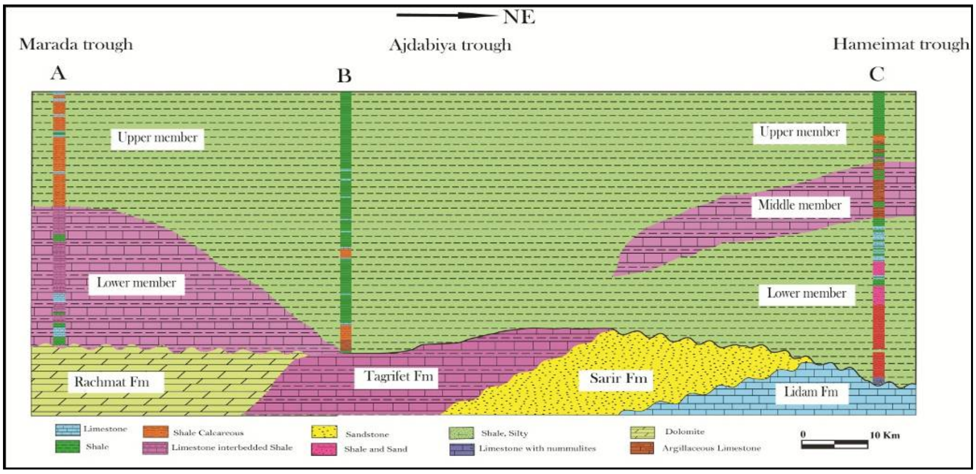


Fig. (4): Gross sedimentological features of the Sirte Fm in the study area.

5. Samples and Analytical Methods

The characterization of the Upper Cretaceous source rock of the Sirte Formation is based onanalysis of 33 cutting samples, collected from three wells in Gialo field (Sirte Basin). The geochemical techniques used in his study include TOC analysis and Rock-Eval pyrolysis. These analyses were done in order to determine the quantity and quality (type) of organic matter (OM) and its maturity in the sediments under consideration.The obtained parameters, in turn, will be adopted for the interpretation of the petroleum source potential and depositional environment of the Sirte Fm in the study area.

Description of the samples under binocular microscope was done to describe the color and hardness. Samples cuttings considered in the present work were drilled with oil based mud. The samples were washed in water, toluene and benzene to remove all traces of drilling mud and then air dried under controlled conditions at 40°C for not longer than twelve hours.

Complete inorganic geochemical analysis was done for18 whole source rock samples representing the sediments of the Sirte Formation in the two boreholes, namely; A and B. The samples were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) technique in ACME Laboratories of Vancouver, Canada. The analysis involves the major elements and about 50 trace elements, including the 14 rare earth elements (REE) and some very rare elements such as In, Re, Te and Tl.

6. Results and Discussions

6.1. Geochemical Source Rock

1.1.1. Organic Richness

In the present study, the organic richness is expressed in terms of total organic carbon percentage (TOC %) which varies between 1 and 5.53%. The frequency distribution of TOC suggests that 4% in the most abundant (Fig. 4). The distribution suggests also that borehole B is the richest, followed by borehole A while borehole C is the least in TOC. The averages of the TOC contents are estimated to be 4.0, 2.9 and 2.4 for boreholes B, A and C, respectively.

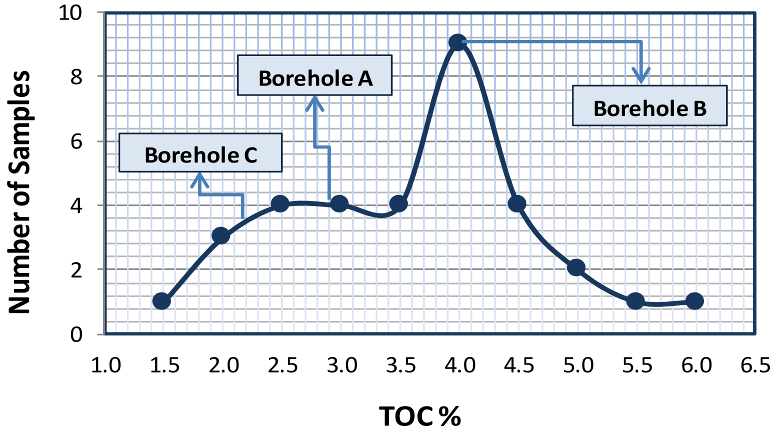


Fig. (4): Frequency distribution of TOC in 33 samples of Sirte Formation.

Considering that the analyzed sediments are mostly imparted by carbonate nature, it can be presumed that the sediments of borehole B are excellent source rocks while those of boreholes A and C are generally very good source rocks. The spatial distribution of TOC suggests general decrease towards the south-western and north-eastern parts of the study area. The Sirte Fm is of variable thickness and richness of total organic carbon TOC, according to many authors, e.g., Parsons *et al.*, (1980), El-Alami *et al.* (1989), Ibrahim (1991), Baric *et al.* (1996), El-Alami (1996), Rusk (2001), Hallett (2002), Burwood, (2003), and Lüning *et al.* (2004), among others.

The very strong relationship between TOC and S2 proposes that the preserved organic matter is principally of the pyrolyzable type (Fig. 5). This means that prospective yield can be obtained upon proper burial and adequate catagenetic condition.

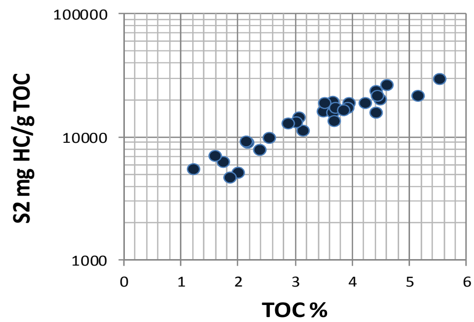


Fig. (5): Intimate coherence between TOC and the pyrolyzable fraction (S2)

6.1.2. Kerogen Type

The organic matter in the study area shows potential yield values (S2) of 26120, 29250 and 12810 ppm for wells A, B and C, respectively. These values are generally indicative of organic material suitable for gas and condensate oil production.

Organic matter richness with potential yield values up to 2420 and the best quality source rocks were concentrated towards the top of the Sirte Formation. The oil window generation increases with depth in the present study. The top of the oil window was estimated at a depth of 2800m, with peak generation below 3250 m (Hallett, 2002). This is formation the oil-generating window between depths of 2.700 and 3.400 m in the central and eastern Sirte Basin (Futyan and Jawzi, 1996, Ahlbrandt, 2001).

The kerogen type as inferred from the plot of HI versus T_{max} (Fig. 6) indicates the following important inferences:

1. There is no confident dependence of kerogen type on depth.
2. The values of HI vary from depth to another while the T_{max} is almost consistent with very limited variation from 431 to 438.
3. In all cases, kerogen belongs to type II, but sometimes drop towards middle or lower field of this type. This indicates organic matter of marine origin receiving subsidiary but variable quotients of terrestrial organic matter.
4. The kerogen quality of wells A and B are relatively better than that of well C.

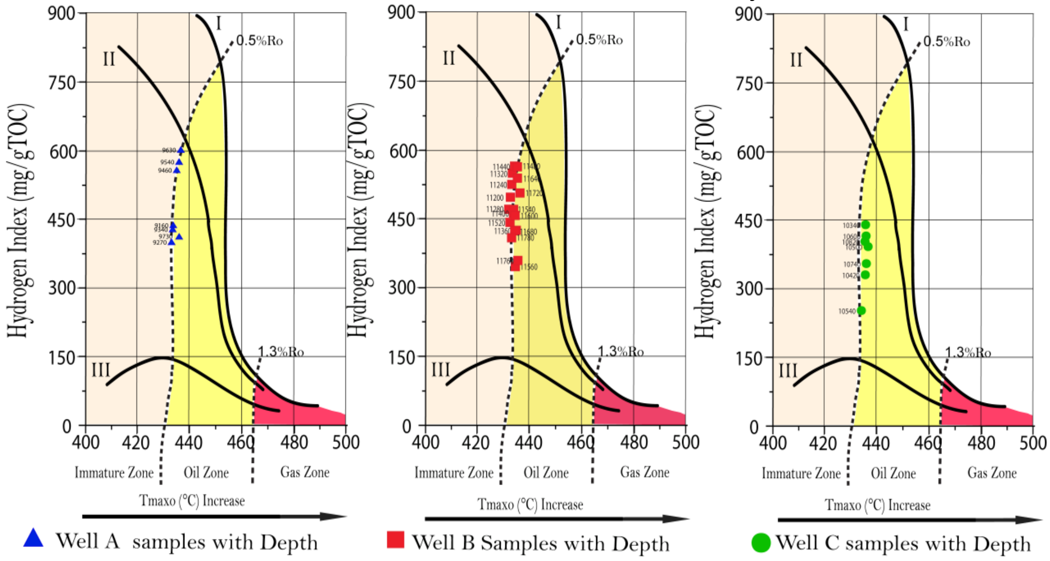


Fig. (6): Kerogen type as perceived byT_{max} versus hydrogen index plot for the Sirte Formation samples collected from the three wells; A, B, C.

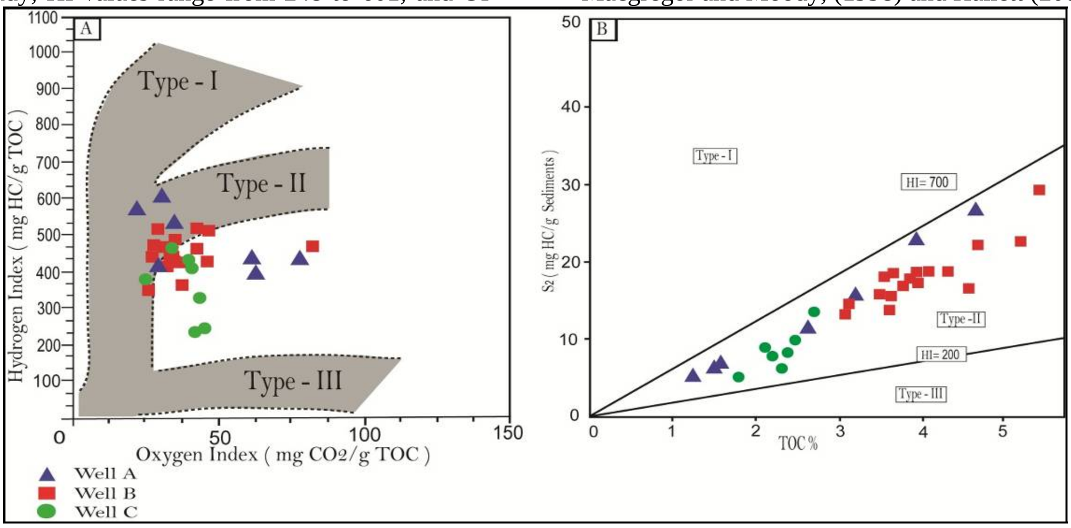
The plot of oxygen index versus hydrogen index produces a pseudo–van Kervelen diagram (Espitalie *et al.*, 1977). The position of a point on this diagram shows not only maturity of the organic matter but also organic matter type. With increasing maturity the HI and OI values of a sample will decrease.

In Well (A), kerogen plotsin the field of type II and mixed II and III (Figs. 7 and 8) and have fair to good hydrocarbon potential generation (pyrolysis S2 ranges 5380 to 26120 ppm).The organic matter is a mixture of marine algal and variable terrestrial contributions. This suggests that this kerogen is capable to generate mainly oil with some gas. However, oil generation organic matter seems to be concentrated in thin organically-rich shale and limestone interbeds (Fig. 4). In this well, the kerogen type II and the high HI, which ranges from 394 to 601 HC/mg TOC, indicates good preservation of marine organic matter and high oil prone potential.

In Well (B), kerogen belongs mostly to type II but some samples are occasionally shifted to type II-III (Fig.7), with good to very good hydrocarbon potential generation (pyrolysis S2 ranges from 14290 to 29250 ppm) and their HI from 355 to 529. The organic matter has more marine character with limited terrestrial participation. This kerogen type is capable to generate mainly oil with some gas. It was deposited and preserved with medium sulphur content.

In Well (C), kerogen belongs mostly to mixed II and III type (Figs. 7 and 8) with god hydrocarbon potential (pyrolysis S2 ranges from 12810 to 4640 ppm) with their hydrogen indices (248-445), which indicate that these rocks have mixed marine and terrestrial organic matter, and capable to generate oil and gas.

Generally, the kerogen of study Sirte Formation is dominantly of type II which proposes high quality of source rocks where organic matter is essentially of marine sources mixed with variable quotients of terrestrial organic matter. This suggests that the section is dominated by oil-prone material, but with some minor gas-prone vitrinitic material. In this study, HI values range from 248 to 601, and OI from 21 to 84. Such high HI and low OI propose high kerogen quality and potential for generation of hydrocarbon. This conclusion agrees well with Macgregor and Moody, (1998) and Hallett (2002).



(Fig .7 and 8): (A) Plot of the samples from Sirte Fm on van Krevelen diagram. (B) Langford and Blanc-Valleron (1990) diagram.

6.1.3 Maturity of organic matter

In this work, a general assessment of thermal maturity using T_{max} values shows no major difference between the outcrop samples; T_{max} values are rather consistent where they range from 431°C to 438°C, which indicate immature organic matter. However, the plot of the analyzed samples on the HI versus T_{max} diagram (Fig. 6) suggest that the organic matter is at the end of the diagenesis stage and possibly experienced the beginning of catagenesis as they plot in the zone of early oil generation (early Oil Window).

Production Index (PI): The plot of PI versus T_{max} indicates an early oil zone (Fig. 9). Locally, there is no confidence dependence of oil generation on depth. Production index (PI) reveals that the amount of total hydrocarbon potential (S1+S2) that is transformed to free hydrocarbon (S1) remained within the rock before the maturity during the burial-based thermal evolution (Bordenave, 1993). PI is an indicator of the amount of volatile "free" hydrocarbons relative to the presence of migrated oil or the amount of redistributed liquid hydrocarbons (generated by the cracking of kerogen) by primary migration. The samples that contain more than 4 % TOC show anomalously high PI values (0.01-0.38) suggesting possibility of redistributed hydrocarbons, or migrated oil, in most of the non-contaminated samples. As the maturity increases, PI values are also increased; indicating that maturity of Sirte shales fluctuates between immature and early mature stages.

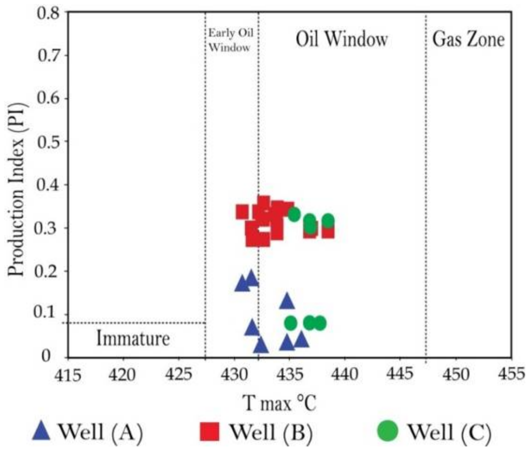


Fig. (9): Plot of T_{max} against PI for samples, the plot shows that samples are thermally in early mature to mature stage.

6.1.4. Depositional environments.

The content of Al_2O_3 expresses the relative abundance of the clay minerals. The strong positive correlation between alumina and silica demonstrates their common association as clay minerals (Fig.10). The SiO_2/Al_2O_3 ratio is calculated to range from 3 to 5, suggesting preponderance of three layer clays rather than double layer. This agrees well with the mineralogical data which concluded that illite, smectite and their mixed layers are the main clay minerals encountered inequivalent sedimentary sequence (El-Kammar, *et al.*, 1990).

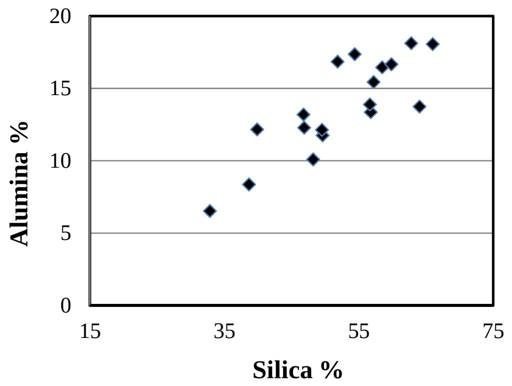


Fig. (10):Silica versus alumina in the analyzed sediments of Sirte Formation

The strong positive correlation between alumina and K_2O confirm their mutual association in the illitic mode (Fig.11). It is evident that the sediments of well B are richer in potash and alumina being more argillaceous relative to those of well A.

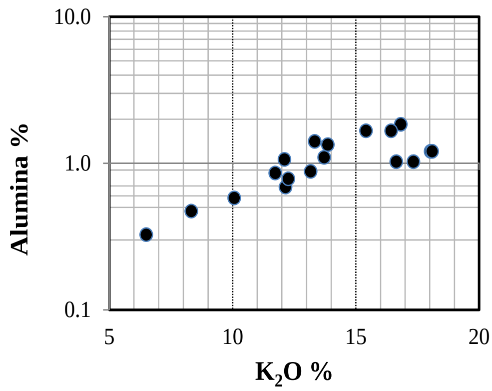


Fig. (11): Alumina versus K_2O in the analyzed source rocks at wells (A and B) of Sirte Formation

The calculated non-pyritic iron correlates intimately with the content of alumina, suggesting mutual accommodation as clays (Fig.12).

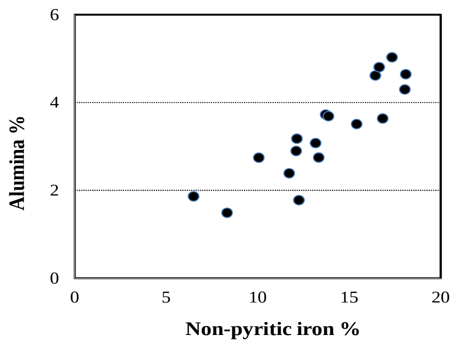


Fig. (12): Non-pyritic iron versus alumina in the analyzed source rocks at wells (A and B) of Sirte Fm

The content of alumina is reversely related to the content of CaO, where the latter designates the marine carbonate sedimentation while alumina measures the clay admixture which is essentially allochthonous (Fig.13). The relation suggests also that the sediments of well A have more marine character compared with those of well B.

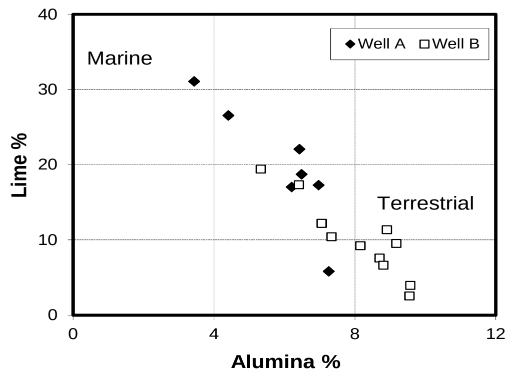


Fig. (13): Alumina versus lime in the analyzed sediments of Sirte Formation

The U and Th contents of shale are affected by a number of syn-depositional and post-depositional processes not readily manifested by elemental concentrations. At the anoxic water-sediments interface, the soluble U^{6+} can be reduced and precipitated as U^{4+}. Therefore, the organic-rich sediments under study, may contain Th/U ratio lower than the chondritic value (2.8) as a result of the secondary U uptake (Fig. 14).

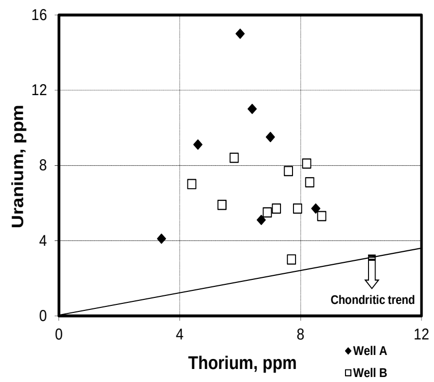


Fig. (14): Relationship between thorium and uranium in the analyzed source rocks of Sirte Formation

However, more recent considerations of the problem of U accumulation in sedimentary rocks indicate that high organic carbon content alone does not govern the U concentration (Kochenov and Baturin, 2002 and Galindo, *et al*., 2007). This seems to be also valid for the present work, where the correlation between U and TOC is not strong. This is possibly because uranium is liable to oxidation-reduction, sorption and complexation during the long and complicated diagenetic history.

6.2. Burial history (Depths and Timing of Hydrocarbon Generation)

The burial history and thermal maturity investigation have been carried out on the study Upper Cretaceous deposits from the Sirte Basin that forms part of a rich hydrocarbon province defined by the presence of potential hydrocarbon source rocks. The burial history predicts the depth interval, in which oil is being generated, and the timing in the geologic past, when oil source beds became thermally mature.

In the well (A), the burial history reconstruction and thermal modeling suggest that Sirte Fm entered the oil window at the early Oligocene, when it was buried to a depth of (9100 ft.) 2732 m. The oil generation peak entered at depth 2800 m, during the late Miocene. Based on the burial history diagram, the maximum burial temperature of the Sirte Formation ranges from 70 to 84°C, which is below the lower limit of the onset of early oil generation (Fig. 15).

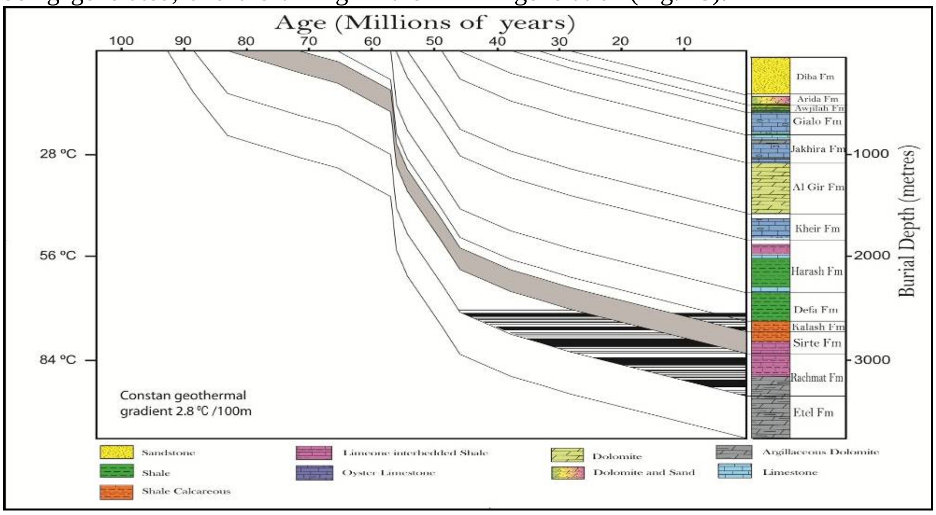


Fig (15): Well (A) burial history curves, the main zone of oil generation of the Upper Cretaceous–Tertiary formations in the Sirte Basin. The geothermal gradient is estimated to be 2.8°C /100m, by Hallett (2002).

In the well (B), the burial history reconstruction and thermal modeling suggest that the Sirte Formation went through oil generation at the middle Eocene, when it was buried to a depth of 11187 ft.(3359 m), and the oil generation peak was attained at depth 3700 m, during the late Miocene. The maximum burial temperature of the Sirte Formation ranges from 70 to 91°C, which is below the middle limit of the oil generation (Fig. 16).

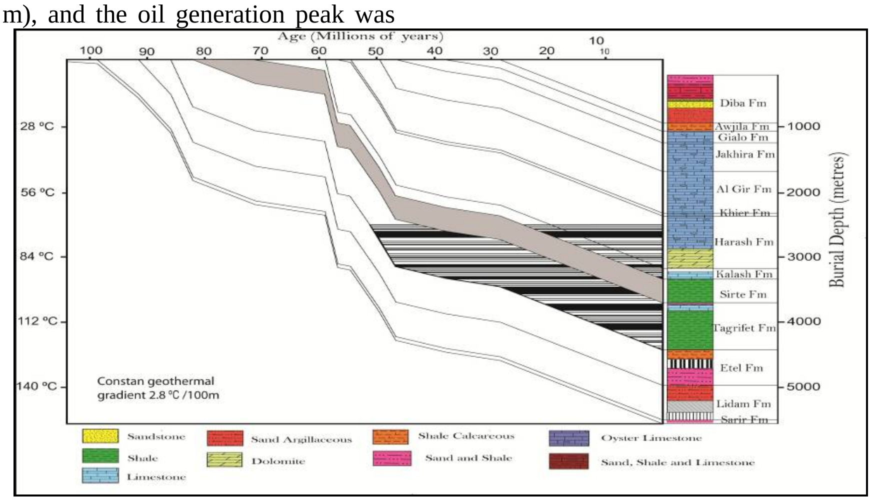


Fig (16) Well (B) Burial history curves, the main zone of oil generation of the Upper Cretaceous–Tertiary formations in the Sirte Basin.The geothermal gradient is estimated to be 2.8°C /100m, by Hallett (2002).

In the well (C),the burial history reconstruction and thermal modeling suggest that the Sirte Formation interred oil generation at the early Eocene, when it was buried to a depth of 10180 ft.(3057 m), and the interred peak oil generation at depth 3500 m in the late Miocene. The maximum burial temperature of the Sirte Formation ranges from 70 to 91°C, which is below the middle limit of the oil generation (Fig. 17).

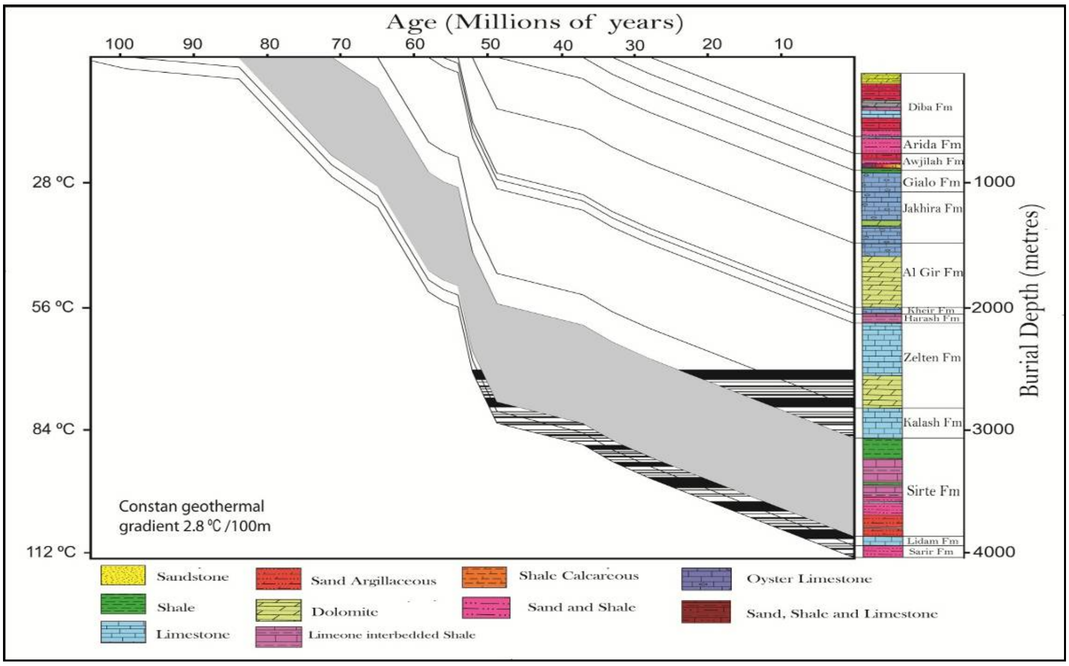


Fig (17) Well (C) Burial history curves, the main zone of oil generation of the Upper Cretaceous–Tertiary formations in the Sirte Basin. The geothermal gradient is estimated to be 2.8°C /100m, by Hallett (2002).

Generally, the burial histories of the study boreholes are similar and include the major depositional phases regarding Sirte Fm, which entered into the oil window during the Oligocene but reached the generation peak during the Miocene time at the deeper parts of the troughs. The source rock is still in the oil generation window at the present time.
The Sirte Fm entered the early phase of oil generation during the mid-Eocene and reached generation peak during the Oligocene. The timing of onset of oil generation is Eocene, in the deep troughs, to Oligocene, in the shallower areas (Hallett, 2002). The younger and shallower Sirte Fm entered the oil window toward the end of the Eocene and is currently at peak oil maturity (Burwood, 2003).

Conclusions:

Sirte Basin is one of the largest oil provinces in the world with reserves exceeding 40 billion recoverable barrels. The main source rock in the basin is the organic-rich Upper Cretaceous limestone and shale sequence known as Sirte Formation. The present work is concerned with that source rock in the eastern side of the basin (Gialo oil field) where maturation is not appropriately innovated. From the sedimentology point of view, the Sirte Formation (Fm) is mainly composed of brown to dark brown, and gray to dark gray shale, commonly calcareous, pyritic but also silty and carbonaceous with interbeds of limestone, especially at its lower part. The thickness of the formation decreases from 783m innorth-east(Hameimat rough), to 255m in the south-west (Marada trough). This variation in the thickness is assumed to be due to tectonic activities which triggered variation in the rate of subsidence and, in turn, affected variation in thickness.

The present evaluation of the Sirte Fm source rock is based on 33 cuttings samples collected from three wells, namely; “3M1-59”, “5P1-59” and “3Y1-59”, hereafter abbreviated as A, B and C, respectively. These samples were analyzed for TOC, Rock-Eval pyrolysis and inorganic chemical composition by ICP-MS. It can be presumed that the study sediments are excellent to very good source rocks with general decrease in quality towards the south-western and north-eastern parts of the study area. Kerogen belongs to type II, but sometimes drop towards middle or lower field of this type indicating dominant marine organic matter receiving subsidiary but variable quotients of terrestrial input. The quality of kerogen and the high HI indicate good preservation of marine organic matter and high oil and gas prone potential. The organic matter is at the end of the diagenesis stage and possibly experienced the beginning of catagenesis at early oil generation (early Oil Window).

The inorganic chemical composition is used to characterize the influence of the allochthonous supply to the depositional basin. The contents of Al, Ga, Ti, Th and REE are considered as direct indicators of the terrestrial supply, while Ca and Sr are good indicators of marine nature.

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