Sedimentology and petrophysics of upper Devonian F3 sandstone Wafa filed(NC-169) Ghadames basin-south west Libya

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Abstract

Wafa Field is located along the Libyan-Algerian boarder in the South-Western part of the Ghadames Basin. F3 Sandstone Frasnian age is the main producing reservoir in the study area. F3 of the Awaynat Wanin Formation of Upper Devonian was depositional units are considered as a regressive sequence responding to drop in sea level. The

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F3 is interpreted as localized shallow marine sandstone beds that pinch-out towards the north south direction with up structure towards the east and southeast of Wafa area and pass into equivalent shaly facies of F4 shale .From available data , logs and Core data, the Lithofacies descriped as sandstone body coarsening upward where, the grain size profile possibly produced by seaward progradation indicating a Barrier Island of sandstone that was possibly emerged in the manner of a barrier island which, was interpreted as discontinuous large sandstone body that thins or absent towards the southwest of the study area, the gross thickness of F3 sandstone is around 150 ft. where the upper 100 ft is a very fine to medium grained sandstone. is considered to have the best reservoir quality, where the porosity reached up to 18% and permeability up to several hundred mD. Generally across the reservoir permeability deteriorates with depth possibly passes vertically downward to lagoonal siltstones and shaly beds lacking reservoir properties. From our Petrophysical evaluation, the main reservoir estimated the average volume shale is 2% in Northern part and increases towards the southern part of the study area. The average porosity is 10.5%. The average water saturation is 2.8%. Our interpretations using cross plot between Density and Neutron indicate that the lithology mainly of sandstone with minor shale. This observation probably efected the Gas/Water contact of the F3 reservoir which were not defined.

1- Introduction

Wafa Field covers an area of about 1000 km2 and located Southwest of Ghadames Basin adjacent to the Libyan-Algerian border, about 100 Km South of the Ghadames city (Figure1). Generally Wafa Field is a stratigraphic trap pinches out dipping towards the northwest as part of possible monocline. F3 Sandstone name was derived from the Algerian nomenclature which is a facies of F4 shale of the Awaynat Wanin Formation of Upper Devonian Figure (2). reservoir of southern Wafa Field (porosity, permeability, and volume of shale) of the study area and estimation of reserves within the entire Wafa field.

The study area geographically is located in the Southwest of Ghadames Basin between UTM (Xmin: 586000/Xmax: 590500) (Ymin: 3166000/Ymax: 3170500). Wafa Field is divided North pool and South pool. The study area is located within the South pool of Wafa Field. The area is situated approximately 540Km South-West of Tripoli and around 100 Km South of the city of Ghadames where the basin took its name after as Ghadames Basin.

The objective of this study is to understand the geology and the environment of deposition of Wafa Gas/Oil Field and regional lithology, structural, and reservoir characterization of Ghadames basin extension into the study area. The configuration of the general stratigraphy of the study area is related to the petroleum system within the Ghadames basin. One of the main objectives of this study is to investigate the petrophysical characteristics of the F3 Sandstone

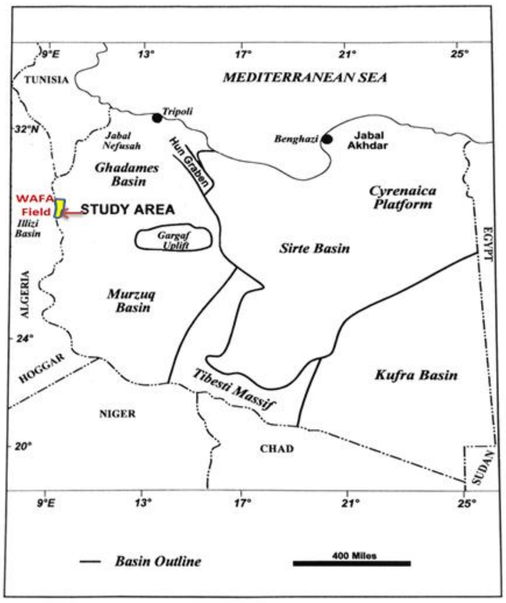

Figure 1. Location of Wafa Field NC169 Ghadames Basin.

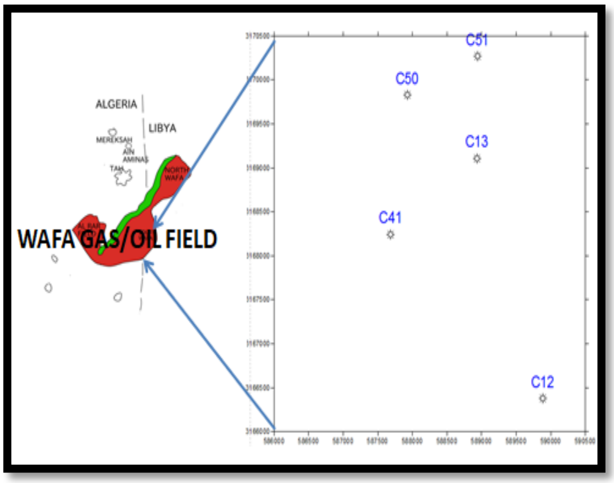

Figure 2. Location of study area.

2- Structure Setting of Ghadames Sedimentary Basin

Ghadames Basin contains up 20,000ft of Paleozoic and Mesozoic sediments. The Paleozoic section have been separated from the Mesozoic deposits by a major regional unconformity of the Hercynian (Permian-Carboniferous) age. The early Paleozoic history of the basin is controlled by the northwest-southeast Pan-African tectonic trend, although the evidence of this has come to light due to the thickness of the overlying sediments. The Jifarah basin began to subsidence during the early Mesozoic, and major subsidence occurred in the Miocene. The Ghadames Basin is beneath the western margin of the Sirt Basin. The Pan-African basement trends into Tripoli-Tibisti Arch barely noticeable and much less significant than in the Murzuq Basin. Structurally, Ghadames Basin is characterized by fault bounded structural highs surrounding a central depress. The main tectonic elements bounding the basin are of Paleozoic to Mesozoic age. The Nafusah uplift (Talemzane Arch) is to the north, and Gargaf high flank the basin from the Southern area and the Hugger shield to the southwest, and Hon Graben marks the eastern limits, and Amguid-El Biod high to the west, the basin has an asymmetric shape with gentle southern flank, has a less complex Tectonic history. Pan-African lineaments that widely affect the basement have played a major role throughout the basin’s history. Several structural elements had been active since Cambro-Ordovician time, of these structures the Tihemboka area, and southern part of Amguid El-Biod underwent strong uplift phases during different stages through time. Ghadames basin was under the influence of the Hercynian Orogeny. The existed uplifts remained active during the Hercynian Orogeny. Nafusah height dome had gone through erosion of several hundred meters of sediments. The Alpine Orogeny marked the last major geodynamic event to affect Ghadames basin. It had a great impact on the details of the final structural architecture of the basin and led to the change in Tectonic conditions, from passive to an active margin over the entire North African region (from different literature sources).

2-1 Structure Geology of study area

The Wafa field lies on the southwest area of the Ghadames Basin. The structural configuration in the NC 169 area on the Devonian levels shows a mild monocline dipping to the WNW. The Devonian is strata generally on lapping on the Caledonian (Pafalzian Paleohigh) F. Belhaj 1996. Faulting in Wafa area is rare displaying a dominant NS trend and may be locally found reverse or steeply dipping and generally dying out faults within the thick Carboniferous section above the Devonian or in the Mesozoic cover. Wafa Field is a stratigraphic trap mainly producing from F3-sandstone member of the Aouinet Ouenine Formation of Middle Devonian age. Structural contour map at top of F3 sandstone member of the Aouinet Ouenine Formation is shown in Figure (3) with contour interval 10 ft. Generally the area of Wafa field dipping towards the southeast gradually and gently indicated by structure contour map of F3 sandstone reflecting probably the deposition of barrier Island environment as a stratigraphic tarp due to the nature of the stratigraphic deposition environment influence. The structural contour map of the F3 sandstone Figure (3 reflects clearly the nature of stratigraphic trap deposition pattern also shows that the area is not disturbed by any faults. The study area of south Wafa represents a paleohigh region relatively higher than the Wafa North. Only 5 wells data probably is not enough to have more precise and accurate interpretation of the structure map Figure (3). A good coverage in the study area of possibly 3D seismic if available is highly recommended to insure more accurate drillable locations in the southern area of Wafa Gas/Oil field.

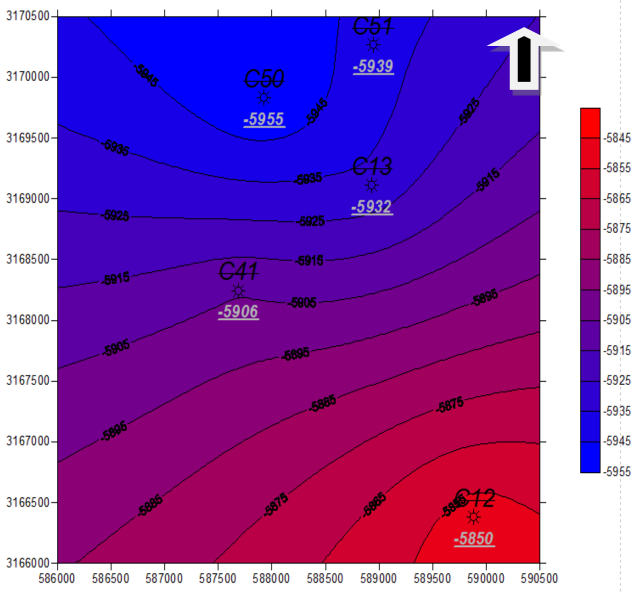

Figure. 3: Structural map on top of F3 sandstone reservoir (Aouinet-Ouenine Formation) Wafa field, NC169.

3- Stratigraphy of Ghadames Basin

Ghadames Basin contains up to 20,000 ft, of Paleozoic and Mesozoic sediments, the Paleozoic section being separated from the Mesozoic deposits by a major regional unconformity of Hercynian (Permian-Carboniferous) age. Erosion patterns and the topography that developed on the surface of this regional unconformity have had a direct influence on the petroleum systems within the basin. These factors controlled the preservation of Paleozoic hydrocarbons, communication between source and higher reservoirs, and long-distance migration within the Triassic reservoirs. The basin contains a variety of structural and stratigraphic traps in reservoirs of late Silurian and early Devonian age. Migration occurred along conduits within a sequence of deltaic sediments. In the south, where these seals become ineffective, oil has spread into middle and upper Devonian reservoirs. Faults provide additional migration pathways in some parts of the basin. During the late Cenozoic era, water entered the basin from the Al Gargaf arch, and allowed more permeable formation, particularly those of the lower Devonian sequence which have been partially flushed. The Paleozoic section is composed of a sequence of alternating sandstones and mudstones with occasional Interbedded carbonate beds. During Cambrian time, deposition of continental clastics, mainly fluvial sandstones occurred. This was followed by a marine transgression of the Ordovician, with subsequent deposition of transgressive marine mudstones. During the late Ordovician, marine conditions persisted in the north, whereas, in the further south a glacial periglacial environment was established. A major post-glacial transgressive episode in the early Silurian, resulted in the deposition of these sediments are truncated towards the SE of the basin against the Caledonian unconformity. The Caledonian unconformity separates the Silurian deposits from the overlying Devonian succession. Continental sandstones and mudstones of the early Devonian Tadrart Formation are overlain by shallow marine sandstones and mudstones (Ouan kasa Formation). Continued marine transgression resulted in the deposition of argillaceous marine sediments of the Aouinet-Ouenine group. Thick continuous marine mudstones (Tanezzuft Formation) that display marine mudstones This formation would display remarkable lateral extent across the Saharan Platform. The lower 20-100m comprises the most organically richest part of the section, which represents the richest source of petroleum source rock(Hot shale). The overlying Late Silurian marine sandstones and mudstones (Akakus formation) were deposited during the subsequent regression of the Silurian sea. (Mellitah Oil and Gas Co,2016). Lower Cretaceous sediments are continental in origin and are confined to east-west-trending belt in Ghadames basin. It's unconformity overlie both Mesozoic and Paleozoic sections. Such unconformity has been termed the basal Cretaceous unconformity. Upper Cretaceous and Paleozoic rocks overlie the Austrian unconformity.

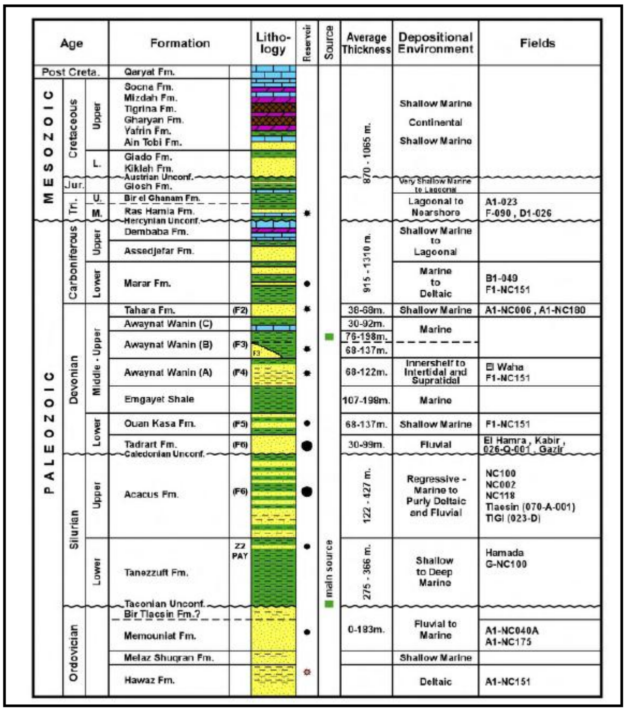

Figure 4. Generalized stratigraphic column of Ghadames Basin

3.1-Aouinet-Ouenine-"B" F3-Sandstone

SANDSTONES is quartzose, clear, colorless, light brown to light gray, hard to moderately hard, medium to fine grained, sub-rounded to sub-angular, poor to moderately sorted, siliceous cement, poor to fair intergranular porosity, with traces of oil shows. SHALE: gray to light gray, soft, to poorly indurate sub-flakey and non-calcareous silt. This formation has a thickness ranges from 134 to 184 ft. Locally F3 sandstone reservoir is mainly respected to the area between Alrar and

Wafa fields and the surrounding areas. The F3 sandstone can be found in some discovered field in the Algerian areas adjacent to the eastern border. Farther north adjacent to western border of Libya the F3 sandstone is reported to be found in old concession 26 of Waha Oil Company but it was water bearing as it is below the gas water contact. Regionally F3 sandstone and F4 sands are part of Awaynat Wanin A are Givetian to Frasnian of the middle to upper Devonian. The Awaynat Wanin B is Frasnian and the overlying Awaynat Wanin "C" is Famenian of Late Devonian works as a seal for the lower reservoirs. The F3 sandstone is the most important local reservoir sandstone in the area and vicinity of Alrar/Wafa fields. It may represent regressive sequence but it is not widely developed as a reservoir unit in Algerian Libya Ghadames basin The F3 sand is the main reservoir unit of the Al Wafa and Alrar fields area. The sand is not known south of Alrar and the west of Alrar Ouest, and the northern limits are unknown. The F4 sand is present in the area of Wfa/Alrar and farther south in Atshan saddle area. It forms productive reservoirs in several Algerian oil and gas fields near the Libyan border. These fields are Ouan Taredert, Zarzaitine, Tihalatine, Edjeleh, Tan Emeller, Tan Emeller Est, Nord Dome a Collenias, and Dome a Collenias. This provers that the Libyan side is under explored on the level of Aouinet Ouenine Formation is of middle to late Devonian age. This formation contains hydrocarbons in the F4 and F3 reservoirs in Ghadames Basin. The lithology for F3 sandstone Aouinet-Ouenine “B” is composed mainly of sandstone interfered with minor amount of Shale, there for a cross plot chart made to illustrate the relationship between bulk density and porosity which used to determine the lithology of the studied reservoir. The accumulation of most points was found around the sandstone through these relationships between GR versus depth showed the reservoir consist mainly of pure sandstone and there are also found a low amount of shale in the lower and the most upper parts as shown in Figures (7 & 8). These figures clearly define the boundaries of sandstone through each well of the F3 sandstone reservoir. The formation tops and bottoms are shown in Figure (9)

3.2-The environment of deposition of F3 Sandstone Reservoir:

F3 and F4 Sands which are both derived from the Algerian nomenclature. Bothe F3 & F4 sandstone units are facies within each other of the Awaynat Wanin Formation of Upper Devonian Figures (7 & 8). The F3 sandstone and F4 sandstone of Frasnian/Givatian age of the Upper Devonian. The F3 sandstone is the main reservoir sandstone in the area of Concession NC169 southwest Libya. F3 reservoir sandstone was developed as a regressive sequence due to a drop in sea level. The F3 reservoir sandstone is also the main reservoir sandstone unit in Algerian fields such as Alrar and other fields in the area in the vicinity area of Alrar Gas field. The F3 sand is the main reservoir unit in Wafa and Alrar fields and in the area of Concession NC169. The F3 sandstone is very thin or absents in the southern part of the study area. The F3 sandstone extends to the eastern area of Wafa field with defined line limit identified seismic and drilling. The F3 reservoir sandstone extends to the Northern area Wafa field outside of Concession NC 169 into the area of old Sirt Oil Company

The F3 sandstone is interpreted as localized shallow marine sand beds that pinch-out and pass into equivalent shaly facies (unpublished report Mellitah Oil and Gas Co, 2016). These sandstone body shape generally is elongated towards the North-South direction with up structure towards the east and southeast of Wafa areas(unpublished report

Mellitah Oil and Gas Co, 2016). This large body of these marine F3 sandstone reservoir bodies in the area of south-east Libya is of Stratigraphic trap in nature Figure (11) and extends north-south along most of the length of the concession NC169 also extends east into Alrar Gas/Oil field of Algeria.

The general description of Lithofacies from top to bottom

For the available Electric logs and Core for this study Figure (12) is as followes:

- Cross laminated massive sandstone of coarse-grained, cross-laminated to massive sandstone.
- Sandstone of fine-grained & well-cemented sandstone.
- Draped Sandstone of thin sandstone beds with mudstone drapes.
- Sandstone of alternating with horizons of laminated heavily burrowed sandstone.
- Units of bioturbated shale & sandstone.
- Fine Sandstone with carbonate shell fragments & calcareous cement.
- Thinly Lenticular beds of Sandstone & Shale.
- Thinly Laminated Shale.

The Wafa sandstone body can be used as a sedimentological model in nearby areas to explore for the F3 east of the Wafa field. The Wafa sandstone body generally has a coarsening upward grain size profile possibly produced by seaward progradation Figure (12 & 13). The environment of deposition of F3 sandstone main reservoir of South Wafa field current study suggested being Barrier Island

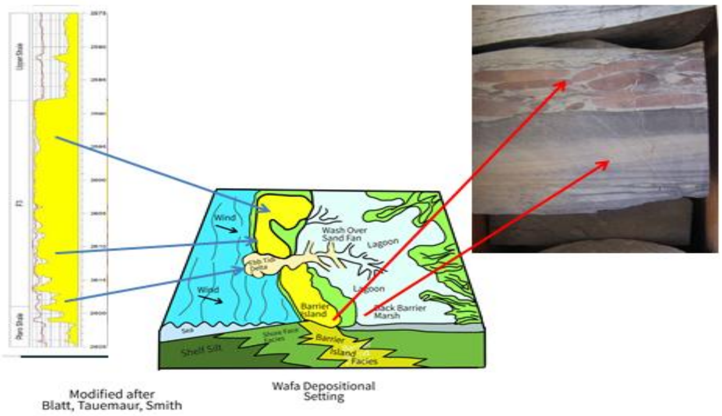

Figure 5 Wafa depositional model Barrier Island related

4-Petrophysical Study

A complete package of porosity and resistivity logs including neutron, density and induction Logs, have been recorded across the Wafa field F3 sandstone reservoirs study area. Determination of volume of shale implies using several types of the logs, such as Gamma ray logs, Neutron and Density cross plot to calculate and estimate the volume of shale in the F3 Sandstone of Aouinet-Ouenine formation which dependent on Gamma Ray log only. **Gamma Ray Log (GR):** It is common to find radioactive materials associated with clay minerals that constitute shale, it is also common practice to use the relative gamma ray deflection as a shale volume indicator. The simplest procedure is to rescale the gamma ray between its minimum and maximum values in one consistent geologic zone including both sandstone and shale. The scale is from **0%** to **100%** shale. The gamma ray index (**IGR**) is defined as a relationship between gamma ray minimum (**GRmin**) and maximum (**GRmax**). This formula can be written as follows:

IGR= (GRlog-GRclean)/(GRsh-GRclean)

Where:

- ***IGR***: is the Gamma ray index (**API**).
- ***GRlog*:** is the Gamma ray reading on the log.
- ***GRclean***: is the minimum reading on the log.
- ***GRsh*** :is the maximum reading on the log.

4.1 Porosity (Ø) Determination:

All porosity logs of neutron and density logs are used to determine the density porosity (**ØD**) and the total porosity (**ØN-D**)) are good indicators of the **F3** sandstone reservoir preliminary porosity determination. The density porosity (**ØD**) was used to determine porosity based on the type of reservoir rock from Equation (5.4), while the Total Porosity (**Øt** or **ØN-D)**

4.1.1-Density Porosity formula:

ØD = (pbma-pblog)/(pbmax-pfl)

Where:

- ***ρb*** =bulk Density, gm/cc (**log**).
- ***ρfl*** =Fluid Density, (**equal 1.1 gm/cc**).
- ***ρb ma*** =Matrix Density, **equal 2.65** gm/cc (for Sandstone)**.**
- ***ØD*** =Density Porosity**.**

4.1.2 Neutron Porosity:

The neutron porosity has been directly read from the neutron logs after correction for shale line. The average porosity of the F3 sandstone reservoir (Aouinet-Ouenine Formation) in the southern portion of Wafa field of studied wells as part of this project is around 10%.

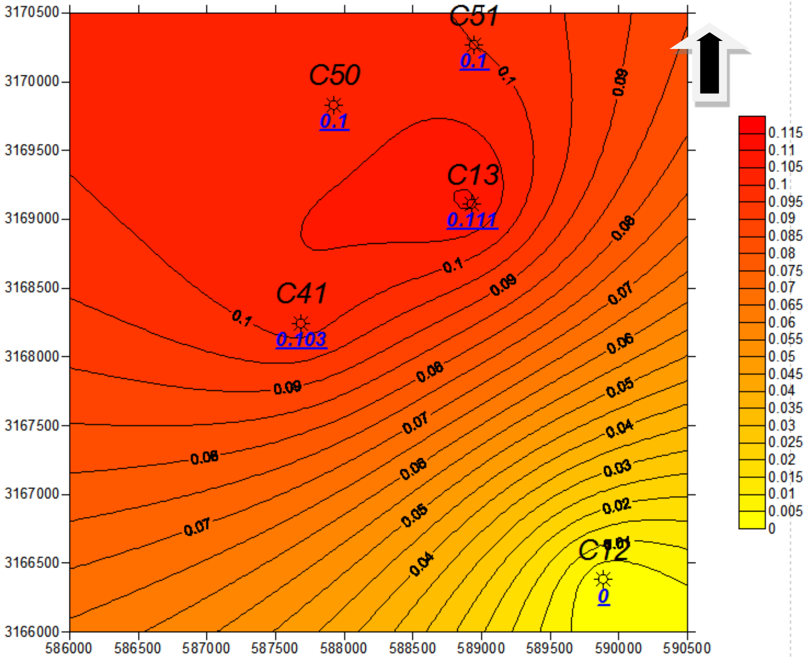

Figure 6 Average porosity map of F3 Sandstone

4.2 Determination of water Saturation (Sw):

The water saturation is calculated using Archie Equation.

$$Sw = [(a \times RW) / (Ø^m \times Rt)]$$

Where:

- **a** = Tortusity or Tortuosity factor = **(0.81).**
- **Ø** = Total porosity **($Ø_{N-D}$)%**
- **m** = Cementation factor = **(2).**

- **Rt** = Formation resistivity **(Ω.m).**
- **n** = Saturation exponent = **(2).**
- **Rw** =Water Resistivity = **(0.0205 Ω.m).**

The value of water saturation ranges from **6.3%** to **100%** increases toward the southern part of the study area where the lithology change from sandstone to shale and the F3 sandstone reservoir is absent. The lowest value was found in well C51 of 6.3.

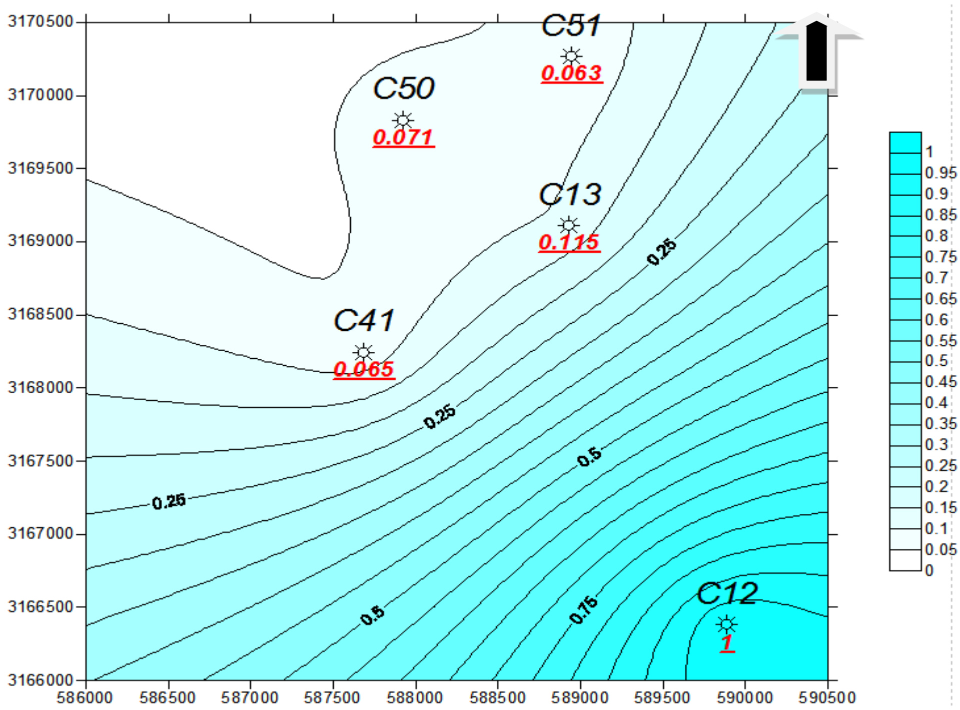

Figure 7 Average water saturation map of F3 sand

Based on the results of most wells gross thickness of wells (C13, C41, C50 and C51) is above the fluid contact and water still below the F3 sandstone reservoir. This case is an indication of no Gas/Water contact in the study. The lithology change in the South pool of Wafa field from sandstone to shale and the gross thickness equal the net pay thickness. The lithology was not clear to recognize in the southern area which recommended the need to reinterpret seismic or needs 3-D seismic survey for better distinction of the type of lithology. This information about the lithology is not available at the present time of the study.

4.3 Reservoir interpretations result:

The result of well log interpretation of the study area was confirmed by Agip company and there is no Water Contact in the study area and also the southern area of Wafa field where C12 well have no reservoir of F3 Sandstone.

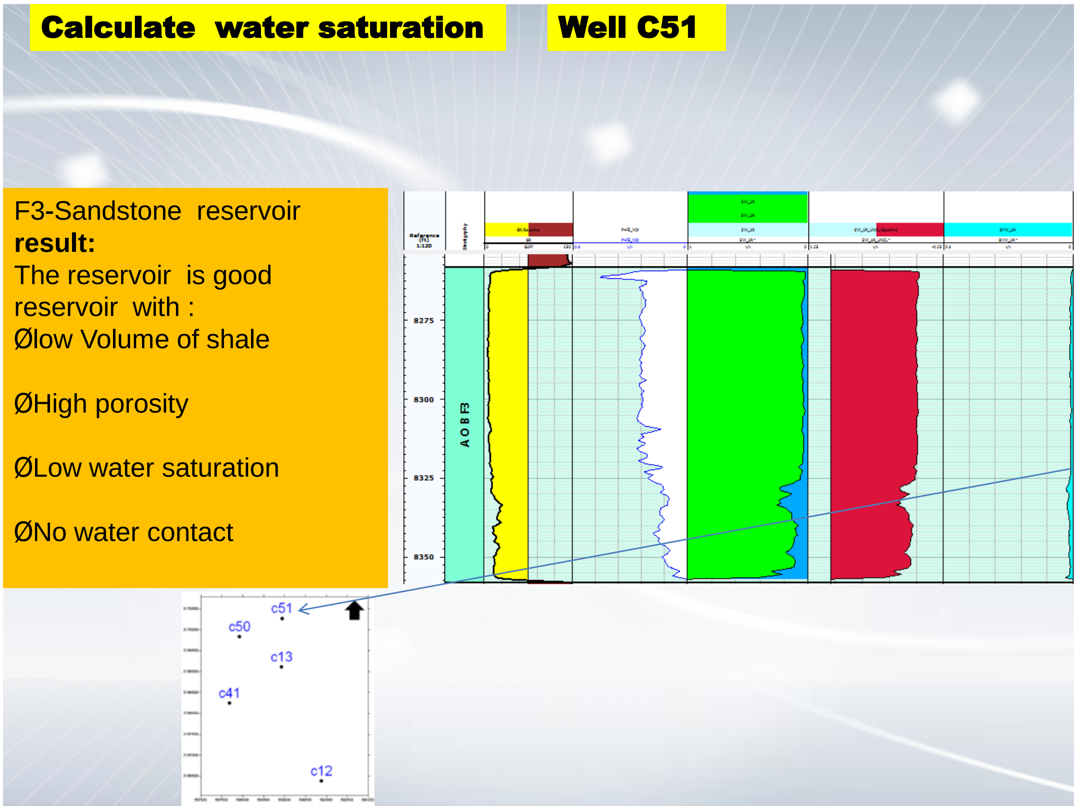

Figure 8 show the result water Saturation in well C51.

4.4-Net pay thickness:

The net pay thickens of the F3 reservoir represents intervals having porosity greater than or equal to the porosity cut-off of (**9** %), water saturation is less than cut-off of (**50**%), and volume of shale of less than of (**20**%). The net pay thickness of each well is A net pa map was constructed Figure (8) show the net pay distribution of the **F3** sandstone reservoir**.**

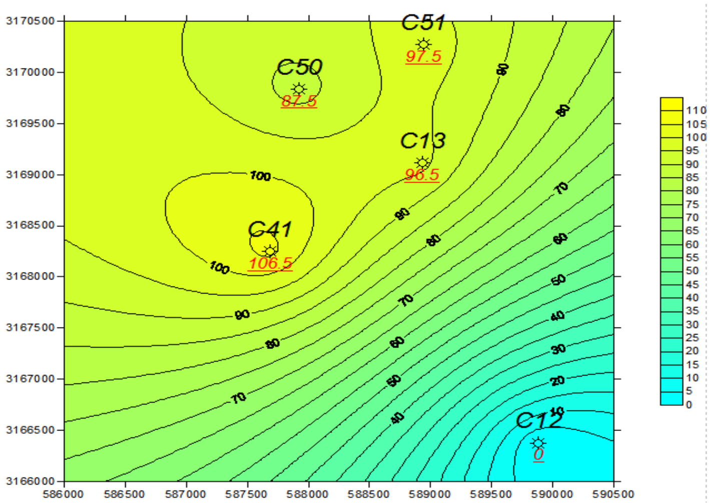

Figure 9 Net pay of F3 sandstone reservoir

4.5-Estimation of the Reserves The Initial Oil Reserves:

To calculate the hydrocarbon pore volume of Wafa field, we collected all values of **HPV** of the **F3** sandstone reservoir in each wells and entered them in the equation

$$HPV = h \times \text{Ø}_{avg} \times (1 - Sw).$$

Where:

- ***HPV***= Net hydrocarbon pore volume (ft).

- ***h*** = Net pay thickness (ft).
- *Ø* = Net pay porosity (%).
- ***Sw*** = Net pay water saturation (%).

HPV = 101* 0.105* (1- 0.286) = 7.878

OGIP= HPV× 7758× A

at Formation Volume Factor (F.V.F) of **1.4738** calculated using equation (**5.14)**

IGIP =OGIP/FVF)

Where:

- OGIP: is the Original Gas in Place.
- A: is the Area in acres (33.336 Acre).
- 7758: is the number of barrels per feet.
- IGIP: is the Inition Gas in place (STB).
- FVF: Is the Formation Volume Factor equal to (1.4738 RB/STB), obtained from the reservoir data summary of (Mellitah Oil & Gas Co, report, 2013).
-

OGIP= 7.878×7758×33.336 = 20374

OGIP=2037413 MMCF

IGIP =2037413÷1.47=138599 MMFC

The original Gas in place was estimated to be 2037413MMcf using equation (5.13). This is equation to initial Gas in place of 138599MMCF at formation volume factor (F.V.F) of (1.4738RB/STB) calculated using equation (5.14). The recovery factor (R) in WAFA field is (70%) in South Wafa field (Mellitah Oil & Gas Co, 2016). The Recoverable gas is 96041 MMCF in Wafa field using equation

Gas recoverable = IGIP * RF

Where:

- **IGIP:** Is initial Gas in place (**STB**).
- **RF:** Is recovery factor, considered as (**70%**).

Gas recoverable = 138599 * 0.7 = 97019 MM CF

the Recoverable reserve to the factor , the recoverable gas is **97019 MMCF** in Wafa field

5-Conclusions:

The main reservoir in the Wafa field is F3 sandstone (derived from the Algerian Stratigraphic Nomenclature). F3 Sandstone reservoir belongs to the Frasnian stage of middle Aouinet-Ouenine Formation of the Devonian age deposited as transgression sandstone on top of eroded surfaces. F3 Sandstone is described as quartzose, clear, transparent, off whit, light brown to grey, medium hard to friable, medium fine to coarse grained, sub-angular to sub-rounded, and moderately sorted with silica cement.

The study area is located in the Southern pool of Wafa Field includes C13, C50, C51, C41, and C12 wells. The logs of these wells were analyzed to determine the top of the reservoir, thickness, porosity and hydrocarbon saturation. From these logs, the data (thickness Gross and net pay) results were used to draw contour maps, which was done by using the surfer software and well correction of the producing reservoir. The available electric logs, four cores, and general information from wells C12, A30, A19 and A37 in the study area helped preliminary attempts determining the environment of deposition, which was concluded to be a Barrier Island instead of Submarine fan.

F3 Sandstone reservoir thickness decreases towards the southern portion of the study area reaching up to 4 feet (well C12). The lithology of F3 sandstone changes from sandstone to mix of shale and sandstone toward the southern area of Wafa Field probably related to change in sea level fluctuation during the deposition of F3 Sandstone.

Gas/Water contact of the F3 sandstone reservoir was recognized in the study area but not in the extreme southern portion of the study area due to poor reservoir quality and the decrease of thickness of F3 sandstone to less than five feet in well C12.

The total thickness of the F3 sandstone reservoir in Wafa Gas Field ranges from 4 feet in well C12 in southern area (study area) to 115 ft. in the northern area of the producing Wafa Gas Field. The net pay thickness in general in Wafa Field ranges from 0 to 115 ft. ???

The main conclusions from our study on Wafa Gas/Oil field are:

1- Wafa field is located as part of Ghadames Basin in the concession NC169a; close to the Libyan-Algerian border at the South-Western part of Ghadames Basin.
2- From our Petrophysical study Evaluation, the main reservoir F3 sandstone parameters estimated as follows:
   - The average volume of shale is **2%** in North area of Wafa field and 58% in South part of Wafa field where the shale increasing. The average F3 reservoir porosity is **10.5%**. The average F3 reservoir water saturation is **2.8% in the producing area.** The average F3 sandstone reservoir net pay thickness is **105 ft.**

3- The interpretations of using a cross plot chart between Bulk Density and Neutron Porosity provide insight to the lithology which consist mainly of Sandstone with minor amount of shale in the north part of study area of southern Wafa field, and the relationships indicate the F3 reservoir mainly clean sandstone with low amount of shale at the north part of the study area while in the southern where the lithology is change from sandstone to shaly sandstone and volume of sale is increasing up to 50%.

4- The main reservoir zone of the interpreted Aouinet-Ouenine formation shows good clean sand the volume of shale is low indicating the presence of good effective porosity. In the southern area where the non-reservoir is mainly shale zone, the volume of shale is higher than **50%** and porosity is low.

5- Upper and middle layers of F3 sandstone reservoir indicate fairly good potential reservoir, having a good porosity and low water saturation; however, the lower part of F3 sandstone contains more shale layers with low reservoir potential.

6- The hydrocarbon pore volume of Wafa field was **7.878**and the original gas in place was201687 **MMCF.**

7- The initial Gas in place was 137202 MMCF, and the recoverable Reservoir was 96041 **MMCF**.

6-Recommendations

1. We recommend to use 3 D seismic data for undefined the Lithology change and reservoir extend in area as well as reservoir quality also to draw some maps because its more accurate than well data only specially when we attend to make relationship between wells.

2. We recommend using more other wells located between wells C12 and C41 to calculate the average porosity of the reservoir, in our study we have just used only 5 wells and the data was not enough and we also recommend choses the best wells to covering the all of area.
3. We need to study the sedimentology, if it's possible to take some samples cutting sample or core sample, for the interpretation to compare with petrophysics results.

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