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SHALE GAS IN A LACUSTRINE RIFTING BASIN, NEEM_AZRAQ AREA, MUGLAD BASIN, SUDAN CONCEPTS AND APPLICABILITY

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ABSTRACT

Shale gas has become an increasingly more important source of natural gas in the United States over the past decades. Less attention given to shale gas in lacustrine basins and few cases are not encouraging. Abu Gabra formation acts as the main effective source rock and reservoir in the same time gross thickness reach to about 7000m at the depocenter and characterized by the interbedded sands which producing condensate, light oil and recently considerable volumes of associated and non associated dry gas.

Geochemical evaluation carried to evaluate the source rock, pyrolysis analysis results of 617 geochemical rock samples from Azraq wells and 337 geochemical rock samples from Neem wells, used to evaluate the richness of source rock (TOC), kerogen type (HI, S2) and thermal maturity (Tmax). VRo readings of 119 rock samples from Azraq wells and 73 geochemical rock samples from Neem wells used to measure the thermal maturity. 1D modeling processed to predict the geothermal history and heat flow of the study area. The geomechanical characteristics of the source rock (brittleness) evaluated using the mineral and metal analysis result of 3 conventional core samples from selected wells.

Based on the main key parameters used to evaluate shale gas in Marine basins there is high feasibility of shale gas in Lacustrine basin, where the average TOC in the study area (2.0 wt% - 3.0 wt %), VRo (0.48% to 1.0% in penetrated intervals) high heat flow (peak in tertiary 83 mw/m^2).

Many challenges of; litho-facies variation within short distance (difficulty of detecting sweet spot), possibility of suppression of thermal maturity and unprecise reading of VRo%, technological challenge of fracturing tools stands there to answer whether it will be success and economically viable?.

Key words: Shale gas, thermal maturity, geochemical evaluation, kerogen type, feasibility, Abu gabra formation

INTRODUCTION

The Muglad Basin is the most important of sedimentary rifting basins in Africa, extending up to 800 km long, 200 km wide (Genik, 1993), accommodating sediments attaining local thicknesses of up to 15 Km in the deepest parts of the basin (Bosworth, 1992). Similar to all Sudan Rift Basins, sedimentary sequences of Muglad Basin consists of nonmarine cyclic sequences of Lacustrine, fluvial braided/meandering streams, flood plain and alluvial fan facies of early Cretaceous to recent, that unconformably rested upon the Precambrian basement (Shull,1988).

The Muglad Basin was formed at late Jurassic to Early Cretaceous and the structural development was marked by three major rift cycles, each characterized by coarsening upward sequences of clastic sediments (Stead & Awad, 2005).

The Neocomian - Barremian Abu Gabra formation represents the period of greatest lacustrine development. Several thousand feet of organic – rich lacustrine claystones and shales were deposited with interbedded fine grained sands and silts (Shull, 1988). Those shales represent the main effective source rock of the Cretaceous petroleum system in the study area.

Abu Gabra formation source rock has been divided into three subunits (lower , middle and upper) based on lithofacies pattern and geochemical parameters (Ahmed, 1996), according to Ahmed lower and upper units represents the same facies, which characterized by gray, massive mudstones while the middle unit consists of dark brown laminated shales, sapropellic amorphous organic matter . The deposition environment for lower and upper facies is shallow, low stand, oxygenated and agitated lake-marginal deltaic environment. The middle subunit is deposited in high-stand anoxic water/sediment interface, quite deep-water environment. The sand bodies within Abu Gabra formation are proven to be very good oil producers as the sand and oil quality are very good.

Geochemical parameters indicate rich source rock of average TOC up to 4.0 wt% and maturity increasing depth wise to VRo.0.5 – 1.0% and present-day temperature of 100C° at interval 2400m (data from drilled well in the study area).

Theoretical Background

Natural gas (methane) is generated from the organic matter that is deposited with and present in the shale matrix. The potential of a shale formation to contain economic quantities of gas can be evaluated by identifying specific source rock characteristics such as total organic carbon (TOC ≥ 2.0 wt %), thermal maturity (ideally in gas window, VRo≥ 1.3%) Jarvie, 2007, kerogen analysis (adsorption capacity type III> type II> type I) Noble, et al., 1997 and (HI, type I> type II> type III). Together these factors can be used to predict the productive shale to produce economically viable volumes of natural gas. Shale resource plays can be described as biogenic or thermogenic based on gas type. Minerals and petrophysical characteristic of the rock are essential for the geomechanic (brittleness of the rock) and this directly proportional with fracturing method and the productivity of the shale.

Area of Study

The area of study is located at the west Kordofan, North, Northwest block 4 of GNPOC Concession, includes Neem, Azraq and Alsandal oil fields of Muglad rift Basin of the interior Sudan (**Fig.1**).

The area bounded to the west by the Baggara basin, to the east by White Nile River, to northeast by Nuba Mountains and to the south extending to Anza basin in Kenya. The Muglad basin trends in the NW-SE directions and terminates against the Central African Shear Zone (CASZ).

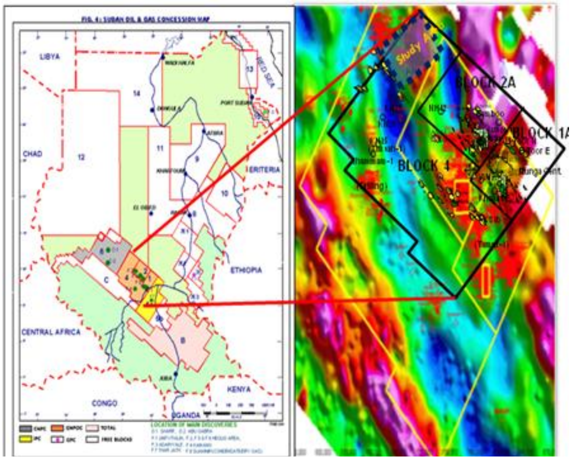


Fig.1. Location map of the Study area

Rationale of this Study

Shale gas has become an increasingly more important source of natural gas in the USA over the past decades, and interest has spread to potential gas shales in Canada, Europe, Asia and Austalia. Most of shale gas produced from marine sediments and less attention paid to non marine sediments.

The thick shale of Abu Gabra formation rich, and has high mature hydrocarbon with high rate of associated gas. Recently evaluated dry gas zones encrouage finding out the characteristics and feasibility of shale gas in the study area.

Aims and Objectives

1. Evalute source rock richness since it is one of the key parameter of shale gas.
2. Kerogen types affect the produced hydrocarbon (oil and gas).
3. Most important parameter in shale gas where the onset of gas generation is determined. To evaluate thermal maturity data of vitrinite reflectance, Tmax from pyrolysis analysis, maturity parameters from oil analysis, and carbon isotope, and ID modeling.

Geological Setting

Muglad basin is one of the major, largest extensional rift basins in Sudan. Three episodes resulted in non-marine/ non-volcanic, 13km thick of Cretaceous – Tertiary sediments (**Shull, 1988**). The basin oriented in NW-SE trend and extends across 120,000km^2 and up to 200km wide and over 800km long. Three major episodes of extensional tectonics recognized in the Muglad basin:

1- Paleogene (65 – 30 Ma) of about 5400m sediments.

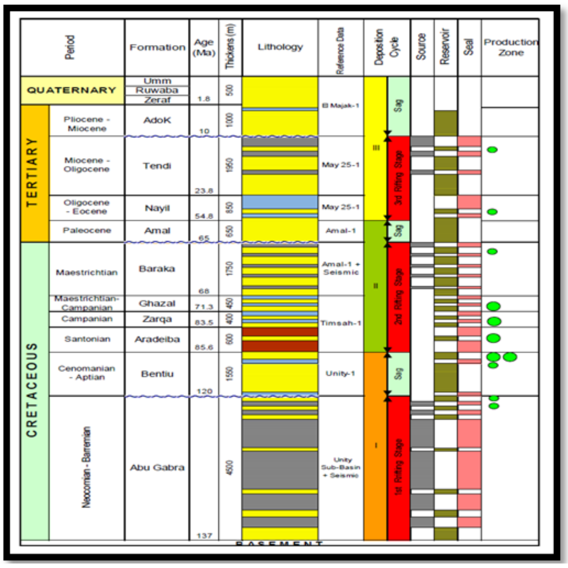
2- Late Cretaceous (95 – 65 Ma) of about 4200m sediments.

3- Early Cretaceous (140 – 95 Ma) of about 5400m sediments.

Abu Gabra Formation

Is the main source rock of rich-organic lacustrine claystones and shales interbedded with fine-grained sands and silts (Shull, 1988). Abu Gabra formation sub-divided into three units, based on lithofacies patterns and geochemical parameters (Ahmed, Y.M., 1996). Upper and lower Abu Gabra have the same facies of light gray massive mudstones and middle Abu Gabra of thick mudstones of dark brown laminated shales (**Fig. 2**).

FMI shows conductive and resistive fractures in shales and interbedded sands.



Abu Gabra Formation

Fig. 2: Composite Column of Muglad basin.

Abu Gabra reservoirs produce about 60% of hydrocarbon in block4, GNPOC Concession. Recently considerable percentage of associated and non-assocaited gas produced from Abu Gabra reservoirs.

MATERIALS AND METHODS

Geochemical cutting samples from Neem – Azraq wells were analyzed for pyrolysis analysis using rock-eval6, Vitrinite reflectance using PMT microscope, GC-GC/MS/MS. 1D modeling using Genex@ software.

Rock-eval6 used for identifying possible source and reservoir intervals. It provides a rapid semi-quantitative source rock analysis on small sample of rock by heating it, using special temperature program using the generated information in evaluating the source rock richness (TOC). Free hydrocarbon in source rock (S1), hydrocarbon generating potential (S2) represents the amount of hydrocarbon that formed during thermal pyrolysis of the sample.

Hydrogen index (H1) represent the amount of hydrogen relative to the amount of organic carbon present in a sample defined as (S2/TOC) X100 which used to determine the type of organic matter, maximum pyrolysis temperature (Tmax), the temperature at which the maximum rate of hydrocarbon generation occurs in kerogen sample during pyrolysis (S2 peak).

For this study about 617 geochemical rock samples from Azraq wells, and 337 geochemical rock samples from Neem wells. The samples washed by tape and distilled water and let to dry in an oven 40C˚ overnight. Homogenous samples picked and grinded and about 70-100mg of pulverized sample was placed in the crucible and progressively heated to 650C˚ under an inert atmosphere (pyrolysis oven). The hydrocarbons that already present in the sample were volatized at a moderate temperature. The amounts of hydrocarbons measured and recorded as peak S1. The kerogen present in the sample generated hydrocarbons and hydrocarbon like compounds recorded as peak S2. CO_2 and water, the CO_2 generated was recorded as peak S3. At oxidation oven sample was heated up to 850C˚ where residual carbon was measured and recorded as S4. The present TOC not measured directly it was calculated from formula:

%TOC = 0.082 (S1+S2) +S4)/10.

119 geochemical rock samples) from Azraq wells and 73 geochemical rock samples from Neem wells virtinite reflectance were read. For cross-check (15) SWC between intervals (1015-3401m) from Azraq SW-1.(10) SWC between intervals (1292.5-2657.5m) from well Alsandal SW-1and (10) SWC between (1587.5-3754m) from the Neem K-1. 10 Geochemical rock samples between (810-3846m) from Azraq SW-3 were analyzed and investigated and vitrinite readings were taken in HRT lab – Brazil. SWC samples from Azraq SW-1 in Netherland lab. – UK prepared and readings taken.

PMT-III photometry system was used for the measurement of light absorption, where the sample is illuminated with monochromatic light and the transmitted light is registered. The wave length is determined by the use of corresponding band passfilters. The calculation is usually carried out according to the Lambert Beer Law and the results are provided in terms of the extinction of the sample solution in relation to the standard solution.

Vitrinite reflectance measurement was made using J&M MPM 200 photometer under oil immersion at a wavelength of 546 nm. Prior to the analysis, the photometer was calibrated using (saphir) standard of 0.591% reflectance and checked by (gadoliniumgallium-granat) standard of 1.718% reflectance. 3 mg of washed geochemical samples picked grinded using Agate mortar and pestle and sieved using 250 micron mesh size. The blocks prepared by preparing plastic mounting cup then the sample added followed by pouring the 60ml resin and 10ml of hardener and stir thoroughly using spatula . Then enough resin mixture poured into the plastic mounting cup and stir to remove all bubbles between the samples fragments. The plastic mounting cup top upped by resin mixture and placed in fume overnight to harden. The mounted sample removed from the plastic cup and labeled.

Four fluid samples (oils & condensate) and three source rock solvent extracts of Azraq K-1, Azraq SW-1, Neem K-1, Alsandal SW-1.

The samples were analyzed for bulk organic composition (volatiles, asphaltenes and hydrocarbon group composition), gas chromatographic composition and biomarker content and composition. The three geochemical rock samples of Azraq SW-1 (1920m), Alsandal sw-1 (2195m) and Neem k-1 (2550m) were extracted using Soxhlet extraction method. The MPLC was constructed as described by (Radke, et. al., 1980).

Gas Chromatography of whole Oil a HP5890 II instrument was used. The column is a HP PONA, length 50 m, i.d. 0.2mm and film thickness 0.5 µm. 2,2,4-tri-methyl-pentane was used as an internal standard. Temperature program was 30 C˚ (10min.) – 2 C˚/min. – 60 C˚(10 min.) – 2 C˚/min. – 130 C˚ (0 min.)-4 C˚/min. – 320 C˚ (25 min.). Gas Chromatography of saturated fraction: A HP5890 II instrument was used. The column is a CP-Sil-5 CB-MS, length 60 m, i.d. 0.25 mm, and film thickness 0.25 µm. C20D42 was used an internal standards. The temperature program 50 C˚ (1 min.) – 4 C˚/min. – 320 C˚ (25 min.).

RESULTS AND INTERPRETAION

Using well log characters, Abu Gabra formation subdivided into upper, middle and lower based on lithofacies variations (**Table 1**).

Table 1: Top of Abu Gabra Formation sub-units

WELL	Top Upper AG	Top Middle AG	Top Lower AG	T.D. of the Well
Azraq C-1	998	1293	2200	2325
Azraq K-1	901.8	1529	2136	2560
Azraq W-1	945	1275	2154	2560
Azraq SW-2	0 fault out	1631	2174.5	3055
Azraq NW-1	1130	1378	1911	2485
Neem S-1	2465	3005	-	3558.9
Neem SE-1	2467	3005	-	3425
Neem SW-1	2848	3204	-	3322
Neem N-1	2163	-	-	3177.4
Neem E-1	2377	2847	-	3058
Neem A-1	2701	-	-	3150
Neem T-1	1457	1771	2152	2467.8
Neem K-2	2586	3204/3340	-	3870
Neem F-1	2630	3114	-	3239
Alsandal SW-1	1767	1948	2542	3198
Alsandal-1	1553	1825	-	2330
Hubara-1	1103	1223	1656	2516
Alsandal S-1	2047	-	-	2675

Using the pyrolysis data and Abu Gabra sub-division to characterize lithofacies upper and lower Abu Gabra not shows systematic or homogeneous correlation. While middle Abu Gabra shows systematic and homogeneous correlation in all Azraq wells.

Organic Matter Richness

The geochemical data for the rock samples from Abu Gabra, Azraq wells and from Neem wells (**Fig. 3**). Average of total organic carbon (TOC) for Azraq wells is 3.0 wt% and can reach to 8.0 wt% in some intervals indicating good to excellent organic richness while in Neem wells average total organic carbon (TOC) is 2.0 wt% and can reach more than 5.0wt% in some intervals which indicate good to excellent organic richness for shale gas.

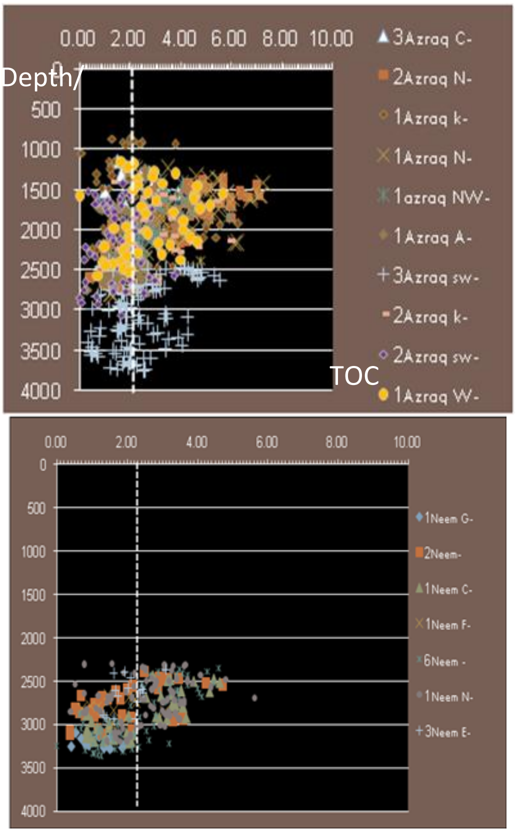


Fig (3): TOC vs. Depth/m in Azraq & Neem wells.

Kerogen Type

Average hydrogen index (HI) 400-460 (immature readings of HI reach 800). Kerogen type mainly of type I few percentages of (which lay within type II is due to either oxidation or a mixture of type I&III) type III especially in upper Abu Gabra for both Azraq and Neem wells.

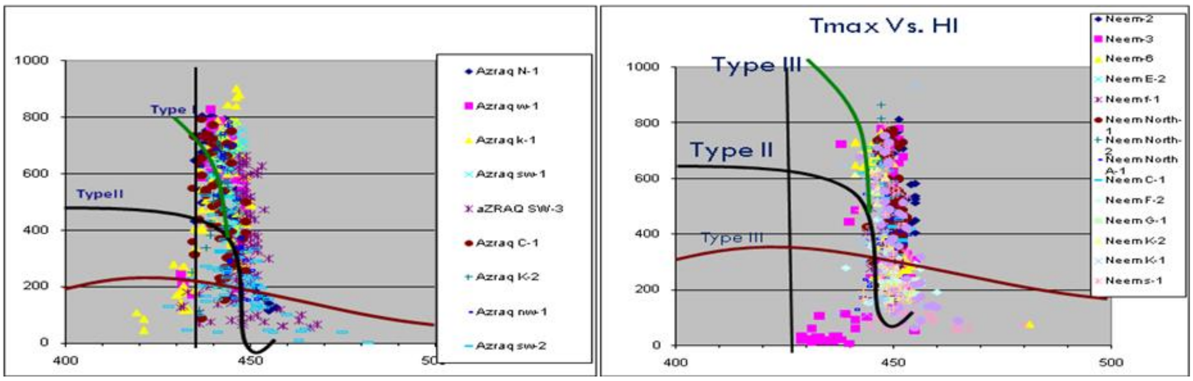


Fig 4. Tmax vs. HI in Azraq & Neem wells

Thermal Maturity

1- From pyrolysis analysis using Tmax and PI as maturity indicator (Fig. 5 & 7).
2- Microscopic readings using vitrinite reflectance as maturity indicator (Fig. 6).

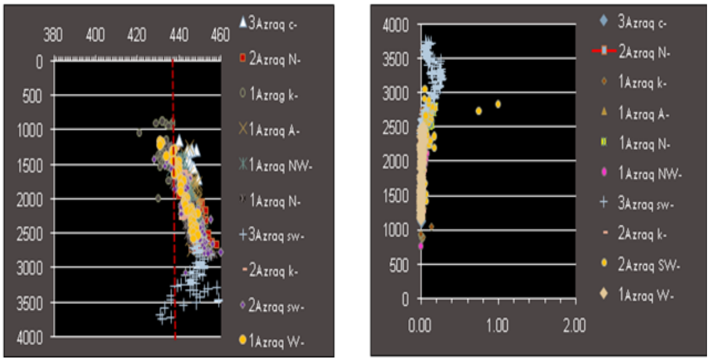


Fig 5.Tmax and PI vs. Depth/m in Azraq wells.

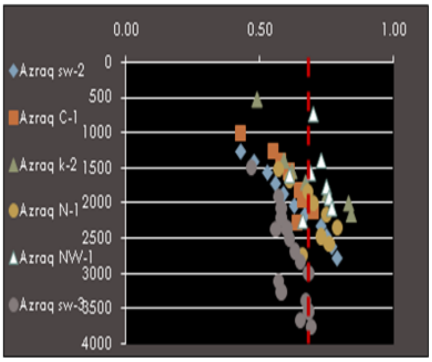


Fig 6.VRo readings Vs. Depth/m in Azraq wells.

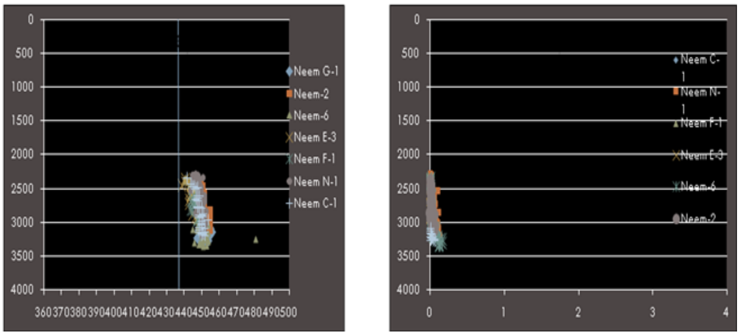


Fig 7. Tmax and PI vs. Depth/m in Neem wells.

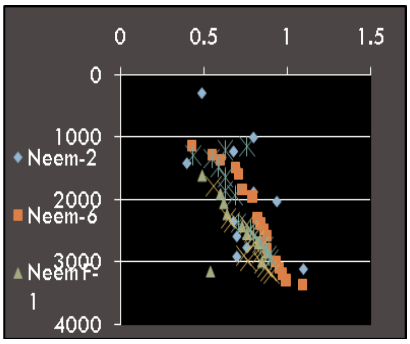


Fig 8.VRo readings vs. Depth/m in Neem wells.

Vitrinite reflectance readings carried out for SWC samples in three different labrotaries for the Azraq sw-1 well, variation in the readings were obtained (Fig. 8) (Fig. 9).

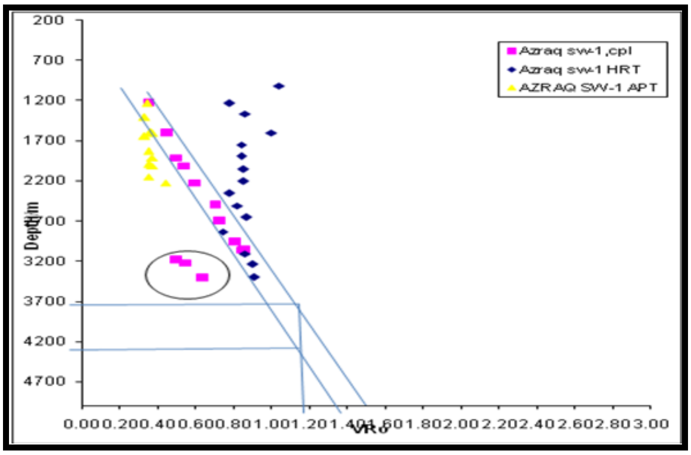


Fig. 9. VRO reading from 3 different labs. For Azraq SW-1.

3- Using Phenanthrene ratios as maturity indicator, equivalent vitrinite reflectance (VRo*, VRo** and VRo***) calculated (Table 2) (Kvalheim et al., 1987).

MPI-1(Methylphenanthrene, m/e 178 and m/e 192) ratio = 1.5*(2-MP+3-MP)/(P+1-MP+9-MP)

MPI-3 (Methylphenanthrene, m/e 178 and m/e 192) ratio = 3*(2-MP)/(P+1-MP+9-MP)

F1 (Methylphenenthrene distribution fraction (MPDF), m/e 192) = (2-MP+3-MP)/(1-MP+2-MP+3-MP+9-MP)

F2 = methylphenanthrene distribution fraction (MPDF) = 2-MP/(1-MP + 2-MP + 3-MP + 9-MP) (m/e 192).

Equivalent VRo%* = 0.166+2.242F1
Equivalent VRo%** = 0.112+3.739F2
Equivalent VRO*** = 0.6(MPI-1)+0.4

Emprical correlations of the methylphenanthrene ratios (MPI-1 and MPI-2) are applicable, dependent upon the maturity range. The relationship between MPI-1 and vitrinite reflectance for VR <1.35% is VR***=0.6* (MPI-1)+0.4 and for VR>1.35% is VR***=0.6 (MPI-1)+2.3 (Radke and Welte, 1983). Comparing the vitrinite reflectance (VRo) with the equivalent vitrinite reflectance of rock extract of the same depth (Table 3).

Table 2. Phenanthrene Ratios Maturity parameters (Phenanthrene and methylphenanthrene).

Well	Depth/m	MPI-1	MPI-2	F1	F2	VRO%*	VRo%**	VRO***
Azraq k-1	2313	0.44	0.46	0.14	0.07	0.47988	0.3773	0.664
Azraq sw-1	1920 extract	0.38	0.42	0.36	0.2	0.97312	0.8598	0.628
Azraq sw-1	1961	0.54	0.57	0.39	0.2	1.04038	0.8598	0.724
Azraq sw-1	2452	0.5	0.52	0.43	0.23	1.13006	0.97197	0.7
Elsandal sw-1	2195 extract	0.42	0.46	0.35	0.19	0.9507	0.82241	0.652
Neem k-1	1682	0.52	0.56	0.41	0.22	1.08522	0.93458	0.712
Neem k-1	2550 extract	0.48	0.51	0.4	0.22	1.0628	0.93458	0.688

Table 3. VRO and VRO equivalent readings for Extract of source rocks.

Well	Dept/m Discription	VRO% from Cuttings	VRO*%	VRO**%	VRO***%
Azraq SW-1	1920 Extract	0.82	0.97	0.86	0.63
Elsandal SW-1	2195 Extract	0.78	0.95	0.82	0.65
Neem k-1	1682 Extract	0.74	1.09	0.94	0.71

Oil and source rock characteristic

Whole oil analysis of oil samples and source rock samples discribe and characterize the source rock in the study area (**Table 4**). The extracts and oils are of paraffinic nature (Alkanes). The Gas Chromatography results for both oils and extracts show the characteristic of source rock in the study area (Figs. 10 & 11)

1D modeling using Genex@software for six wells (Table 5) from the area of study, to detect the heatflow regime through the three rifting phases (Fig. 12).

Table 4. Quantities amount of oil and source rock components

Well	Depth/m	Description	EOM (mg)	Alkanes (wt% of EOM/Oil	Aromatics (wt% of EMO/Oil)	Pols (wt% of EOM/Oil	Asphltene (wt% of EOM/Oil)	HC (wt% of EOM/Oil)	Alks/Arom
Azraq K-1	2313	Pale condense		91.2	6.9	1.7	0.2	98.1	13.2
Azraq SW-1	1920	Black extract	1242	26.4	6.6	66.1	0.9	32.0	4.0
Azraq SW-1	1961	Waxy black solid		66.8	13.6	11.6	8.0	80.4	4.9
Azraq SW-1	2453	Pale condense		89.7	8.5	1.7	0.2	98.1	10.6
Elsandal SW-1	2195	Black extract	563	30.3	15.2	53.0	1.5	45.5	2.0
Neem K-1	1682	Waxy black oil		58.6	12.9	18.9	9.6	71.5	4.5
Neem K-1	2550	Black extract	257	33.1	10.5	52.7	3.6	43.7	3.2

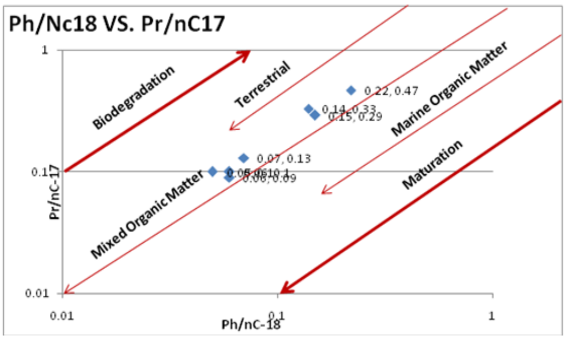


Fig. 10. Cross plot of Isoprenoid/normal alkane ratios: oils & source rocks.

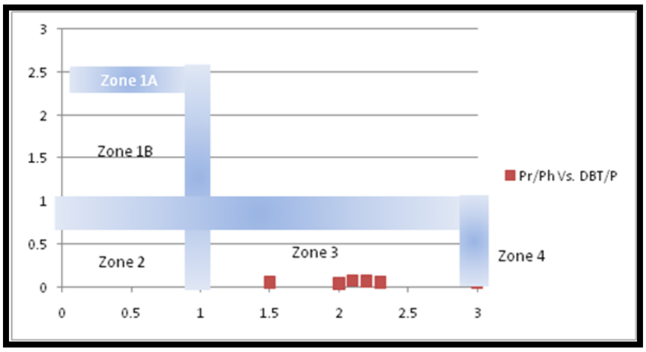


Fig. 11. Cross plot of aromatic and isoprenoid source parameters (DBT/P against Pr/Ph) ratios: oils and source rocks.

Table 5. Peak of Heat flow during the three rifting phases in wells in the study area.

Well Name	**1st rift HF mW/m^2**	**2nd rift HF mW/m^2**	**3rd rift HF mW/m^2**
Azraq k-1	44.6	43.4	82.2
Azraq C-1	43.1	43.5	82.02
Azraq N-1	44.6	43.7	85.9
Neem k-1	40.7	38.8	53.5
Neem E-1	41.9	37.9	70.7
Neem S-3	43.6	38.16	64.3

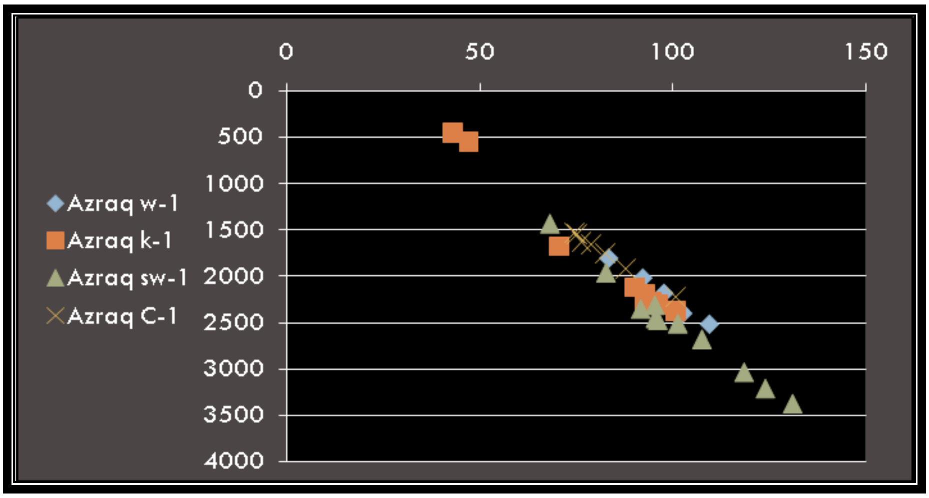


Fig. 12. Present-day Temperature from DST data of some Azraq wells.

Formation Micro Imager Data

The natural fractures from FMI data and the good percentage of quartz are good data for better evaluation of Shale gas in Abu Gabra formation (Figs. 13, 14 & 15). The composite logs (Figs. 16 & 17) show the whole gas component within the shale which indicate generation of hydrocarbon even in this shallow depth of Abu Gabra Formation, this contradict with the VRo reading which relatively low (immature).

DISCUSSIONS

Abu Gabra formation is the only effective source rock and acts as source-reservior rock; characterized as a good source rock, average of total organic matter 3.0wt%, 2.0wt% with high hydrogen index gives indication of kerogen typeI as the main kerogen type with few percentage of type III. To predict the thermal maturity using the pyrolysis results Tmax looks unsuitable for type I kerogen since the readings remain constant, and again this mixture give different chemical response then different Tmax readings (Tissot et al., 1987: In Whelan and Thompson-Rizer, 1993). The vitrinite reflectance show more than three populations and this lead to uncertinity of statistical clibrations (Hart, 1986). The rich source rock cause suppression of vitrinite reflectance, the cross check with the three labrotaries again show the difficulties to establish appropriate measurement for thermal maturity. The phenanthrene looks more suitable and gives reltively high readings and thermal maturity indication. A good percentage of quartz (Brittleness) and presents of natural fractures in both sands and shales (laboratory work needed to measure fracability); gas readings to C5 lead to conclude on the feasibility of shale gasin the area of study.

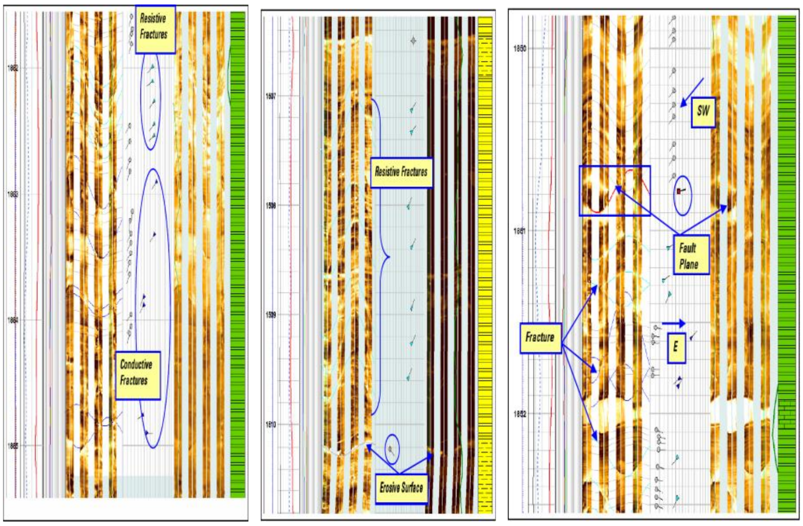


Fig.13. Conductive and Resistive fractures in sand and shale in Abu Gabra formation in Azraq sw-1 well.

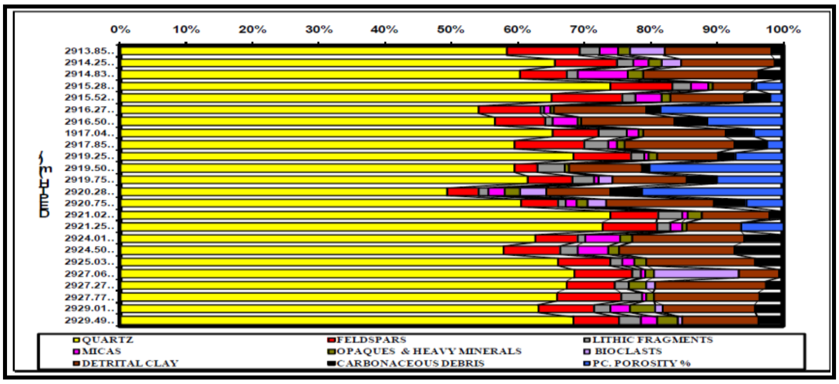


Fig 14. Vertical distribution of major detrital components and porosity of core1, well Neem-3

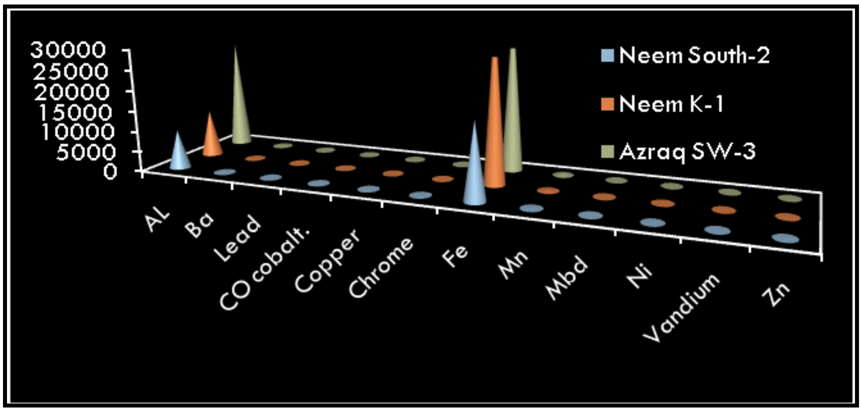


Fig. 15. Metals in core samples from Neem South-2, Neem K-1, Azraq SW-3 wells

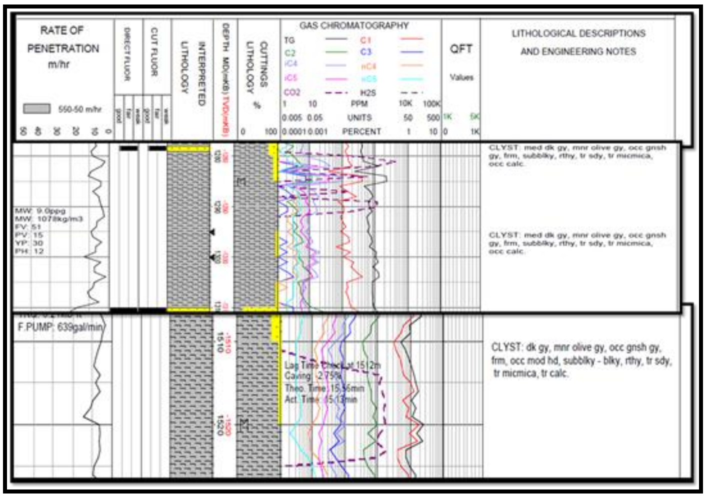


Fig. 16. Snapshot of Composite Log Data of Azraq C-3 well

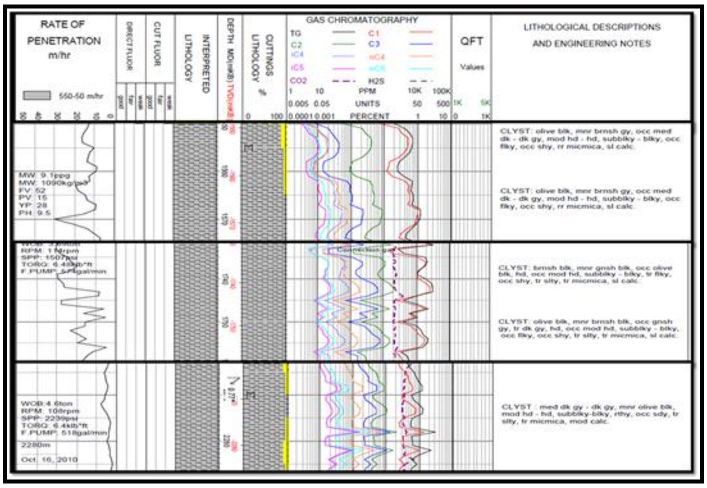


Fig. 17. Snapshot of Composite Log Data of Azraq N-2 well

CONCLUSIONS

Abu Gbara is a typical infraformational and of mixed lithofacies of conventional and unconventional hydrocarbons system. A good richness with high hydrogen index (more hydrocarbons). One of the most important difficulties is to establish thermal maturity. The changes of lithofacies vertically and laterally within short distance will lead to complicate prediction of sweetspots and horizontal drilling. This will remain the main challenges to develope shale gas in lacustrine basins.

Recommendtions

Feasibility is there, but more work needed to be done to estimate and reconice the economic viability of shale gas in deepest intervals and whether the technology can make new success in producing gas from lacustirne rifting basins.

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