Journal of Research in Environmental and Earth Sciences, 06 (2019) 173-185
Print ISSN: 2356-5799; Online ISSN: 2356-5802

www.knowledgejournals.com

Research article

Lithofacies and depositional environments of the Hawaz formation, Murzuq basin, SW Libya

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Article history:
Received 11 November 2018; Received in revised form 12 November 2018.
Accepted 17 November 2018; Available online 1st January 2019.

Abstract
Middle Ordovician Hawaz Formation is represents the primary reservoir rocks in Murzuq Basin, in J oil field consists of a 550 feet thick succession made of fine-grained quartz-arenite displaying a variable degree of bioturbation. This J oil field study is an integration approach and it is based on 235 feet thick of slabbed cores photographs from well J4-NC186, with core samples, petrography, wireline log data, and conventional core analysis of the Hawaz siliciclastic sediments. The Hawaz Formation was deposited in wave-dominated shoreface and shelf environments. The stratigraphical and sedimentological characteristics of the Hawaz Formation in the study area in the Murzuq Basin are attributed to shoreface and shelf facies associations within which some 9 facies have been distinguished. The lower part of the cored section of the Hawaz Formation is dominated by the outer and inner shelf facies associations. The outer shelf association is dominated by mudstone whereas the inner shelf association is dominated by siltstone/sandstone. This variation probably corresponds to variations in water depths and energy levels on the shelf. Storm deposits of sand grade are restricted to the inner shelf association. These were deposited immediately below fairwater wave-base and represent shallower water and higher energy than the outer shelf association. In the lower shoreface the wave effect is very weak and, as a consequence of this, fine to medium grain sands dominant in this zone, intercalated with layers of laminated mudstone, both showing abundant bioturbation and trace fossils.

Key words: Lithofacies, reservoir rock, Bioturbation, Murzuq formation, Libya.

1. Introduction

Sedimentation, through the construction of its root and suffix, is a noun of action or act of doing. Geologically it means the act or process of depositing sediment, and without needlessly changing the prior accepted definitions of the two parts of the word it can mean nothing else. The word sedimentology encompasses not only the material itself and its deposition, but also its genesis, transportation, diagenesis, geochemistry, and physics.

Murzuq Basin is located on the North African Platform, covers an area of some 350,000 km², extending southwards into Niger. Thomas (1995) mentioned that the present-day borders of the basin is defined by erosion resulting from multiphase tectonic uplifts (Figure 1). It is not a sedimentary basin in the normally accepted sense, and could more accurately be described as an erosional remnant of a much larger Palaeozoic and Mesozoic sedimentary basin which originally extended over much of North Africa. The flanks comprise the Tihemboka high to the W, the Tibesti high to the SE, and the Gargaf and Atshan highs to the North and NW. These uplifts were generated by various tectonic events ranging from middle Palaeozoic to Tertiary time, but the main periods of uplift took place during Middle Cretaceous to Early Tertiary Alpine movements. The present-day Murzuq Basin contains a maximum sedimentary fill of about 4000m. Davidson, et al., 2000, pointed out that, despite successive erosive episodes during several phases of uplift and erosion throughout the history of the basin, the maximum sedimentary thickness probably never exceeded 5000 m at any single point in time. This Basin has different concessions containing some oil fields one of them is J oil field in concession NC186 in Murzuq Basin. The petroleum system is represented by structural Hawaz paleo-high created during the post Hawaz erosional event, the main regional seal is the Silurian Tanezzuft shale Formation, and the basal Tanezzuft hot shale member acts as the main source rock in the area of study. This Formation is considered the main target. The strata are faulted and the faults are most frequently parallel to the axis. Tectonic movements affected the basin to a greater or lesser degree from middle Palaeozoic, Oligocene (Alpine) times, Bellini and Massa, (1980). Hawaz Formation rests conformably over the Ash Shabiyat Formation. Both formations are cut by an erosive surface recognizable in outcrop and subsurface, Hawaz Formation "typically consisting of cross bedded, quartzitic sandstone with kaolinitic and thin shaley intercalations (Tigillites) bioturbated levels and ripple marks are conspicuous. The formation thickness ranges from 50 m at Dor al-Qussah to 300m at al Qarqaf in outcrops, and 30 to 230 meters in the subsurface.

The main aims of this study, to provide a detailed sedimentological description of the core from well J4-NC186. To integrate the sedimentological and wireline log data in order to derive depositional models which adequately account for the Hawaz Formation in the study well.

2. Material and methods

2.1. Location of the study area

Concession NC186 is located in northwestern flank of the Murzuq basin, southwest part of Libya (Figure 1).

2.2. Structure of study area J oil field

J-Field-NC186 is located in Murzuq Basin, SW Libya; in the middle southern part of NC186 block between H and B fields NC186. J field NC186 is an elongated NW-SE Hawaz paleo-high tilted to the SE, associated with a 4 way dip structural closure. Middle Ordovician Hawaz Formation is the main reservoir in J oil field. Hawaz Formation comprises a distinctive suite of facies associations representing a broad range of environments from low energy shelf marine sediments deposited largely below storm wave base, through to sub-aerial delta plain channel environments. The depositional environment is characterized by gently dipping shelf covered by epi-continental seas developing an extensive coastal plain area dissected by fluvial-tidal channels. Unconformable, upper Ordovician sediments overlap the paleo-high, The Tannezuft shale which covers the structure is the seal of the reservoir (Davidson et al., 2000).

2.3. Lithofacies analysis

Facies is a Latin word meaning face, figure, appearance, aspect, look, condition. It signifies not so much a concrete thing, as an abstract idea. The word was introduced into the geological literature for the entire aspect of a part of the Earth's surface during a certain interval of geologic time (Curt Teichert, 1958). The word facies is now used in both a descriptive and an interpretive sense. Descriptive facies include lithofacies and biofacies, both of which are terms used to refer to certain observable attributes of sedimentary rock bodies that can be interpreted in terms of depositional or biological processes (Miall, 1984). The setting in which sediment accumulates is familiar as geomorphological entities such as rivers, lakes, coasts, shallow seas, and so on.

One of the goals of sedimentary geology is to determine the environment in which any given succession of sedimentary rocks accumulated (Walker et. al, 1992; Reading and Levell, 1996). The facies concept is not just a convenient means of describing rocks and grouping sedimentary rocks seen in the field, it also forms the basis for the interpretation of strata. The lithofacies characteristics result from the physical and chemical processes which were active at the time of deposition of the sediments, and the biofacies and ichnofacies provide information about the paleoecology during and after deposition (Nichols, 1999).

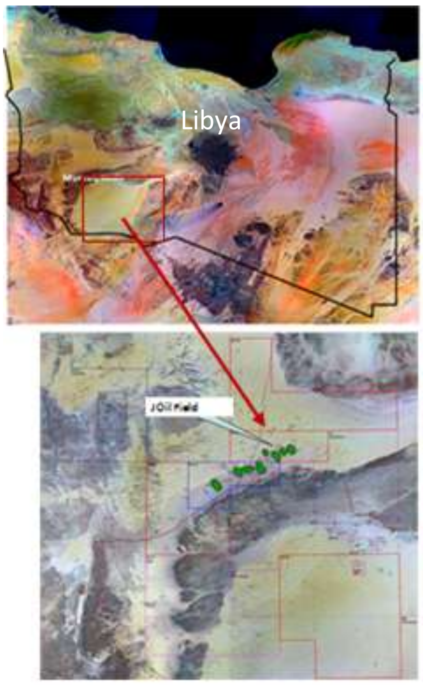

Fig. 1: Location map of J-Oil-Field in Concession 186 in Murzuq Basin.

2.4. Facies models

The primary goal of facies analysis is to produce a facies model which is in effect a hypothesis about the environments signified by the rocks and fossils under study (Hallam, 1981). The vertical succession of strata would be formed by the lateral migration of adjacent environments containing the original sediments that eventually became rocks (Fritz and Moor, 1988).

3. Results and discussion

3.1 Sedimentary facies in the Hawaz formation

The analysis of sedimentary facies of the Hawaz Formation is based on lithology, sedimentary structures and biogenic feature seen in core section and wireline logs. Many of the facies described are very similar to one another and are differentiated in some cases on subtle differences in texture and biogenic features. This part describes and interprets the facies in the type well, J4-NC186. All of the samples used for this study are from well J4-NC186; (30 samples) which have been cut into thin sections. All these samples were provided by Acacus Oil Operation (Table 1) and the recognized lithofacies of the Hawaz Formation were interpreted (Figure 2) the following facies have been recognized and are described below from bottom to top of the core section, based on detailed description and analysis of both the color photographs of the slabbed core and GR-logs.

Table 1: Core samples used in this study from type wells J4-NC186, showing the cored intervals and core sample depths.

Core Number	Interval Cut. Ft.	Interval recovred ft.	Footage recovred ft.	Percentage recovred	Formation
1	4116-4172'	4116-4172'	56'	100%	Hawaz 5
2	4176'-4231'	4176-4231'	55.5'	100%	Hawaz 5&6
3	4231-4291'	4231-4291'	59.5'	100%	Hawaz 6&7
4	4291-4351'	4291-4351'	60'	100%	Hawaz 7&8

3.2. Heterolithic facies

This facies occurs in the well J4-NC186, at depth of 4324ft., to 4339ft. (Figure 2). It is the second most abundant facies in the Hawaz Formation in the study area and attains a thickness of about 9 meters. It typically comprises very thin to thin bedded sandstone interbedded with thin beds of siltstone or micaceous black mudstone, the boundary between these lithologies sh0wing subtle gradations in color. The upper portion of this facies is dominated by thin to medium-bedded fine-grained sandstone, siltstone and mudstone. The sandstone is moderately well-sorted and contains mostly subrounded to subangular grains. It occurs either as individual beds, separated by interbeds of mudstone or siltstone, or as amalgamated lenticular beds with little or no finer sediment between them. Individual sandstone beds are 6cm thick, and predominantly fine to medium-grained, parallel laminated sandstone, with very begin with a sharp base and mostly grade upwards into overlying mud layers. The sand layers are either evenly laminated or are developed as laminated rhythmists, in which the lower laminae are thicker and coarser grained and grade upwards into thinner and finer-grained laminae.

The presence of escape burrows suggests that storm-sand layers and some of the accompanied mud layers were deposited rapidly. Storm and hurricanes are considered to be the main factors in the genesis of these laminated sands (Reineck and Singh, 1972, 1980).

Fig. 2: Close view slabbed core sample, showing parallel to wavy, ripple cross-lamination sandstone and mudstone. This facies comprises very thin to thin bedded sandstone interbedded with thin beds of siltstone or micaceous black mudstone.

3.3. Burrowed heterolithic sandstone facies

This facies comprises centimeter to decimeter-thick alternations of sandstone and siltstone-claystone, which mostly occur in the lower part of type well J4-NC186, where it is represented by the cored interval 4300ft, and 4309ft. It is lithologically variable, from sandy heterolithic to muddy heterolithic and argillaceous sandstone; the mud content varies throughout the facies. Some small sets of cross-lamination could also be distinguished in the sandstone. The effect of biogenic reworking can be seen in the light grey colored mottling of shale and sand, with some coarse-grained siltstone (Figure 3). The entire facies shows a general coarsening-upward trend, and is intercalated with burrowed sandstone. The burrows are sand-filled vertical and horizontal burrows, dominated by *Cruziana*, *Skolithos* and *Planolites*. They are up to 30cm long and 4mm-8mm in diameter. The sandstones are fine to medium-grained, and well-sorted with angular to subangular-grains.

Fig. 3: Close view slabbed core sample, showing burrowed heterolithic sandstone.

3.4. Burrowed sandstone lithofacies

Description. This facies forms the bulk of the cored section and consists largely of burrowed sandstone interbedded with thin, burrowed muddy sandstone. This facies is represented by the cored interval from C#1: 4116' to 4540'; C#2: 4176' to 4231'; C#3: 4231 to 4291', and C#4: 4291 to 4351' in type well J4-NC186, (Table 1). This facies is dominated by vertical burrowing which passes through beds and destroys most internal sedimentary structures (Vos, 1981). Turner (2002) describes the upper part of the Hawaz succession as consisting predominantly of intensely rippled and vertically burrowed fine-grained, thinly bedded, well-sorted white sandstone. It comprises fine-grained, pale grey to brownish sandstone, depending on clay content. Where it contains more clay the color is light grey whereas in other intervals the color is brownish. The sandstone is well-sorted, containing angular-subrounded grains, and is characterized by burrows and local bioturbation (10-40%), most notably *Skolithos*, *Cruziana* and *Diplocraterion.* The burrows are from 2-5mm in diameter, and up to 4cm long, including horizontal burrows such as *Paleophycus, Planolites* and rare *Thalassinoides.* Bedding is poorly defamed or where defined it as thinly bedded, with stylolitic mudstone partings defaming bed boundaries. The content of mud in this subfacies is more than in the upper burrowed sandstone subfacies. This subfacies is overlain by the heterolithic facies and underlain gradually by the burrowed heterolithic facies (Figure 4).

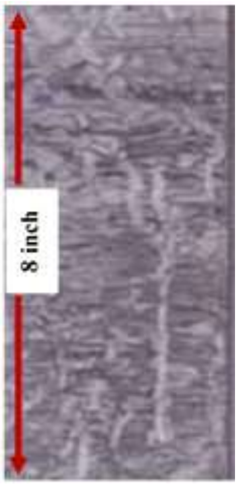

Fig. 4: Close view slabbed core sample (J4-NC186), showing burrowed heterolithic sandstone.

3.5. Ripple cross-laminated sandstone facies

This facies overlies the burrowed mudstone and sandstone facies at from well J4-NC186 at depths of 4267ft. to 4270ft.; at 4276 to 4279ft. and at 4282ft. to 4285ft., (Figure 5). It consists of fine to medium-grained, light brownish grey sandstone. The sandstone is well-sorted to moderately well-sorted, clean to slightly argillaceous and micaceous. The sandstones which are quartz rich, with individual grains mostly subrounded to subangular, are locally interbedded with thin, micaceous mudstone. The sandstone is characterized internally by small-scale sets of ripple cross-lamination <3cm thick, and rare sets of low angle cross-stratification.

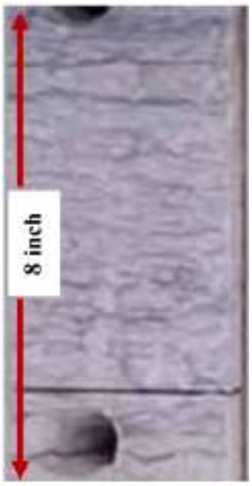

Fig. 5: Close view slabbed core sample, showing burrowed and ripple cross-lamination.

3.6. Cross-bedded sandstone facies

This facies occurs in well J4-NC186 at depth of 4197ft. to 4209ft **(**Figure 6). It comprises light olive grey, fine to medium-grained, well-sorted, clean sandstone, dominated by subrounded to subangular grains, with occasional rounded grains. It is internally structured by small to medium-scale, high-angle planar, tabular cross-bedding (15°-25°), with individual fore-sets from 16cm to 40 cm thick displaying thin < 1 mm thick stylolitic mud drapes.

Fig. 6: Close view slabbed core sample, showing cross-bedded sandstone facies.

Some small sets (<5cm thick) of cross-lamination, burrows are absent or poorly defined. Some cross-bedded sets are underlain by an erosion surface or burrowed sandstone. This facies shows good permeability and porosity, the permeability ranges from 442.0md to 666.3md and the porosity ranges from 15% to 18% in well J4-NC186. In well A1-NC186 the permeability ranges from 324md to 784md and porosity from 13.1% to 20%.

3.7. Low angle cross-bedded and planar-laminated sandstone facies

This facies is well developed in well J4-NC186 at depth of 4185ft., to 4200ft. It comprises light brownish, fine-grained, moderately-sorted, clean sandstone, characterized by sets of low angle (<15°) cross-bedding, which vary in set thickness from 15 to 45cm, and less commonly low angle (5°) lamination, with stylolitic clay drapes (Figure 7), the low angle cross-bedding occurs between slightly higher angle crossbedding, and the angularity of the fore-sets increases upward. Fore-set laminae are well defined and usually <10cm thick. Burrows are abundant in some intervals. However the base of this facies is sharply defined by an erosion surface. Some of the low angle intersecting fore-sets could be part of large-scale hummocky cross-stratification.

Fig. 7: Close view slabbed core sample at depths of at 4199ft. showing low angle cross-bedded sandstone.

3.8. Burrowed mudstone and sandstone facies

This facies occurs in different parts of well J4-NC186 at depth of 4164ft. to 41170ft. (Figure 8). In this type well. It comprises mudstone irregularly interbedded with very thin to medium-bedded, very fine to locally fine-grained sandstone, containing small-scale wave and current ripple cross-lamination. The amount of sandstone to mudstone varies from 90% to 55-60%. The facies is locally disrupted by vertical and horizontal burrows, most notably *Planolites*, *Palaeophycus*, *Teichichnus*, and *Skolithos.* This facies is gradationally intercalated with burrowed fine to medium-grained sandstone.

Fig. 8: Close view slabbed core samples, showing burrowed mudstone and sandstone facies

3.9. Massive sandstone facies

This facies is more prominent in well J4-NC186, at depth of 4158 to 4168ft (Figure 9). This facies consists predominantly of fine to medium-grained, clean to slightly argillaceous, light olive grey sandstone. The sandstones comprise well-sorted, subrounded to subangular-grains, and are characteristically massive or contain faint horizontal laminations. The massive sandstone grades upwards into horizontal parallel laminated sandstone, with some black drapes or irregular wisps of organic matter.

Fig. 9: Close view slabbed core sample. Showing massive sandstone facies.

3.10. Ripple cross-laminated siltstone facies

This facies occurs in the lower part of the cored section in type well J4-NC186 at depth of 4119ft. to 4128ft. (Figure 10), between 4761.5-4764ft. It comprises very fine-grained, micaceous and burrowed, very well-sorted to well-sorted. The siltstone is characterized by small-sets of ripple cross-laminated fore-sets which are separated by streaks of paler color sand, with some soft sediment deformation. Burrows are from 1.5mm to 7mm in diameter, the most notable burrows are *Skolithos.* The siltstone facies is bounded above by the burrowed heterolithic facies, which has a higher mud content and greater intensity of burrowing. Below it is bounded by the heterolithic facies which also has a higher mud content**.**

Fig. 10: Close view slabbed core sample, showing cross- laminated siltstone facies.

3.11. Facies analysis and interpretation

Facies 1: The position of this facies above the lower shoreface burrowed fine-grained sandstone, and the marine fauna, indicate an offshore shelf receiving-mainly fine-grained sediments. This facies is interpreted to have been deposited from suspension under low energy storm-influenced conditions, below fair weather wave base, in an open-marine inner-shelf environment. The dominance of shale and subordinate thinner siltstone and sandstone indicates a shelf receiving mainly fine-grained detritus (Turner, 1980). The laminations are composed of clay and silt, with smaller amounts of very fine-grained sand in the heterolithic siltstone, all deposited from suspension (Pedersen, 1985). Settling from suspension after storms appears to be the main process responsible for the sandy intercalations (De Raaf, et. al., 1977). The upward decrease in thickness of finer- grained interbeds through the facies as well as the upward increase in abundance of thicker sandstone beds indicates a progradational shallowing environment (Vos 1977) and decrease in accommodation space. In the shallower part of the shelf any sediment will be extensively reworked by wave processes. Sand deposited in these settings is texturally and compositionally mature with wave ripple cross-lamination and horizontal-stratification. Streaks of mud in flaser beds may have been deposited during intervals of lower wave energy in deeper water further offshore (Nichols, 1999). Johnson (1977) interpreted this type of facies as a very low energy facies, in which two hydraulic regimes were present. Low energy periods are represented by deposition of silt layers from suspension, whilst high energy conditions were marked by the introduction of sand layers, also from suspension since there is an absence of current-formed structures. During -these higher energy periods oscillatory wave motions were the dominant process (Johnson, 1977). Formation of sandstone and shell beds is attributed mainly to storm wave surge currents. Individual beds probably record a single event of storm turbulence with resuspension of sand from the shelf floor, followed by sand deposition from suspension, with wave surge currents causing ripple-drift and ripple cross-lamination, as well as hummocky cross-bedding (Vos, 1977).

Facies 2: Burrowed heterolithic sandstone has been widely described as distal shoreface to innermost shelf (offshore shelf), receiving fine-grained sediments (Vos, 1977), deposited under storm influenced conditions. The offshore shallow marine environment is sedimentologically complex because of the number of different processes which operate within it (Banks, 1973), and probably it is the least well understood of all sedimentary environments (Anderton, 1976). To produce the alternation of mudrock and rippled sandstone, processes operated at two different intensities. Sands and silts were emplaced and deposited under the oscillatory and current conditions related to storms and their late-stage phases. Some muds were deposited by post-storm fall-out of material placed into turbulent suspension during storms, whereas other muds accumulated more slowly during inter-storm periods. Parts of the heterolithic succession that are richer in rippled sandstone formed during periods when sand was more available and storms were more frequent, more intense, and/or closer. Mudrock-rich parts of the heterolithic succession formed at times of sand starvation, possibly when storms were less frequent, weaker, and/or more distant. Alternation of sandstone-dominated and mudrock-dominated parts of the succession might reflect either changing patterns of storm incidence or changes in shelf bathymetry (Cotter, 1985).

<u>*Facies 3:*</u> The intense burrowing, presence of marine burrowing organisms, and ripple cross-lamination and parallel lamination, are consistent with deposition in a shallow water marine environment. Bottom conditions were ideal for colonization by a variety of burrowing organisms, suggesting a well oxygenated environment supplied with nutrients, possibly from a nearby terrestrial input. The association of clean and dirty sandstones may reflect differing energy levels within the near shore environment, which is interpreted as a lower shoreface/nearshore shelf. The argillaceous sandstones are considered to represent normal back-ground sedimentation interrupted periodically. The high density ichnofacies suggest deposition took place in a low energy fully marine environment. Skolithos is indicative of relatively high levels of wave or current energy, and typically is developed in slightly muddy to clean, well-sorted, loose or shifting particulate substrates. The *Skolithos* ichofacies ordinarily grades landward into supratidal or terrestrial zones and seaward into the *Cruziana* ichnofacies. The *Cruziana* ichnofacies is most characteristic of subtidal, poorly sorted and unconsolidated substrates. Conditions typically range from moderate energy levels, in shallow waters below fair-weather wave base to low energy levels above storm wave base (Figure 11) (Pemberton *et al*., 1992). The change from a *Cruziana* ichnofacies to a mixed *Skolithos*-*Cruziana* assemblage may be related to increasing energy and more proximal and unstable substrates, possibly resulting from relative sea-level falls.

<u>*Facies 4:*</u> For many years, two basic types of ripple mark were widely recognized, based on their planform geometry: symmetrical and asymmetrical. These have been interpreted generally as the products of wave action and current flow respectively (Tanner, 1967). Where waves alone are responsible for ripple generation, the stronger positive (normally shoreward) component of oscillation controls the ripple internal structure. Although this conclusion is based on samples from relatively shallow water, the water depths include the border between rippled and un-rippled sand where the waves are just beginning to feel bottom (Newton, 1968). The argillaceous, micaceous nature of the sandstone, and ripple cross-lamination suggests an environment swept by low energy currents promoting the formation of ripple-scale bedforms. Bed-form formation was probably controlled· mainly by bottom current velocities, down to normal wave base, which together with the high incidence of mud in these sediments and local burrowing suggest the possibility of a nearshore shelf environment, possibly distal to the low-angle, cross-bedded and high angle cross-bedded facies. Some of the fore-set irregularities are similar to intra-set deformation features attributed to shear stress exerted on the top of the sandy bedforms, accompanied by pre-deformation sediment liquefaction. Campbell (1971) described similar low angle cross-laminations between parallel bedding surfaces as deposited in the surf zone bordering beaches.

<u>*Facies 5:*</u> The presence of well-sorted, fine to medium-grained, locally burrowed sandstone with small to medium-scale planar, tabular cross-bed sets is indicative of the development of two-dimensional dune bedforms, within a relatively high energy marine environment. Cross-beds are interpreted to represent lower-flow regime sedimentation under unidirectional and/or combined-flow currents. The presence of burrowing and mud drapes suggests a possible tidal influence. Maximum current velocities during transport episodes for cross-beds were probably in the range of a few tens of cm/sec to 1m/s (Winn, 1991). The high angle of the forests suggests a high rate of bedload-dominated sediment supply to the dune slip face during migration, with most of the finer suspension load carried down-current beyond the slip face. Based on the relationship between dune bed-form height and current strength documented by Allen (1982), current velocities of the order of 3 m5 - 1 may have been

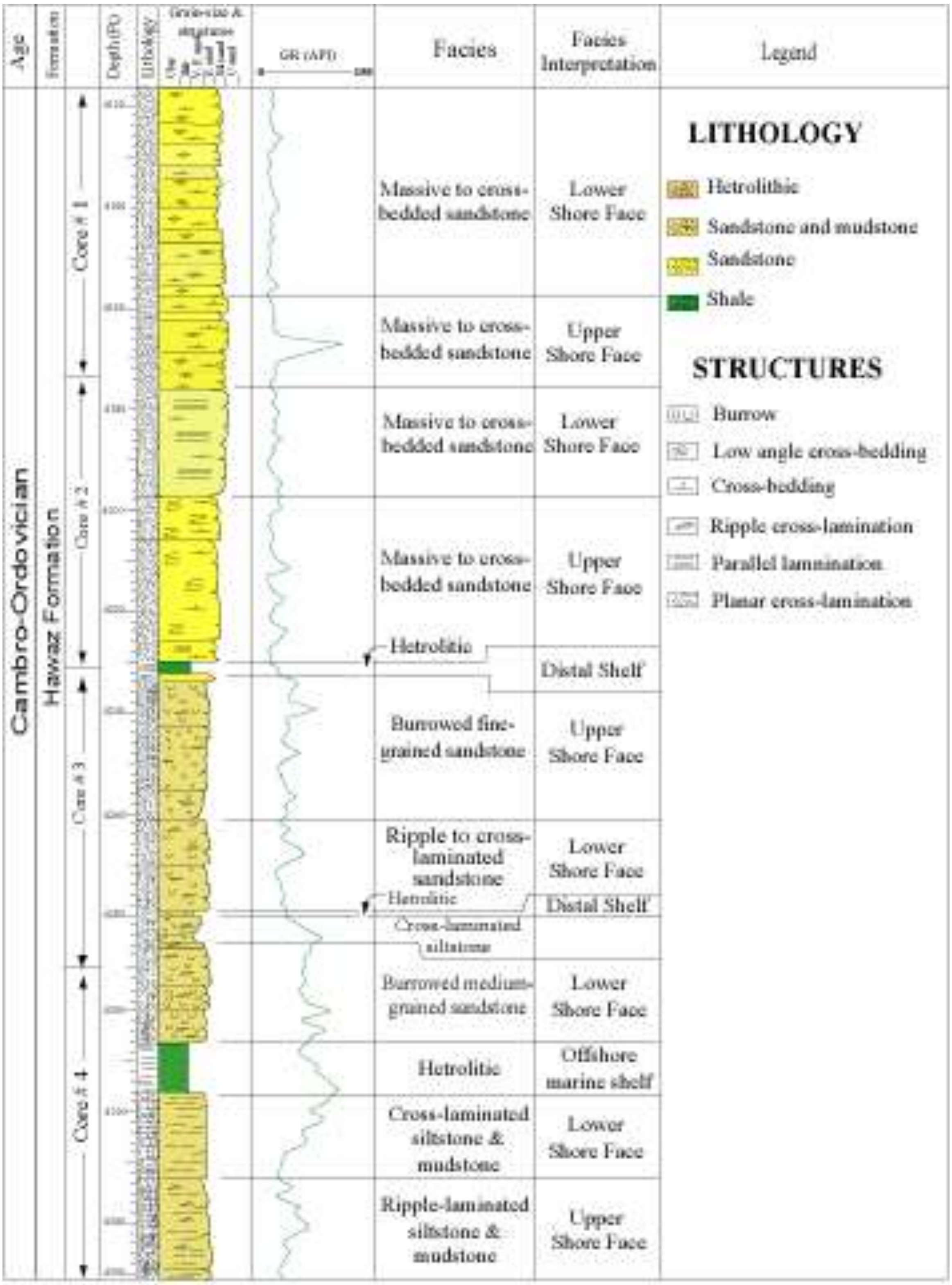

Fig. 11: Lithology, sedimentary environments and gamma-ray in the cored section of type well J4-NC186.

responsible for bed-form generation and migration. Such high energy conditions are typically found in lower to middle shoreface, wave-dominated environments characterized by wave-generated two and three-dimensional bed-forms, which differ in dimensions according to energy levels coming off the shelf. The *Skolithos* ichnofacies is typically found in high energy nearshore shallow water conditions associated with moving sands, and is consistent with a lower-middle shoreface interpretation. This facies has the highest proper values in the Hawaz Formation, and has good reservoir potential.

Facies 6: The low angle, clay-draped fore-sets suggest that a significant component of suspension load was periodically supplied to the slip face of the dune bed-forms, possibly during lower energy intervals, such as reversing tides when clay and silt were released from the separation bubble or eddy system to the downstream slip face. Although there is no direct evidence of a strong tidal influence on deposition, it could account for the clay drapes on fore-sets. Most fines deposited in this way concentrate on the lower part of the slip face producing downward thinning, tangentially-based fore-sets. The low fore-set angle suggests that the dune bedforms may have formed close to the dune-plane bed hydrodynamic boundary, as the dunes become washed out and fore set angles significantly decline. The low dip angles on many fore-sets may have been caused by the effect of wave action on a unidirectional current. Many low-dipping cross-beds are interpreted as a form of hummocky cross-stratification (Nottvedt and Kreisa, 1987). The localized presence of an erosion surface at the base of the facies could be indicative of channelization, or a local, high energy event on the shoreface. This facies may be the distal facies equivalent of the high angle cross-bedded facies C, comparable with a landward shift from lower to middle-upper shoreface, along a transgressive coastline, concomitant with increased accommodation space.

Facies 7: The interbedded silty mudstone and wave and current ripple cross-laminated sandstone indicate differing energy levels during deposition. The silty mudstone may represent normal background sedimentation and the sandstone higher energy, possibly storm-influenced sedimentation. The mix of high energy (*Skolithos*) and low energy (*Planolites*) trace fossils supports the interpretation of variable energy levels during deposition. Skolithos is characteristically developed in high energy shallow water conditions, whereas *Planolites* is typically developed below normal fair weather wave base in well sorted sands and silts in relatively quiet water conditions. The variety and abundance of burrows is again consistent with a marine environment, particularly a nearshore shelf

Facies 8: Lamination in sandy sediments is the interleaving of particles in thin layers which differ slightly among themselves in average grain size. It can arise, in the context of a turbidity current, only if an individual grain is free to transfer a sufficient number of times between the sub-population and the static bed so that it can become associated with others similar to it in a patch on the bed moving beneath the current (Allen, 1991). In some cases the lack of internal stratification may be a result of post-depositional liquefaction or intense bioturbation, but in many, if not most examples, the massive sand divisions appear to be the products of discrete depositional events from one or more gravity currents. The massive sand may grade laterally or vertically into sand that exhibits some diffuse internal stratification.

Facies 9: Siltstone can be interpreted as being deposited from suspension in outer shelf areas. Neither the wave component, dominant during deposition of the thin-bedded facies, nor the current component can be thought of as 'fair-weather' processes in that silt deposition from suspension presumably occurred at yet lower water velocities. However, even during silt deposition waves were capable of rippling the bottom, producing the silty drapes on fore-sets. It is impossible to say whether this represents fair weather activity or silt deposition after storm stirring (Levell, 1980). This facies may have been deposited in a shallow marine shelf environment during periods of little detrital influx from the fluvial system. The silt and sand streaks were rather rapidly deposited from suspension which started to fall out suddenly and terminated gradually. During the settling wave oscillation apparently could reach the bed thus molding the lamination into a weak cross-lamination. This suggests that the silt and sand intercalations represent thin storm sand-layers which to variable degrees are affected by wave agitation related to the same storm (De Raaf *et al.*, 1977).

3.12. Depositional environmental of the Hawaz FM

It is clear from previous studies and the present study that the sediments that make up the Hawaz Formation are dominantly clastic and are composed of interbedded sandstones and mudstones which display a range of sedimentary structures, ichnofacies and composition.

3.13. Environmental diagnostic criteria

Reading (1986) proposes three main groups of environmentally-diagnostic criteria: 1) Sedimentological, 2) mineralogical and 3) biological. With respect to shallow marine and shoreface environments.

3.14. Shoreface environment characteristics

The shoreface is a seaward sloping, sandstone depositional wedge that grades basin-ward into offshore sandy and silty shales, and landwards into foreshore sandstones and/or conglomerate. It can be subdivided into a lower, middle and upper shoreface.

3.15. Hummocky cross stratification (HCS)

The sedimentary structures commonly include hummocky cross stratification a feature which is generally taken to indicate storm wave activity below fair-weather wave base but above storm wave base (Walker, 1984) and to be typical of deposition on storm-dominated shelves (Harms *et al.*, 1975; Duke, 1985). It is considered to be generated by the interference of oscillatory flow and a storm-generated unidirectional mean flow. Swift and Niedoroda (1985) further interpreted HCS to represent storm-flow regimes in which the wave orbital component is high relative to the mean flow component.

3.16. Offshore zone

With continued increase in depth (>20 meter) into the offshore zone, the sediment becomes silty clay. Silty layers are produced mainly by sediment taken into suspension during heavy storms on the coast and transported away from coast**.** This silty sediment is deposited in shelf mud in the form of silty layers. Silty layers of shelf mud are evenly laminated and sometimes a weak grading is developed (Figure 12).

3.17. Depositional model of the Hawaz formation

These interpretations together with the present study suggests several points with respect to a regional model for the Hawaz Formation. With these points to consider it is possible to present a depositional model for Hawaz Formation sedimentation. The area was supplied with a sample supply of detrital grains from weathered older Palaeozoic Formations and Precambrian basement. The Hawaz Formation was deposited in wave-dominated shoreface and shelf environments. The stratigraphical and sedimentological characteristics of the Hawaz Formation in the study area in the Murzuq Basin are attributed to shoreface and shelf facies associations within which some 9 facies have been distinguished (Figure 13). The lower part of the cored section of the Hawaz Formation is dominated by the outer and inner shelf facies associations. The outer shelf association is dominated by mudstone whereas the inner shelf association is dominated by siltstone/sandstone. This variation probably corresponds to variations in water depths and energy levels on the shelf. Storm deposits of sand grade are restricted to the inner shelf association. These were deposited immediately below fairwater wave-base and represent shallower water and higher energy than the outer shelf association (Figure 14). In the lower shoreface the wave effect is very weak and, as a consequence of this, fine to medium grain sands dominant in this zone, intercalated with layers of laminated mudstone, both showing abundant bioturbation and trace fossils. The repetition of similar facies suggests a recurring pattern of similar depositional processes and environments. This is attributed to dynamic interaction between shoreface (upper and lower) and shelf environments (inner and outer) along a NW-SE oriented shoreline, but with the possibility of a contribution from a continental source area by a small percentage (2 samples) of the sandstone samples falling in the fluvial field. The rivers are thought to have fed in sediment from the Ghat/Tihemboka Arch to the southwest of the study area.

Constant interaction between the shoreface and shelf must have affected the more landward depositional environments to the southwest outside the study area as well. Thus, small-scale relative sea level fluctuation evidenced on the relatively minor shifts in facies, were the dominant force on the depositional system, and enable sequence stratigraphy to be applied effectively to the succession. The relatively small scale shifts in facies tracts from shoreface to outer shelf may reflect the very low gradient of the shelf and/or very minor changes in relative sea level. Middle Ordovician, Hawaz Formation unconformably overlies the lower Ordovician, Achebyat Formation which in turn overlies the upper Cambrian. The Cambrian Period was a long warm interval followed by a major phase of glaciation in Late Ordovician in central northern Africa (Caputo and Crowell, 1985), when ice spread northward from glacial centers in central Africa.

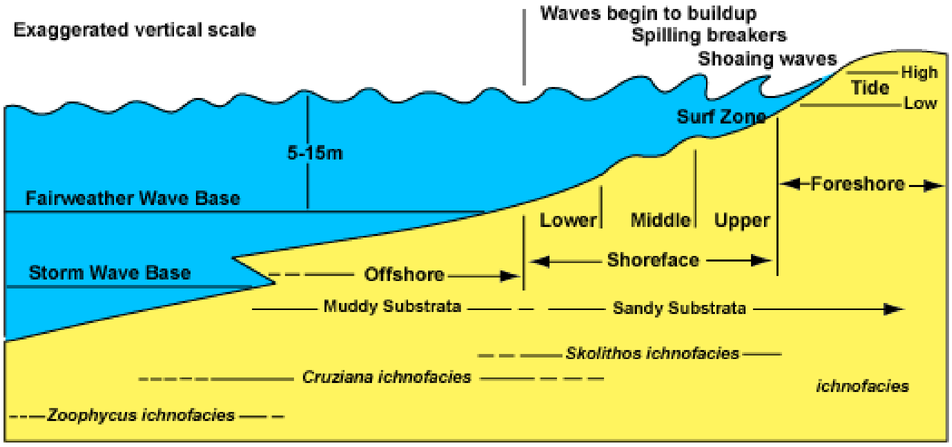

Fig. 12: Offshore - shoreface model developed for the Hawaz Formation in the Murzuq Basin.

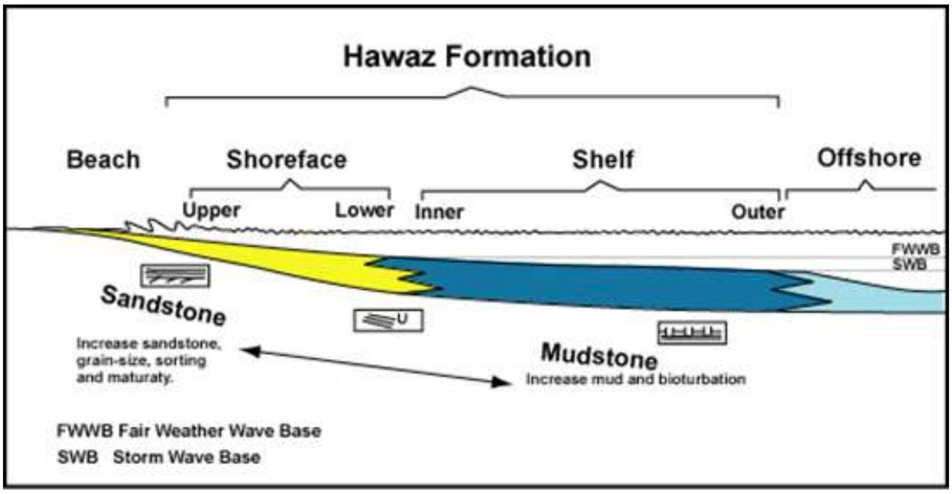

Fig. 13: Cross section showing the two facies association recognized in the Hawaz Formation (shoreface and shelf).

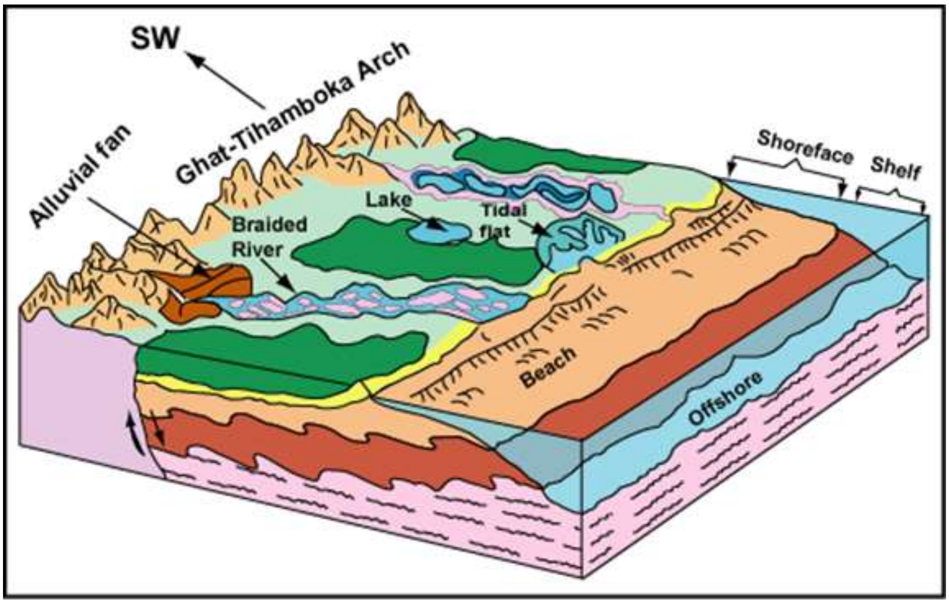

Fig. 14: Schematic depositional model of the Hawaz Formation in J4-NC186 of the study area.

4. Conclusion

This study of the Hawaz sandstone shows that:
Hawaz Formation consists predominantly of alternating fine to medium-grained, well-sorted to moderately well-sorted sandstone displaying a variable degree of bioturbation.

- Petrographic data shows that the Hawaz sandstones can be classified mainly as a quartz arenite, with local subarkoses.
- Diagenetic cement is mainly in the form of quartz overgrowths, and local calcite and clay matrix, all of which have reduced the porosity.
- The Hawaz Formation was deposited in wave-dominated shoreface and shelf environments. The stratigraphical and sedimentological characteristics of the Hawaz Formation in the study area in the Murzuq Basin are attributed to shoreface and shelf facies associations within which some 9 facies have been distinguished. The lower part of the cored section of the Hawaz Formation is dominated by the outer and inner shelf facies associations.
- The outer shelf association is dominated by mudstone whereas the inner shelf association is dominated by siltstone/sandstone.
- This variation probably corresponds to variations in water depths and energy levels on the shelf.
- Storm deposits of sand grade are restricted to the inner shelf association. These were deposited immediately below fairwater wave-base and represent shallower water and higher energy than the outer shelf association.
- In the lower shoreface the wave effect is very weak and, as a consequence of this, fine to medium grain sands dominant in this zone, intercalated with layers of laminated mudstone, both showing abundant bioturbation and trace fossils.

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