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Sedimentological Analysis and Reservoir Quality Assessment of the Hawaz Formation in the O2 Well NC-115 Concession Murzuq Basin, SW LIBYA

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Abstract - *Murzuq Basin is one of the major Libyan basins, and it occupies the southwestern part of the country and covering an area of about 350,000 km². It contains a sedimentary fill up to 4,000 m thick, containing mainly a marine Paleozoic unit and a continental Mesozoic unit. The Upper Ordovician Mamuniyat Formation can be considered as a primary reservoir target in the basin. In some places, where the Mamuniyat Formation is missing, the Middle Ordovician Hawaz Formation is considered the primary target. The Ordovician reservoirs are sourced and capped by Lower Silurian Tanezzuft Shale. The present study focuses on the sedimentological study of the Hawaz formation, which is based on the slabbed core, wireline log data, and thin sections from core samples for the Hawaz Formation within the exploration well O2 NC-115 in Murzuq Basin. The core analysis and petrographic study show the sandstones are fine to medium-grained, moderately to well-sorted, and sub-angular to sub-rounded grains. Facies analysis shows that the Hawaz Formation was deposited along a marine shoreline in shallow marine shoreface and distal shelf. The average porosity of the Hawaz Formation ranges between 7 - 17%. The reservoir quality of the Hawaz Formation varies from poor to good, represented by the middle part of the core section, to good quality, represented by the lower and the upper parts.*

Key Words: Hawaz, Sedimentology, Core, Tine section, Facies, Reservoir Quality.

1. INTRODUCTION

Murzuq Basin is one of the several intracratonic basins on the North African platform with a predominantly marine Palaeozoic clastic infill (Sola and Worsley, 2000). Murzuq Basin covers a massive area of about 350,000 km² in the **s**outh**w**estern part of Libya. The stratigraphic column of Murzuq Basin consists mainly of clastic deposits. To assess its reservoir characteristic and petroleum potential, the Upper Ordovician Mamuniyat sandstone represents the primary reservoir rock in the Basin. In contrast, the Hawaz Formation is represents the second reservoir target, and the main reservoirs sourced and capped by Lower Silurian Tanezzuft Shale. Potential younger traps, mainly in the Upper Silurian-Devonian, is considered in the basin (Aziz, 2000). The hydrocarbon exploration activities in Murzuq Basin have passed through three stages: (1) in the first exploration phase from 1956 to 1980, 17 wells were drilled, with oil discovery in B2-1 (Atshan) and hydrocarbon shows in several other wells; (2) the second phase from 1980 to 1992 with several companies had some discoveries in the basin, and the most attractive discovery was made by Rompetrol within the study area, where the results of drill on twelve structures with six new commercial discoveries; also LASMO and BOCO oil companies had Ambiguous discoveries; (3) the third phase is Development Exploration Repsol which was restricted to the central part of the original block, within an area about 5,000 km², which started in 1993, and has been characterized by the development of the three main fields discovered (A, B and H field) (Aziz, 2000).

The Hawaz formation, the focus of this paper, presents an exciting opportunity for hydrocarbon exploration. As a potential second reservoir rock in the petroleum system of Murzuq Basin, the Hawaz Formation Middle Ordovician age (Llanviru-Llandeilo) is a significant interest. It is conformable with the underlying Achebyat Formation and unconformable with the overlying Melez Shuqran Formation (Hallett, 2002). The Hawaz Formation is the second major unit of Burollet's Qarqaf Group named by Massa and Collomb (1960) after Jabal Hawaz from the type section on the western part of the Qarqaf Arch. Collomb divided the formation into three subdivisions, an upper 'Tigillites superieurs', a middle 'Gres intermediaires' and a lower 'Tigilliites inferieurs' (Massa and Collomb, 1960). The Hawaz Formation on the Qarqaf Arch comprises 120 m of alternating siltstone and thinly bedded, cross-bedded sandstones with abundant Tigillites. Vos 1981 interpreted this sequence as a coarsening-upwards delta front/delta top high-stand deposit. The type section of the Hawaz Formation on the Qarqaf Arch consists of fine to medium-grained sandstone, with subordinate siltstone and shale. This section has been described by Vos (1981), who suggested that the sediments were deposited in a fan delta complex which progreded across the Qarqaf Uplift towards the north. The formation is present in the Dur al Qussah Trough and around the Qarqaf Arch and in the subsurface of the Ghadamis Basin and at least into the northwestern part of the Sirt Basin (Hallett, 2002).

The uppermost Ordovician Mamuniyat Formation is usually considered to be the primary reservoir interval in NC-115. However, this formation is not preserved in the eastern part of the H-field, where the Hawaz Formation directly underlies the lowermost Silurian Tanezzuft shale

and constitutes the main reservoir. The cross-section through the H-field shows the Hawaz Formation in the east, juxtaposed along an escarpment with the western part of the field, where an infill of Mamuniyat deposits provides the reservoir. The Hawaz Formation has also given promising results in the F-structure, where the Mamuniyat Formation is very thin. However, only a limited number of wells in the area have been drilled deep enough to penetrate the Hawaz Formation (Aziz, 2000.). The concession NC-115 is located in the north-western part of the basin and covers an area of about 25000 sq km (Figure 1).

6 to 900 mD, respectively. The porosity and permeability in F1 and F2 generally range from 3.6 to 14.6% and 0.02 to 0.32 mD, respectively, with a maximum permeability of about 50 mD in F1 NC-115. Acritarch assemblages within the formation indicate a Lower to Middle Ordovician age. The depositional environment is transitional from fluvial to shallow marine, with increasing marine influence upwards. The Hawaz Formation varies in thickness in the NC-115 Concession area, ranging between 0 to 280 m (Aziz, 2000).

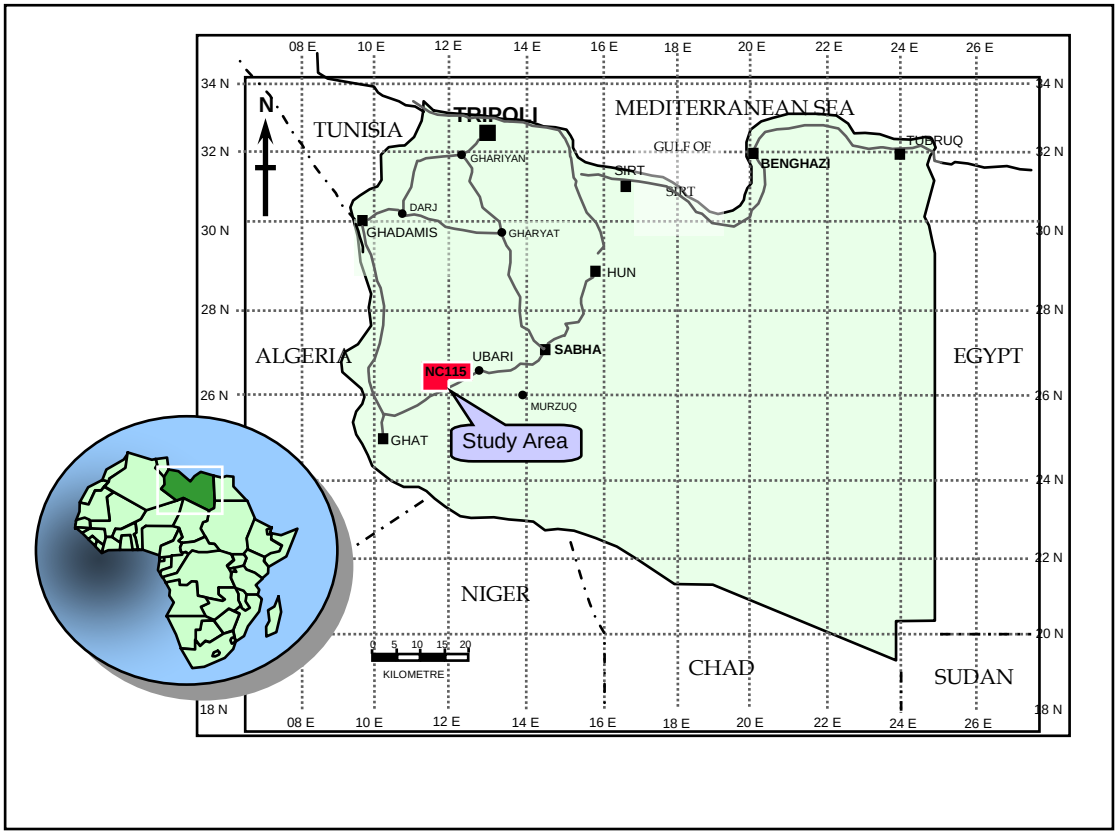

Figure 1. A general location map of Libya shows the study area in SW Libya from ROO.

Petrographically, the Hawaz Formation consists of very fine to coarse-grained quartz arenite, which is moderately to well-sorted. Detrital components are dominated by monocrystalline quartz, but some lithic grains also occur. The common diagenetic components are quartz overgrowth, pore-filling recrystallized detrital clay, and crystallized clay. The quality of the formation as a reservoir rock varies from poor to good. The upper parts of the formation within the H-Field, display poor reservoir quality with high shale content and sandstone porosity and permeability ranging from 6 to 12% and 0.2 to 2.5 mD, respectively. In contrast, the lower part of the formation exhibits better quality and forms the main reservoir zone, with average porosity and permeability from 10 to 16% and

2. OBIECTIVES

The main subject of this research is to perform a detailed petrography and sedimentological study of the Hawaz Formation on the slabbed core of the exploration well O2 NC-115, which was drilled and cored in 2004 by Repsol Oil Operations within NC-115 Concession. The main objectives of this study could be summarized as follows:

- To perform a detail sedimentological description of the slabbed core of the O2 NC-115 well of the Hawaz Formation.
- To study the vertical distribution and characteristic of the Hawaz Formation within the study well by provide additional evidence of the sedimentary facies.

- To examine the petrographic characteristics to identify the texture, mineral composition, diagenetic feature, and porosity to assess the reservoir quality and classify sandstone.

- To integrate petrographic, sedimentological, and wireline log data to derive depositional environment, reservoir quality distribution, and hydrocarbon potentiality.

3. METHODOLOGY

The main methodological steps in this study are:

- Collect the data.
- Quality control by reviewing the raw data and the available reports.
- Correct the depth core shift using the core and log Gamma ray.
- Describe the slabbed core of the O2 NC-115 well and select samples.
- Prepare the thin sections. These thin sections were obtained from six scattered intervals of core hand specimens from the O2 NC-115 core, and these thin sections have been prepared in the Petroleum Research Centre (PRC) in Libya.
- Describe the thin sections to predict the mineral composition, type of sandstone, and diagenesis history.
- Draw and plot the core description chart and combine it with the logs.
- Break down the facies.
- Integrate and interpret the data and predict the depositional model to have the distribution quality of the Hawaz reservoir.

3.1. Core Description

Repsol Oil Operations cored the core of the Hawaz Formation intervals from O2 NC-115 on the northwestern flank of the Murzuq basin, SW Libya. The core inventory of O2 NC-115 is shown in Table 1. The core has been slabbed 1/3 to 2/3 parts. In this study, we examined and investigated 172 feet of the Hawaz reservoir in O2 NC-115 exploration well to perform detailed sedimentological description to define the sedimentological features, the diagenesis and try to predict the depositional environment of this formation.

Table 1. Core intervals drilled by Repsol Oil Operations in O2 NC-115.

Core No.	Cored Interval (ft)	Cored Length (ft)	Recovery Feet (%)	Formation
1	5290'-5317'	27	27.00 (100 %)	Hawaz
2	5317'-5347	30	28.70 (95.7 %)	Hawaz
3	5347'-5375'	28	27.00 (96.4 %)	Hawaz
4	5375'-5405'	30	29.00 (96.7 %)	Hawaz
5	5405'-5465'	60	60.00 (100%)	Hawaz
Total			171.7 ft	

In this section, we covered the whole fife cores with investigation and recording all the features that might help in this sedimentological study. For example, core number one, which ranges from 5290 ft to 5317 ft, with a total length of 27 ft, and core recovered 27 feet (100%), three facies have been observed: Burrowed Sandstone Facies is represented by the cored interval from 5290 ft to 5298 ft (Figure 2.A), Heterolithic Facies is represented by the cored interval from 5298 ft to 5310 (Figure 2.B), and Massive Sandstone Facies is represented by the cored interval from 5310 ft to 5317 ft. The vertical open fracture occurred in depth 5304 ft with small fracture occurred in depth 5308 ft and rip occurred in depth 5312 ft. The stylolite features are present in different intervals of this core. The laminated feature occurred at depths 5301 ft and 5307 ft. Also, the cross-bedded feature occurred in depth of 5310ft (Figure 2.C). Core number one has lithological variation; on the top, it is characterized by sandstone extending from 5290 ft to 5298 ft, lay down by a foot of shale from 5299 ft to 5300 ft, another foot of sandstone from 5300 ft to 5301 ft, shale from 5301 ft to 5301.5 ft, and in the lower part of the core appear sandstone from 5301.5 ft to 5317 ft with small streaks of shale. The lithological description summary of core one is sandstone, fine to medium grain size, pyritic, light brown to brown, translucent, whitish grain, friable to medium-hard, mottled may be by organic matter, the shale gray to dark gray, blackish, fissile.

All other cores have been studied and described in details, as shown. The features that have been noticed were recorded as following: one massive sandstone facies in core two, which was represented in the cored interval from 5317 ft to 5344 ft as shown in (Figure 2.D). Core number three contains three facies, these are: Massive Sandstone Facies, Cross-bedded Sandstone Facies, and Laminated Facies. Rip occurred an a depth of 5312 ft with a small fracture occurred an depth 5340 ft and a partly open and partly closed fracture occurred at a depth of5351 ft (Figure 3.A). Laminated Facies is representing the cored interval from 5359 ft to 5374.5 ft

(Figure 3.B). Core number four has many false changes represented by four falsehoods, some of which are repeated, such as Laminated Facies, Massive Sandstone Facies, Heterolithic Facies, and Cross-bedded Sandstone Facies. Core number five ranges from 5405 ft to 5465 ft, with a total length of 60 ft, and recovered 60 feet (100%). It contains four facies with repetition; these facies are: Heterolithic Laminated Facies, Laminated shale Facies, Cross-bedded Sandstone Facies, and Burrowed Sandstone Facies. The lithological description of core fife is sandstone, fine to medium grain size, pyritic with rounded grain of pyrite in depth 5431 ft (Figure 3.C), light brown to brown, translucent, friable to medium-hard, mottled maybe by organic matter, the shale gray to dark gray, fissile, and shale deformation occurred in different depth 5412.2 ft, 5415 ft, 5437 ft, and 5452 ft (Figure 3.D).

Figure 2. A. Burrowed Sandstone Facies, B. Heterolithic Facies, C. Cross-bedded feature, and D. Massive Sandstone Facies.

Figure 3. A. Partly open fracture, B. Laminated Facies, C. Rounded grain of Pyrite, and D. Shale deformation.

3.2. Tine Section Preparation and Description

This section of this study is based on a total of six thin sections. They have been cut from six hand specimens (cores) from O2 NC-115 and have been selected by the authors. They were selected based on the facies distribution of the core and in the interest facies for hydrocarbon accumulation and production. The thin sections have been prepared in the PRC Laboratory by the authors to have a better petrographic understanding of the Hawaz reservoir in O2 NC-115 well. The thin sections have been impregnated with blue resin to facilitate the microscopic examination of texture and quantitative analysis of composition and porosity. Because the mineralogy of sandstone is primarily inherited from the source area, modified by sedimentary processes and diagenesis, a mineralogical examination provides one of the most valuable approaches to obtain information about the provenance, including tectonics, climate, the effects of transportation, including distance and direction, and the addition of mineral composition during sedimentation and diagenesis (Pettijohn et. al, 1987). The thin section inventory and the present facies is presented in Table 2. After that, detail description of the six thin sections using the microscope under normal and polarized states with thin section photos are presented showing unique different features. Table 3 illustrates the model composition of the thin sections of sandstone samples from the Hawaz Formation in O2 NC-115.

Table 2. Thin sections selected intervals and facies.

Thin section No	Depth	Facies	Core No
1	5291ft	Burrowed S.S	1
2	5314ft	Massiv S.S	1
3	5325ft	Massiv S.S	2
4	5366ft	Lamination shale	3
5	5431ft	Burrowed S.S	5
6	5442ft	Burrowed S.S	5

3.2.1. Thin Section No (1):

This sample can be represented as sandstone. It contains about 80 % of monocrystalline quartz grain, ranging from fine to medium in size, moderately to well sorted, containing subangular to subrounded grains, with straight to concave-convex grain contacts. Porosity is estimated as total porosity of 15 %.

3.2.2. Thin Section No (2):

This sample is sandstone, and it contains about 66 % of monocrystalline quartz grain. The quartz grains range from fine to medium in size, moderately to well sorted, containing subangular to subrounded grains, with straight to concave-convex grain contacts to point contact. The authigenic mineralogy predominantly caused by quartz overgrowths of about 5 % with 7 % clay cement. Porosity is estimated as a total of 15 %.

3.2.3. Thin Section No (3):

This sample can be considered as sandstone and contains about 74 % of monocrystalline quartz. The quartz grains range from fine to medium in size, moderately to well sorted, containing subangular to subrounded grains, with straight to concave-convex grain contacts. This sample comprises 5 % pyrite and includes 3 % mica (muscovite) and 74 % monocrystalline quartz. The authigenic mineralogy is about 15% clay cement. Porosity is estimated as total porosity of 3 %.

3.2.4. Thin Section No (4):

This sample is characterized by micaceous shaly sandstone. These quartz grains range from fine to very fine in size, moderately to well sorted, containing subangular to subrounded grains, with straight to concave-convex grain contacts. The detrital mineralogy comprises 30% monocrystalline quartz, 5 % pyrite, and 13 % mica (muscovite) with 52 % shale. Porosity could be less apparent and difficult to estimate.

3.2.5. Thin Section No (5):

This sample can be characterized by sandstone. It contains about 75% of monocrystalline quartz grain. These quartz grains range from fine to medium in size, moderately to well sorted, containing subangular to subrounded grains, with straight to concave-convex grain contacts. The detrital mineralogy of these grains comprises 5 % pyrite beside monocrystalline quartz. The authigenic mineralogy is predominantly by quartz overgrowths, representing about 3 % with 10 % clay cement. Porosity estimation is a total porosity of 7%.

3.2.6. Thin Section No (6):

This sandstone sample contains about 76% of monocrystalline quartz grain, which ranges from fine to medium in size, moderately to well sorted, containing subangular to subrounded grains, with straight to concave-convex grain contacts. The detrital mineralogy comprises 5% pyrite, and 1% mica beside monocrystalline quartz. The authigenic mineralogy is about 2% clay cement with quartz overgrowth about 1%. Porosity can be estimated as total porosity of 15%.

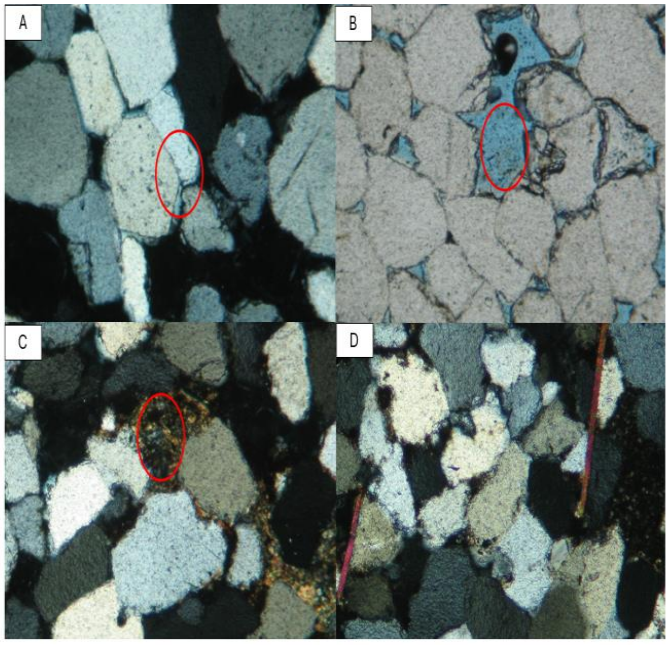

Figure 4. A. Straight quartz grains contact, B. Porosity, C. Clay mineral, and D. Showing the fine to medium grain size.

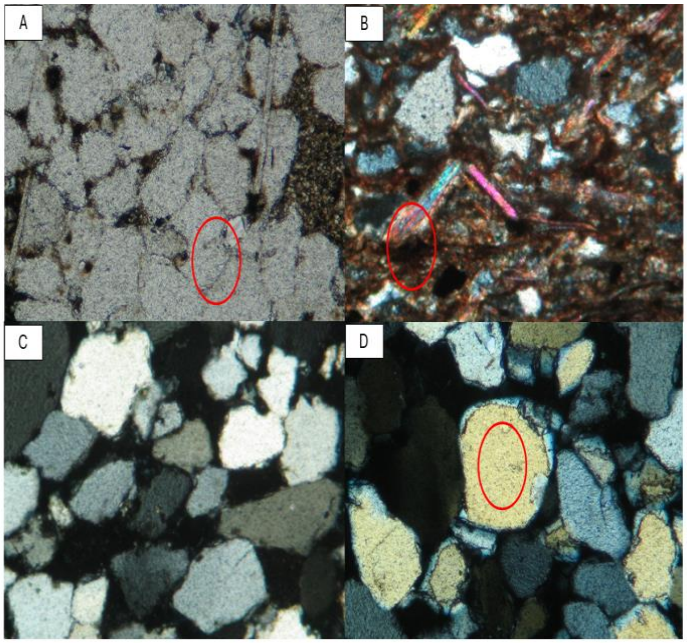

Figure 5. A. Concave-convex quartz grains contact, B. Mica (muscovite), C. Showing the subangular to subrounded grains, and D. Monocrystalline quartz grain.

TS No.	Depth ft	Quartz (%)	Feldspar (%)	Rock Fragment (%)	Heavy Mineral (%)	Mica (%)	Clay cement (%)	Pyrite (%)	Porosity (%)	Quartz Overgrowth (%)
1	5291	80	0	0	0	0	3	2	15	0
2	5314	66	0	0	0	0	7	7	15	5
3	5325	74	0	0	0	3	15	5	3	0
4	5366	30	0	52	0	13	0	5	0	0
5	5434	75	0	0	0	0	10	5	7	3
6	5442	76	0	0	0	1	2	5	15	1

Table 3. Model composition of thin section of sandstone samples from Hawaz Formation in O2 -NC115.

4. INTERPRETATION and RESULTS

4.1. Sedimentological Characteristics and Facies Analysis

Through the construction of its root and suffix, sedimentation is a noun of action or act of doing. Geologically, it means the act or process of depositing sediments. The word sedimentology encompasses not only the material itself and its deposition but also its genesis, transportation, diagenesis, geochemistry, physics, and statistics applicable to its existence (Alan, 1951). A fundamental tool in descripting and interpreting sedimentary rocks is the concept of sedimentary facies. The word facies is defined in slightly differing ways by different authors, but the consensus is that it refers to the sum of the characteristics of a sedimentary unit (Middleton, 1976). These characteristics include the dimensions, sedimentary structures, grain sizes and types, colour, and biogenic content of the sedimentary rocks. The term facies was introduced into geology by Gressly in 1838. It meant the entire aspect of a part of the earth's surface during a certain interval of geological time (Teichert, 1958). The word itself is derived from the Latin facia or facies, implying the external appearance or look of something. The modern usage was introduced by Jamieson in 1860, who used the term to imply a stratigraphic unit's total lithological and palaeontological aspects. The definition of the term facies can be extended. For example, when characteristic biological material is present, the facies is called biofacies. When fossils are not present, the term lithofacies is used. The facies concept does not just describe rocks and groups of sedimentary rocks seen in the field and forms the basis for interpretating strata. The lithofacies characteristics result from the physical and chemical processes that were active at the time of deposition of the sediments, and the biofacies and ichnofacies provide information about the palaeoecology during and after deposition. Knowing the physical, chemical, and ecological conditions makes reconstructing the environment during deposition possible. The process of facies analysis, the interpretation of strata in terms of depositional environments, and can be considered central to the main objective of sedimentology and stratigraphy, which is the reconstruction of the past (Anderton, 1976: Reading and Levell, 1996). Facies analysis has significantly been stimulated over the past few years by rapid conceptual advances in sequence stratigraphy. Facies analysis has been and remains essential for many authors to describe, correlate, and interpret the depositional environment.

4.2. Sedimentary Facies of the Hawaz Formation in O2-NC115

The analysis of sedimentary facies of the Hawaz Formation was based on lithology, grain size, sedimentary structures, and biogenic features seen in the core section and gamma-ray log. Many of the described facies are similar and sometimes differentiated by subtle differences in texture and biogenic features. The 172 feet cored section of the Hawaz reservoir in O2 NC-115 has been divided into three parts, where the following facies have been recognized and are described below based on detailed core description and analysis of both the core samples and the gamma-ray log.

4.2.1. Upper Part of the Hawaz Formation

It represents the interval from 5290 ft to 5353.5 ft, with a total length of 63.5 f. This section is characterized by only lower shoreface deposits, and it consists of three facies, which are: Burrowed Sandstone Facies, Heterolithic Facies, and Massive Sandstone Facies.

4.2.1.1. Burrowed Sandstone Facies

This facies ranges from 5290 ft to 5298 ft with a total interval length of 8 ft. This facies forms the upper part of the core section and consists of vertical burrowed sandstone in depth 5291 ft, 5292 ft, 5294 ft,5295 ft, 5296ft, 5297 ft, and 5298 ft, rich burrowed at depths 5296.5 ft to 5297.5 ft, mottled maybe by organic matter. The lithology can by described as sandstone, fine to medium grain size, pyritic, light brown to brown, translucent, whitish grain, friable to medium-hard. The average porosity in this section is about 13.5%, while the average permeability is about 286.6 mD.

4.2.1.2. Heterolithic Facies

This facies extends from 5298 ft to 5310 ft with a total interval length of 12ft. Stylolite feature appears in depth 5299 ft to 5300 ft, 5301.5 ft, 5302.7 ft, and 5308ft to 5310 ft. Vertical open fracture occurred in depth 5304 ft with a small fracture in depth 5308 ft. Laminated occurred in depth 5301 ft and 5307 ft, and cross-bedded occurred in depth 5310 ft. The lithology of this facies includes a shale within the interval from 5299 ft to 5300 ft, sandstone from 5300 ft to 5301 ft, shale from 5301 ft to 5301.5 ft, and sandstone from 5301.5 ft to 5310 ft with a small streaks of shale. Lithological description is sandstone, fine to medium grain size, pyretic, light brown to brown, translucent, whitish grain, friable to medium-hard, mottled maybe by organic matter, the shale is gray to dark gray, blackish, fissile. The average porosity in this facies is about 9.2%, while the average permeability in this facies is about166.4 mD.

4.2.1.3. Massive Sandstone Facies

This facies ranges from 5310 ft to 5353.5 ft with a total interval length of 43.5 ft. Stylolite feature presents in depth 5310 ft to 5313.5 ft, 5315ft to 5316.5 ft, 5320 ft to 5326 ft, 5328.5 ft and 5350.7 ft. Lithological description is sandstone, fine to medium grain size, pyritic, light brown to brown, yellowish, translucent, transparent to whitish grain, friable to medium-hard, mottled maybe by organic matter, cross-bedded occurred in depth 5328ft. The average porosity in this facies is about 14.8%, while the average permeability in this facies is about 314.1 mD.

4.2.2. Middle Part of the Hawaz Formation:

This part represents the core interval from 5353.5 ft to 5422.6 ft with a total length of 69.1ft. This section is characterized by two facies represented by upper shore face and distal shelf deposits. The upper shore face facies association occurs from 5353.5 ft to 5404 ft, with a total length of 50.5 ft including seven facies with repetition of some of these facies. The distal shelf deposits represent the interval from 5404 ft to 5422.6 ft with a total length of 18.5 ft that consists of two facies.

4.2.2.1. Cross-bedded Sandstone Facies

This facies ranges from 5353.5 ft to 5359 ft with interval length 5.5 ft. Stylolite feature appears in depth 5354.5 ft, 5355.1 ft 5357.1 ft, and 5358 ft, open fracture occurred in depth 5356 ft, and 5358.2 ft, low angle cross-bedded occurred in different depth in this facies. The lithological description of this facies is sandstone, fine grain, light brown to gray, translucent, transparent, friable to medium-hard, and mottled maybe by organic matter. The average porosity in this facies is about 13%, while the average permeability is about 281.1 mD.

4.2.2.2. Laminated Facies

This facies extends from 5359 ft to 5378.5 ft with a total interval length of 19.5 ft. Laminated structure can be seen in different depths in this facies. The Facies can be divided into three subfacies which are: Laminated Shale, Laminated Sandstone, and Laminated Shale/Sandstone subfacies. The average porosity in this facies is about 8.9%, while the average permeability is about 2.9 mD.

4.2.2.3. Massive Sandstone Facies

This facies extends from 5378.5 ft to 5384 ft with a total interval length of 5.5 ft. The lithological description is sandstone, fine to medium grain size, brown to yellowish, translucent, friable to medium-hard. An open fracture can be seen in depth 5379 ft, and 5382 ft, with closed fractures occurred in depth 5380 ft. The average porosity in this facies is about 17%, while the average permeability is about 566.1 mD.

4.2.2.4. Heterolithic Facies

This facies extends from 5384 ft to 5387 ft, with a total interval length of 3ft. The lithology description is sandstone with a strake of shale. Closed fractures appear in depth at 5384.5 ft and 5385.5 ft. The average porosity in this facies is about 11.4%, while the average permeability is about 1 mD.

4.2.2.5. Cross-bedded Sandstone Facies

This facies ranges from 5387 ft to 5390 ft with interval length of 3 ft. The lithological description is sandstone, fine to medium grain size, light gray to brown, translucent, and friable to medium-hard. Open fractures occurred in depth 5388 ft and 5388.8 ft. Cross-bedded appears in depth 5388.5 ft and 5389.3 ft. The average

porosity in this facies is about 19%, while the average permeability is about 920 mD.

4.2.2.6. Massive Sandstone Facies

This facies extends from 5390 ft to 5401 ft with an interval length of 11 ft. The lithological description is sandstone, fine to medium grain size, light gray to brown, translucent, friable to medium-hard with shale streaks in depth 5397 ft. Stylolite structures appear in different depths in the facies. Mottled maybe by organic matter. The average porosity in this facies is about 14.4%, while the average permeability is about 407.9 mD.

4.2.2.7. Cross-bedded Sandstone Facies

This facies extends from 5401 ft to 5404 ft interval with length of 3 ft. The lithological description is sandstone. fine to medium grain size, medium-hard, and light brown t yellowish. Stylolite structure occurred in depth 5401.2 f and 5403 ft. Cross-bedded occurres in depth 5401.3 f 5402.2 ft, and 5403.2 ft. The average porosity in this facies i about 14.4%, while the average permeability is about 297. mD.

4.2.2.8. Laminated Facies

This facies extends from 5404 ft to 5420 ft with tota interval length of 16 ft. The lithological description i sandstone with streaks of shale. The average porosity in thi facies is about 7.5%, while the average permeability is abou 15.9 mD.

4.2.2.9. Cross-bedded Sandstone Facies

This facies extends from 5420 ft to 5422.6 ft, with total length of 2.6 ft. The lithology description is sandstone fine to medium grain size, medium-hard, and light brown t yellowish. Stylolite structure can be seen in depth at 5420. ft, 5420.8 ft, 5421.9 ft, and 5422.5 ft. Cross-bedded appear in depth 5420 ft and 5421.5 ft. The average porosity in thi facies is about11.4%, while the average permeability i about 348.8 mD.

4.2.3. Lower Part of the Hawaz Formation

This part represents the interval from 5422.6 ft to 5465 ft with a total length of 42.4 ft. It comprises of only one lower shoreface facies association, with only one Burrowed Sandstone Facies.

4.2.3.1. Burrowed Sandstone Facies

This facies ranges from 5422.6 ft to 5465 ft with a total length of 42.4 ft. This facies forms the lower part of the core section and comprises of vertical burrowed sandstone in depth 5422.6ft to 465ft with horizontal burrows in depth 5449.5 ft, and some of large burrows extend to one feet length in depth 5442 ft, mottled maybe by organic matter. The lithology of this facies is sandstone extends from 5422.6 ft to 5465 ft with small streaks of shale in depths of 5436 ft, 5437 ft, 5452 ft, 5459 ft, and large bed of shale from 5463 ft to 5464 ft. Lithological description is sandstone, fine to medium grain size, pyritic with rounded grain of pyrite in depth 5431 ft, light brown to brown, translucent, whitish grain, friable to medium-hard, mottled maybe by organic matter, shale deformation occurred in depth 5437 ft and 5452 ft. The average porosity in this facies is about 15.3%, while the average permeability is about 130.7 mD. However, in the upper part of this facies, the average permeability is about 212.4 mD, and the average permeability in the lower part of this facies is decreasing downward to reach 3.1 Md.

4.3. Depositional Environment

In this section, we integrated all the data and results obtained from this study to have a clear understanding of the depositional environment and formation distribution. In O2-NC115, the Hawaz Formation is about 175 ft thick of fine to medium sandstones with streaks of shale. The grain-size analysis and biological and primary sedimentary structures in the core section of the Hawaz Formation from O2 – NC115 that has been described and interpreted suggest that it was deposited in a shallow marine environment. The repetition of similar facies suggests a recurring pattern of similar depositional processes and environments. This is attributed to a dynamic interaction between the lower shoreface and the upper shoreface, as well as the inner and outer shelf. The distal shelf overlies the lower shoreface that involves burrowed sandstone facies in the lower part of succession. The distal shelf facies may have occurred due to rising sea level. Overlain the distal shelf occurs the upper shoreface; this reflects either non-deposition of lower shoreface sediments, possibly due to glacial erosion or erosion during the post-glacial marine regression in this area, leading to deposition of the Tannezuft shale source rocks. The lower shoreface is deposited over the upper shoreface. The source of sediments can originate from the Ghat-Tikiumit Arch located southwest of the study area. To conclude, the Hawaz Formation was deposited in a shallow marine environment dominated by tidal currents on a shelf subjected to periodic storm-generated wave activity.

4.4. Petrography Analysis and Sandstone Classification

The petrographic analysis provides a means of assessing the sandstone's composition and relating to its provenance, tectonic setting, diagenetic evaluation, and economic potential (Pettijohn et. al, 1987). Based on core description and thin sections examination, it can be documented that the Hawaz Formation consists mostly of alternating fine to medium-grained, well-sorted to moderately well-sorted sandstone, subangular to subrounded grains. The detrital mineral components are monocrystalline quartz with subordinate polycrystalline quartz, rock fragments, mica, and pyrite. There are several classification schemes available, and most use a triangular

diagram with members of quartz (Q), feldspar (F) and rock fragments (L). The triangle is divided into various fields, and appropriate modal analysis is given a particular name of rocks. In this study, a widely used classification of sandstone presented by Pettijhn et al. in 1987 based on the origin of the sandstone was used to classify the Hawaz sandstone in O2 NC-115. The sandstone of the Hawaz Formation can be classified as mainly arenites, quartz-rich with poor feldspar and rock fragments.

4.5. Reservoir Quality and Hydrocarbon Potential of the Hawaz Formation

Petrographic studies indicate that the Middle Ordovician Hawaz Formation sandstones cored in the O2 NC-115 well are mainly fine to medium-grained quartz arenites well-sorted to moderately sorted sandstone, subangular to subrounded grains, commonly fining upward. Based on microscope analysis, the detrital mineralogy is dominated by monocrystalline quartz grain, with minor amounts of polycrystalline quartz grains, mica, and pyrite. The porosity reduction is due to many factors, such as quartz overgrowth. It can also reduce the degree of compaction, preserving a well-connected pore system and good permeability. Some of the clay deposits will reduce permeability. The quality of the formation as a reservoir rock varies from poor to good. The upper part (from 5290 ft to 5360 ft) displays a suitable reservoir; the porosity and permeability range from 7 to 17% and 166 to 286 mD; respectively. The middle part (from 5390 ft to 5420 ft) has poor to good reservoir quality with shale content and sandstone, porosity ranging from 7 to 17% and permeability ranging from 1 to 15 mD in the lamination facies and heterolithic facies and range from 297 to 920 mD in the massive sandstone facies and cross-bedded sandstone facies. The lower part (from 5420 ft to 5465 ft) shows a good reservoir, and porosity and permeability are from 7 to 17% and 130 to 348 mD; respectively, but in the lower section is poor due to the low permeability. From the reservoir quality perspective, the cross-bedded sandstone facies, burrowed sandstone facies, and massive sandstone facies are the best reservoir quality, while the heterolithic facies are the worst reservoir quality.

5. CONCLUSIONS

The Hazwa Formation in O2 NC-115, Murzuq Basin has been studied comprehensively by core description, sedimentological and petrographic studies, and well log analysis to evaluate the reservoir quality and hydrocarbon potentiality. The findings from the core description demonstrated that the Hawaz Formation in this location encompasses some facies that are reservoir and non-reservoir facies. Sedimentary facies in O2 NC-115 contain the upper part (lower shoreface facies association), the middle part (upper shoreface facies association and distal shelf facies association), and the lower part (lower shoreface facies association). The Hawaz Formation consists predominantly of alternating fine to medium-grained, well-sorted to moderately well-sorted sandstone, subangular to subrounded grains. The detrital mineral components are monocrystalline quartz with subordinate polycrystalline quartz, rock fragments, mica, and pyrite. Petrographic data shows that the Hawaz sandstone can be classified mainly as a quartz arenite. Diagenetic cement is mainly in the form of quartz overgrowths, and local calcite, all of which have reduced the porosity. The average total porosity of the Hawaz Formation is 7% to 17%. The reservoir quality of the Hawaz Formation varies from poor to good, represented by the middle part of the core section, and good can be represented by the lower part and the upper part of the core section, but in the lower part is poor because of low permeability. Facies analysis shows that the Hawaz Formation was deposited along the marine shoreline in shallow marine shoreface and distal shelf, which represent a quite deposition environment. The source of sediments expected from the Ghat-Tikiumit Arch that is located SW of O well (study well). The results from all the methods agreed to confirm that the Hawaz sandstone possesses fair to good reservoir quality and hydrocarbon potential that was deposited in a shallow marine environment.

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