[PS]High Resolution Sedimentological Interpretation of the Lower Paleozoic Clastic Reservoirs in Ghadames Basin, Libya*

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Abstract

During the last decade, exploration activities in the Ghadames Basin have been intensified by the National Oil Corporation (NOC), national, and international companies. Arabian Gulf Oil Company (AGOCO) was the leader in most of the discovered fields in the basin by drilling numerous wildcat wells targeting siliciclastic Paleozoic reservoirs, mainly of Silurian age. The Silurian rock units are known to contribute both source rock (Tanezzuft) and hydrocarbon reservoir (Acacus) successions in the area. The Acacus Formation is subdivided informally into three main units known as lower, middle, and upper, with the lower unit containing the main reservoir potential. These units have been mapped using basic well log data, nevertheless their sedimentological criteria remained untapped due to operational issues such as cutting cores. It has been observed from the appraisal wells that there is a high uncertainty of the reservoir's lateral continuity even within a few kilometers distance. Therefore, there was a demand to understand the stratigraphic depositional architecture and its lateral continuity and distribution of the sandstone reservoir units in the area. By using basic well log data alone, it was a challenge for the geoscientists to identify the main lateral variations especially in cases where the core is not available. Accordingly, AGOCO has started a new acquisition plan to come up with high resolution sedimentological understanding of the main reservoir in the area.

The exploration team decided to acquire two main wireline tools, those are, borehole images (FMI) which gives a resolution down to 5 mm as well as element capture spectroscopy (ECS) which gives quantitative results of the elements for optimum geological interpretation in a detailed scale. The advantage is having more than 900 ft of core-like description data of the Lower Acacus units as well as a quantitative elements computation. This has in return resulted in a high resolution of sedimentological and stratigraphic interpretation throughout the Lower Acacus clastic reservoir in the Ghadames Basin. Imaging the wellbore and measuring the dip of the features have retained vast knowledge for AGOCO about the vertical succession of the main reservoir and understanding the reservoir geometries. In this poster, a case study from one of AGOCO wells has illustrated the value of the comprehensive wellbore integration and interpretation. As a result, and based on the detailed

interpretation, it was concluded that the Lower Acacus unit was deposited under the conditions of tidal flat/channels (fining up cycles) over the bottom parts, overlaid by tide-dominated deltas (coarsening up cycles). Once more, repetition of cycles has been clearly observed. The contact between the Lower and Middle Acacus Members looks like a gradational conformable contact.

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SILICICLASTIC RESERVOIRS OF THE MIDDLE EAST

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HIGH RESOLUTION SEDIMENTOLOGICAL INTERPRETATION OF THE LOWER PALEOZOIC CLASTIC RESERVOIRS IN GHADAMES BASIN, LIBYA

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Arabian Gulf Oil Company (AGOCO) Optimizes Exploration Decisions with Expert Fullbore Microimaging Data Interpretation. This Advanced Petrotechnical interpretation fills in knowledge gaps in openhole logging for more comprehensive reservoir characterization, Libya

Abstract

During the last decade, exploration activities in Ghadames basin have been intensified by the National Oil Corporation (NOC), national and international companies. Arabian Gulf Oil Company (**AGOCO**) was the leader in most of the discovered fields in the basin by drilling numerous wildcat wells targeting siliciclastic Paleozoic reservoirs, mainly of Silurian age. The Silurian rock units are known to contribute for both source rock (Tanezzuft) and hydrocarbon reservoir (Acacus) successions in the area. Acacus Formation is subdivided informally into three main units known as lower, middle and upper, with the lower unit containing the main reservoir potential. The Ordovician Memounait reservoir has shown complex vertical and lateral variations in the basin from carbonate deposits as the base to clastic at the top, as in the current case of study. These formations have been mapped using the basic well log data, nevertheless their sedimentological criteria remained untapped due to operational issues such as cutting cores. It has been observed from the appraisal wells that there is a high uncertainty of the reservoir lateral continuity even within a few kilometers distance. Therefore, there was a demand to understand the stratigraphic depositional architecture and its lateral continuity and distribution of the sandstone reservoirs in the area. By using the basic well log data alone, it was a challenge for the geoscientists to identify the main lateral variations especially in cases where the core is not available. Accordingly, AGOCO has started a new acquisition plan to come up with high resolution sedimentological understanding of the main reservoir in the area. The exploration team decided to acquire both two main wireline tools; those are; borehole images (FMI) which gives a resolution down to 5 mm as well as element capture spectroscopy (ECS) which gives quantitative results of the elements for optimum geological interpretation in a detailed scale. The advantage is having more than 900 ft of core-like description data of the Acacus and Memounait Formations as well as a quantitative elements computation. This has in return resulted a high resolution of sedimentological and stratigraphic interpretation throughout the Lower Paleozoic clastic reservoir in Ghadames basin. Imaging the wellbore and measuring the dip of the features have retained vast knowledge for AGOCO about the vertical succession of the main reservoir and understanding the reservoir geometries. In this poster, a case study from one of AGOCO wells has illustrated the value of the comprehensive wellbore integration and interpretation.

CHALLENGE: Enhance exploration in high-uncertainty formations
Construct a reliable facies model of two Ghadames basin reservoirs with high vertical and lateral disconnect.

SOLUTION: Improve geological modeling with accurate data
Obtain and interpret high-resolution FMI* fullbore formation microimager measurements; use detailed data to build a geological modeling for further petrotechnical evaluation.

RESULTS: Better understand subsurface variations with expert analysis
Optimized decisions based on better understanding of clastic facies distribution, deepened knowledge of basinal geology, and reduced uncertainty of vertical and lateral facies continuity.

Introduction

The study area, including the case history exploratory well, are located in Ghadames Basin (Figure 1). Ghadames Basin is one of the large intracratonic basins in North Africa, straddling the borders of Libya, Tunisia, and Algeria. The basin covers an area of 340,000 km2 and contains up to 6,000 m [20,000 ft] of Paleozoic and Mesozoic sediments. The most significant tectonic event affecting the basin, succeeding its formation in early Paleozoic time, was the late Paleozoic Hercynian/ Variscan orogeny. This has resulted in a regional unconformity separating the Paleozoic section from the Mesozoic deposits (Figure 2). Structurally, the Ghadames basin is characterized by fault-bounded structural highs surrounding a central depression. The main tectonic elements bounding the basin are the Dahar–Nafusah high (Talemzane arch) to the north, the Qarqaf uplift and the Hoggar shield to the south, the Amguid- El Biod high to the west, and the western flank of the younger Sirt Basin to the east. The record of petroleum exploration in Ghadames Basin proved that it has been an important hydrocarbon province since the 1950s. Recent technology development, interpretation techniques and data quality have led to many discoveries in the basin. Moreover, these factors have convinced geoscientists that there are much greater volumes of hydrocarbons than previously predicted and that undiscovered reserves may still be found. There are three major groups of fields in the Libyan part of Ghadames Basin. Figure 3 shows the location of these fields and their petroleum systems. The northern group includes the Tiji and Tilakshin fields. These fields have their reservoirs in Acacus and Tadrart sands, where hydrocarbons have accumulated in small structural and stratigraphic traps following migration from the southwest. These fields may have been affected by flushing. A second group of fields is aligned along a southwest-northeast trend extending from Ghziel to Al Kabir. These fields are contained in Acacus and Tadrart sands with some leakage into the upper Devonian and Carboniferous reservoirs, and they were changed from the west. Hydrodynamic flushing has also affected this area. The third group, collectively known as the Al Hamadah–Al Hamra fields, has Devonian sand reservoirs because the Wan Kasa and Emghayet shales are ineffective seals in this area. These fields have migration pathways from the northwest. The Tanezzuft–Acacus–Tadrart petroleum system is the most important system within Ghadames Basin. Oil generation from the Tanezzuft hot-shale source rock started during the Carboniferous period and continued into the Cenozoic era. A large proportion of the hydrocarbons generated has been lost by leakage and migration of trap structures. The Tanezzuft source rock was deeply buried during the Carboniferous and Mesozoic periods and is now at a post-mature stage in the center of the basin. The source rocks buried deep in the basin have probably been in the gas window during much of the Cenozoic era, and the oil has probably been generated from shallower sources on the flanks of the basin.

Most of the fields in the basin lie at a depth between 2,000 and 2,500 m [6,600 and 8,200 ft]. 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. Emsian and Eifelian shales provide the major seals. In the south, where these seals become ineffective, oil has spread into middle and upper Devonian reservoirs. Erosion patterns and the topography that developed on the surface of Hercynian 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. Faults provide additional migration pathways in some parts of the basin. On the northern rim of the basin, the Silurian Devonian sequence is truncated by the Hercynian unconformity, and in this region oil is stratigraphically trapped beneath the unconformity by Permo-Triassic shales. The hydrocarbon accumulations are often gas-rich and many pools contain gas and condensate. The principal source rock, as in the Murzuq basin, is the Silurian Tanezzuft formation. In addition to the hot shales developed at the base of this formation, there is a second radioactive zone higher in the section. This unit, which has a limited areal extent and was dated on the basis of graptolite evidence as Telychian. The distribution of hot shales across the basin indicates that they occur in three main depocenters: at the center of the basin near Ghadames; in the Zamzam depression; and in a southern zone that is separated from the main basin by a large subsurface ridge in the area between the Al Wafaa and Tahara fields where the basal hot shale is absent (Figure. 4). The Tanezzuft source rock was deeply buried in the basin center beneath a thick Paleozoic and Mesozoic cover, and its maturity levels are generally high. During the late Cenozoic era, water entered the basin from the Al Qarqaf arch, and the more permeable formations, particularly those of the lower Devonian sequence, have been partially flushed.

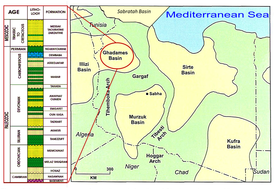


Figure 1. Libya location map refers to the main location of Ghadames basin and its general columnar section with the main lithology.

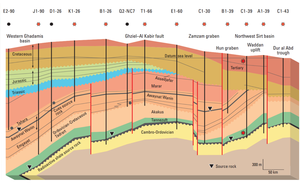


Figure 2. Stratigraphic cross section of the Ghadames basin.

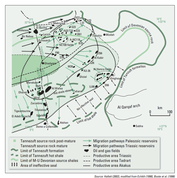


Figure 3. The Ghadames petroleum system and fields.

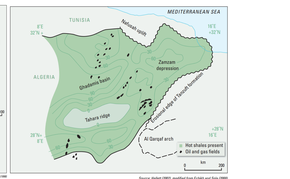


Figure 4. The distribution of Silurian hot shales in the Ghadames basin

Memounait – Tanezzuft Succession

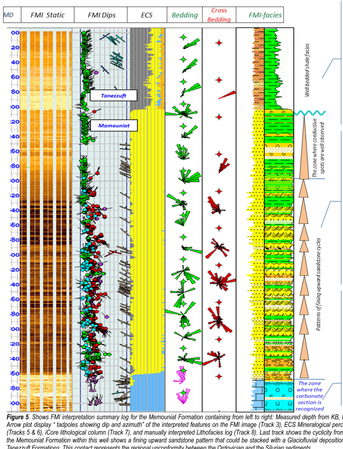


Figure 5. *Shows FMI interpretation summary log for the Memounait Formation containing from left to right: Measured depth from KB, Borehole drift and the FMI dual calipers (Track1), FMI Static image-Straight Image (Track 2), Arrow plot display " tadpoles showing dip and azimuth" of the interpreted features on the FMI image (Track 3), ECS Mineralogical percentages display (Track 4), Neutron-Density and PEF (Track 5), bedding & cross bedding (Traces 5 & 6), iCore lithological column (Track 7), and manually interpreted Lithofacies log (Track 8). Last track shows the cyclicity from log profile and FMI image. According to ECS, ELAN results logs and interpreted FMI facies, the Memounait Formation within this well shows a fining upward sandstone pattern that could be stacked with a Glaciofluvial depositional setting. Sharp unconformity surface was interpreted between Memounait and the overlaid Tanezzuft Formations. This contact represents the regional unconformity between the Ordovician and the Silurian sediments.*

The early Silurian period was associated with marine transgression which took place due to the late Ordovician ice sheets melting. This transgression gave rise to deposition of thick shale sequence (**Tanezzuft Formation**). This formation is known as the major source rock in Ghadames Basin. In this well, however, the interpreted section represents only part of the formation. Low angle shale layers are well identified and represent a quiet marine environment. In some zones within the formation, bioturbation traces are well observed. There is a clear change in lithology (from shaly to sandy facies) in the upper- most part of the section. Bimodal cross bedding trends toward the NE and the SSW have been identified. In the below example, some cross bedding sets have also been observed. In Tanezzuft Formation, sand faces are occasionally observed. The thickness of this zone is 20 ft and the sedimentary structures that were identified from the FMI image are the bedding and cross bedding sand faces. The cross bedding sets have variable azimuth direction. Herring bone cross bedding sets which indicate a local tidal effect have been identified in this sandy facies. The dip magnitude of cross bedding sets ranges from 10 to 30 deg.

Memounait carbonate zone is overlain by a clastic sequence (sandstone and shale facies). The thickness of this sequence is 207 ft. Coarsening up cycles are noticed over the sandy section, while the fining upward cycles are observed in the upper shale section in **Memounait Formation**. The sedimentary structures identified in this section are bedded sand, cross bedded sand, contorted sand, bedded shale, contorted shale, massive sand and shale facies. The cross bedding sets have a polymodal azimuth directions and noticed in many places within the sandy zone. Contorted beddings are also identified and may be formed due to soft sediment deformation. Features, classified as deformed cross bedding, refer to cross bedding sets that were deformed because of a slump process or soft sediment deformation as well. Also, conductive and resistive spots are well observed, presence of such zones could be due mud clasts over the upper Memounait section in this well. The bioturbation sedimentary structure have been observed both in the sandy and the shaly zones, the presence of such feature as well as well stratification of bedding surfaces are an indication of the marine environment. The upper part of Memounait Formation consists of shale facies, bedded, contorted and massive facies. The bedded shale facies represents the dominant feature in this logged section. Soft sediment deformation and concretions were identified and noticed to have an effect on the bedded shale faces.

The basal part of the formation was interpreted to consist of a carbonate faces with a thickness of 48 ft. From the FMI image response, this zone looked very resistive as compared to the other zones within the formation. This was confirmed from the open-hole resistivity values. The reason behind these high resistivity values could be due to compaction which the carbonate facies were subjected to. The internal sedimentary structure which the FMI image displayed are rigid bedding and vugs. The rigid bedding (known as stylolites) were formed due to the pressure dissolution process. The vugs that were identified in this zone exhibited degrees of variety in terms of shape and texture, these vugs were formed as a result of dissolution (a post-depositional process creating secondary porosity in carbonates) that could happen in shallow or deep marine environments. Some of the vugs are isolated while others are connected and they differ in size from one point to another. A final observation in this context is that the carbonate zone is overlain by sandstone facies with an erosional surface marking the contact between them.

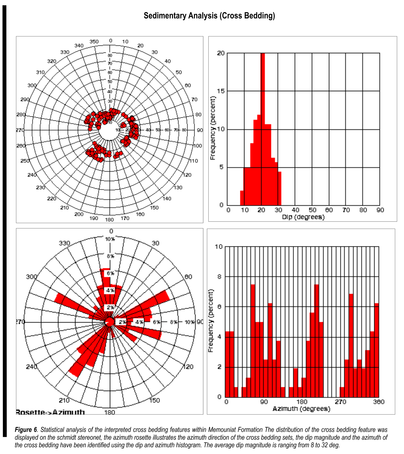
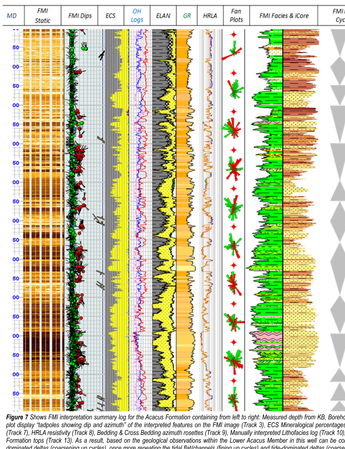


Figure 6 *Statistical analysis of the interpreted cross bedding features within Memounait Formation The distribution of the cross bedding feature was displayed on the schmidt stereonet, the azimuth rosette illustrates the azimuth direction of the cross bedding sets, the dip magnitude and the azimuth of the cross bedding have been identified using the dip and azimuth histogram. The average dip magnitude is ranging from 8 to 32 deg.*

Lower Acacus Succession



Description

Upper Acacus Member; The Upper Acacus Member is characterized by low angle shale, silty layers and cross bedded sand facies. The cross bedded sand sets were identified in many places within this member. The main azimuth direction of cross bedding sets is towards NNW, with other azimuth directions towards the SW and SE. Additionally, some biogenic sedimentary structures such as bioturbation structures have been identified in the Upper Acacus Member.

Middle Acacus Member; The thickness of this member is 230 ft. The lower part of this member consists mainly of shale facies with some silt and silty sand facies in place. In the middle part of this member, the presence of two sand bodies is clearly seen and represent the most conductive zone within this member. Upon moving up to the upper part of the member, the dominant facies again is the shaly facies with a thin sand zone. Cross bedding sets are identified mainly within the middle part of the Middle Acacus Member. The azimuth directions of the cross bedding sets are of poly modal nature. The contact between the Middle and the Upper Acacus Members has a gradational and conformable nature.

Lower Acacus Member; The thickness of this member is 837 ft. It is comprised of sand, silt and shale facies that were better identified by integrating the FMI image fabric to ECS, ELAN, iCore and open-hole lithology indicator logs. Other sedimentological features and findings observed along the Lower Acacus section are described as follows: The sedimentary structures that were identified are bedded sand, cross bedded sand, bedded shale, bedded silt, massive sand and bioturbated sand facies. It has been noticed that within this member, there is a repetition of coarsening upward cycles. The presence of a few fining upward cycles was also observed. The coarsening upward cycles indicate deltaic environment under which these facies were deposited. These cycles are characterized by low angle shale facies at the bottom and cross bedding and bedded sand facies at the top. The contact between the cycles is marked by erosional surfaces. Within the Lower Acacus Member, the traces of the bioturbation are clearly identified and indicate marine environment. The fining upward cycles that were observed in this section were formed as a result of marine transgression where the fine sediments moved toward the onshore and deposited on top of the coarse sediments. Most of the cross bedding features are interpreted to have been formed under the effect of the tides. Two clear azimuth directions which are 180 deg apart are well identified and indicate herringbone cross bedding sets. The coarsening upward cycles and herringbone cross bedding sets are good clues to assign a depositional setting of tide-dominated delta.

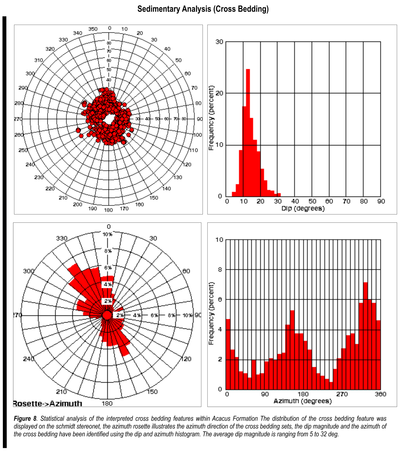
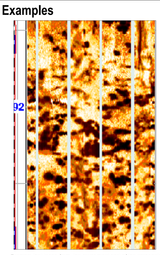


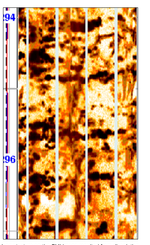
Figure 8 *Statistical analysis of the interpreted cross bedding features within Acacus Formation The distribution of the cross bedding feature was displayed on the schmidt stereonet, the azimuth rosette illustrates the azimuth direction of the cross bedding sets, the dip magnitude and the azimuth of the cross bedding have been identified using the dip and azimuth histogram. The average dip magnitude is ranging from 5 to 32 deg.*

Figure 7 *Shows FMI interpretation summary log for the Acacus Formation containing from left to right: Measured depth from KB, Borehole drift and the FMI dual calipers (Track1), FMI Static image-Straight Image (Track 2), arrow plot display "tadpoles showing dip and azimuth" of the interpreted features on the FMI image (Track 3), ECS Mineralogical percentages display (Track 4), Neutron-Density and PEF (Track 5), ELAN Volume (Track 6), GR profile (Track 7), HRLA resistivity (Track 8), Bedding & Cross Bedding azimuth rosettes (Track 9). Manually interpreted Lithofacies log (Track 10), iCore lithological column (Track 11), Cyclicity from log profile and FMI image (Track 12), and Formation tops (Track 13). As a result, based on the geological observations within the Lower Acacus Member in this well can be concluded as tidal flat/channels (fining up cycles) over the bottom parts and overlaid by tide-dominated deltas (coarsening up cycles), once more repeating the tidal flat/channels (fining up cycles) and tide-dominated deltas (coarsening up cycles). Every so often, the contact between the Lower and Middle Acacus Members looks like a gradational conformable contact.*

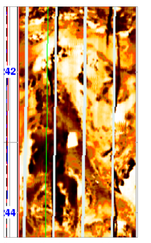
FMI Examples



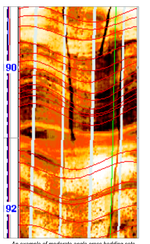
Example that taken from the lower most part of the carbonate zone, rigid bedding which classified as digenetic features at the lower part of Memounait Formation



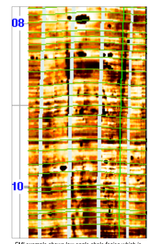
Vuggy texture on the FMI image resulted from dissolution, some of the vuggs were connected and others are isolated at the lower part of Memounait Formation



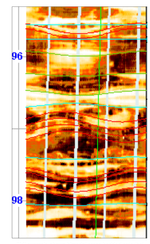
Contorted sand facies formed as a result of glaciation in the lower sandy zone of Memounait Formation



An example of moderate angle cross bedding sets dipping mainly towards the South in Memounait Formation. Presence of bioturbation traces has also been noticed in this zone



FMI example shows low angle shale facies which is dominant in the Tanezzuft Formation, these low angle layers have been deposited in a quite environment



FMI example shows bimodal cross bedded sets that were identified in the Lower Acacus Member.