Facies Analysis of Middle Ordovician Hawaz Formation and the Major effect of the Ichnofacies on the Reservoir Quality, an Example from the NC115 Block in Murzuq Basin, Southwestern Libya

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Abstract: ***The Hawaz Formation in Murzuq Basin is an important part of the lower Paleozoic terrigenous Al Qarqaf siliciclastic group. The formation was thoroughly investigated, described, and classified as a petroliferous reservoir at the NC115 Block. That was sourced and sealed at the same time by lower Silurian Tanezzuft hot and cold shales. The cored portion of the H27 well was used to define the ichnofacies and other diagenetic characteristics of the Hawaz Formation. Also, forty 1-inch core plug samples were utilized to examine the porosity and permeability and eight thin sections used for the petrographic investigation. Separate litho-and ichnofacies analyses were used to identify the various facies of the Hawaz Formation of the H27 well. Based on facies analysis and lithological and ichnological properties, the examined Hawaz Formation may be classified into bioturbated and nonbioturbated facies. The bioturbated facies include the proximal*** **Skolithos, Skolithos,** ***and*** **Cruziana ichnofacies,** ***while the nonbioturbated facies are sandstone cross-bedding and heterolithic facies. These ichnofacies have been deposited at broad depositional settings from the proximal fluvial-tidal channels to the transitional shoreface offshore environment. The sandstone was classified as quartz arenite and showed a similarity in porosity (up to 25%) for both cross-bedding and proximal*** **Skolithos ichnofacies.** ***Also, the measured porosity from core plugs was around 10 to 20%. However, the nonbioturbated facies was impermeable (up to 6 mD) as compared to the cross-bedding facies, which ranged between 88 and 948 mD.***

Keywords: Hawaz Formation, Facies Analysis, Ichnofacies, *Skolithos* ichnofacies, *Cruziana ichnofacies*, porosity, permeability

1.Introduction

The Murzuq Basin is an endorheic intracratonic basin in southwest Libya, located between 23° and 27° N and 11° and 16° E (Figure 1), with a surface area of around 350,000 km^2. The basin's boundaries are the Al Qarqaf Uplift in the north, the Tassili Plateau in the west, the Haruj volcanic complex, and the Tibesti Uplift in the east. Whereas, Djado Basin in Niger is the basin's southern extension. Davidson et al. (2000) define the Murzuq Basin as an erosional remnant of a much larger Paleozoic and Mesozoic sedimentary basin that formerly covered much of North Africa (Boot et al., 1998). All of the basin's structural elements caused by several tectonic processes that spanned the Paleozoic through the Tertiary periods. The vast majority of the sedimentary rocks, more than 4, 000 m in the basin's center, are Paleozoic and Mesozoic sandstones and shales. The oldest Paleozoic Al Qarqaf group is exposed on the basin's outside edges, while an escarpment of Triassic, Jurassic, and Cretaceous deposits rises in the interior. Paleocene marine limestone, dolomite, and marl preserved near the northern and northeastern border of the Murzuq Basin and make up the bulk of the 100 m-thick Cenozoic deposits. The terrigenous Cambrian-Ordovician Al Qarqaf Group consists of at least five formations, from bottom to top, and includes the Hasawnah, Ash Shabiyat, Hawaz, Melaz Shuqran, and Mamuniyat Formations. With reference to the type section in Jabal Hawaz, Massa and Collomb (1960) initially defined the Hawaz Formation and dated it to the middle Ordovician. However, it is not exposed along the basin's southwesterly boundary because to local marine regression or tectonic uplifting (Figure 1). The formation's base is conformably overlies the Lower Ordovician Ash Shabiyat Formation and occasionally unconformably overlies the Hasawnah Formation. The Upper Ordovician Melaz Shuqran Shale or Mamuniyat Sandstone overlies it commonly (Echikh & Sola, 2000; Gundobin, 1985; Jakovljevic, 1984; Parizek, Klen, & Rohlich, 1984). In the Murzuq basin, the pre-Silurian formations sculpted by late Ordovician glaciations as paleo-highs and paleo-lows. Subsequently, if the Lower Silurian Tanzuft Shale directly covers the Hawaz Formation, it would be in excellent juxtaposition as a reservoir sourced from the lower Tanzuft Hot Shale (Aziz, 2000; Echikh & Sola, 2000).

The investigated well (H27) is located in the eastern portion of the H Field, which is a part of the NC115 block, and it produces from the Hawaz Formation reservoir, which has a total thickness of 700 feet (213 m).

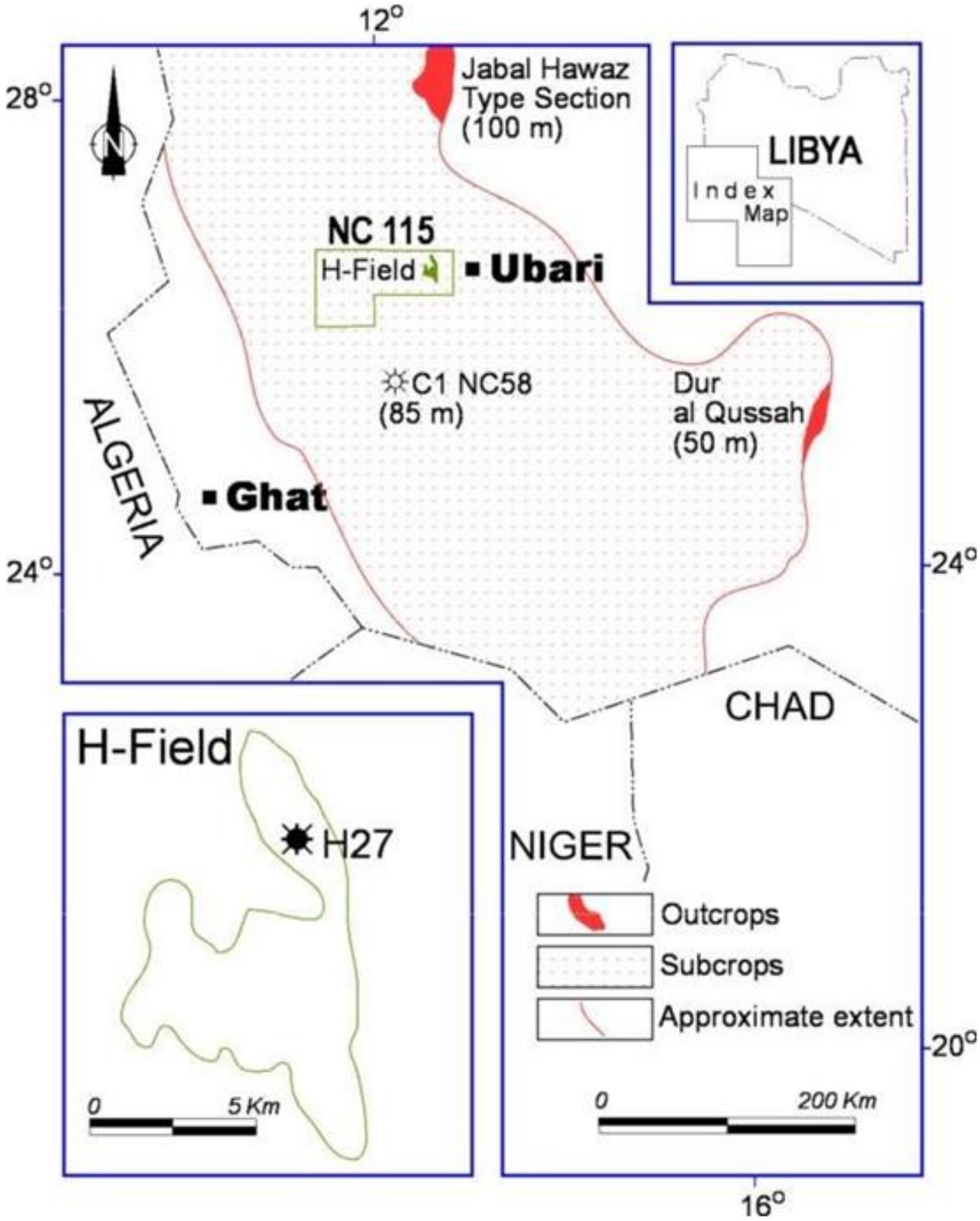

Figure 1: The lateral extent of Hawaz Formation at Murzuq Basin modified from Hallett and Clark-Lowes (2017), and the location of well H-27 within the H-Field of NC115 block

A variety of sedimentary models for the Hawaz Formation developed, all of which fit within the shallow marine to transitional environments. The outcrop succession, according to Vos (1981), was a fan-delta complex. Other researchers, such as Anfray and Rubino (2003), Alkhalas (2006), and Ramos et al. (2006), identified sedimentary structures that indicated considerable tidal effect. *Daedalus*, *Skolithos*, *Siphonichus*, *Diplocraterion*, *Planolites*, and *Cruziana* are among the ichnogenera found in the Hawaz Formation. This extensive ichnology methodology was used to investigate the depositional environment of the Hawaz Formation. After the Murzuq Basin's petroleum boom in the 1990s, further research on the Hawaz Formation done, focusing particularly on the reservoir quality. According to these investigations, the Hawaz Formation has a total hydrocarbon thickness of 190 m, a water saturation of up to 45%, and 12% porosity (Kamel & Kashlaf, 2015; Mohamed, 2016). Abouessa and Morad (2009) looked at how the diagenesis processes affected the Hawaz Formation's reservoir quality. They found that mesodiagenesis and telodiagenesis, which took place at a burial depth of 4 km, were the main diagenetic processes that affected the formation. Additionally, rather than the cementation processes, the chemical and physical compaction of the grains was a factor in the porosity reduction. Ghnia et al. (2017) classified the Hawaz sandstone based on the Th-K concentrations and depending on the clay contents within each lithofacies of the Hawaz Formation. They revealed that the major forms of clay that regulated the Hawaz reservoir's quality were illite and mixed clays, meanwhile, kaolin minerals making up a very small portion.

2.Aim

Despite the fact that the mesodiagenetic processes had a significant impact on lowering permeability, the involvement of the eodiagenetic processes of which bioturbation is the most significant was also crucial. This research attempted to recognize, define, and describe the various ichnofacies of the Hawaz Formation independently before estimating their impact on the reservoir quality and the precipitation of authentic minerals that might cause reservoir destruction.

3.Methodology

The H27 well's cored section was used initially to determine the ichnofacies and diagenetic characteristics of the Hawaz Formation. The porosity and permeability of the formation were investigated using forty 1-inch core plug samples. The stratigraphic log of cored section have been measured, sampled, and reported in detail. Eight oriented thin sections were investigated to a petrographic evaluating of the detrital grain types, cement, matrix, porosity, and authigenic clay precipitation. H. -E. Reineck (1963) and later Taylor and Goldring (1993) suggested a visual evaluation to estimate the degree of bioturbation. This graph was dubbed the bioturbation index (BI), and it assessed the intensity of bioturbation as well as the visibility of primary sedimentary formations. The BI ranged from 0 (nonbioturbated facies) to 6 (totally bioturbated facies; Table 1).

Table 1: Bioturbation index based on the intensity and the destruction of the primary sedimentary structures (H. E. Reineck, 1963; Taylor & Goldring, 1993)

Grade	Bioturbation %	Description
0	0	Unbioturbated
1	1-5	Very slightly bioturbated
2	5-30	Slightly bioturbated
3	30-60	Moderately bioturbated
4	60-90	Highly bioturbated
5	90-99	Intensely bioturbated (some physical structures still discernible)
6	100	Completely bioturbated

4.Facies analysis and Petrography of Hawaz Formation

The examined Hawaz Formation may be classified into bioturbated and non-bioturbated lithofacies based on its lithological and ichnological properties, as illustrated in Figure 2. Also, these Ichnofacies showed a different Petrographically characteristics as it will be discussed in the following sections.

4.1. Bioturbated facies

The bioturbated facies include the proximal *Skolithos*, *Skolithos*, and *Cruziana ichnofacies*. These ichnofacies have been deposited in a variety of depositional settings, ranging from proximal fluvial-tidal channels to the transitional shoreface-offshore environment.

4.1.1 Proximal *Skolithos* ichnofacies.

Description

Skolithos in this ichnofacies are vertical, cylindrical, branched, and/or U-shaped dwellings, as well as equilibrium and escape traces. These borrows are generated by suspension feeders, surface-detritus feeders, and/or passive carnivores. The *Skolithos* are slightly massive and may develop to be 1 foot long and more than 0.25 inches in diameter (see Figure 3 A). The *Skolithos* burrows are occasionally filled with clean white, coarse-grained sand (see Figure 3 B). The rate of bioturbation is slightly and moderately bioturbated, with a bioturbation index ranging from 2 to 3 (see Figure 2).

Petrographically, the Proximal *Skolithos* ichnofacies is made up of fine-grained reddish brown to brown quartzitic sandstone. Quartz was the most abundant grain mineral, accounting for 70% of total grain counts (Table 2 and Figure 4 A). The feldspar content ranged between 0.5 and 10%. The sandstone from these facies is classified as sub-mature to mature quartz arenite based on this petrographic examination. The reservoir quality was poor in the Proximal *Skolithos* sandstone ichnofacies. Where, the porosity was nearly identical to the cross-bedding facies, with up to 25% reported as intergranular porosity, although the permeability was notably low.

Interpretation

Skolithos can be found in both marine and terrestrial environments, however they are more commonly found in high-energy marine environments such as nearshore marine facies (Droser, 1991; Gregory, Campbell, Zuraida, & Martin, 2006). This is evidenced by very fine-grained, thin, uniform sedimentation layers. Intertidal to subtidal facies are interpreted for proximal *Skolithos* ichnofacies. The *Skolithos* are the dwelling borrows of suspended feeders and/or passive carnivores in the foreshore to upper shoreface setting (MacEachern et al., 2012; Mángano & Buatois, 2004). Despite the unstable substrate instability of nonbioturbated facies, the huge and clear sand-filled *Skolithos* showed long-term substrate stability (Desjardins, Gabriela Mángano, Buatois, & Pratt, 2010), and that could allow to more authigenic clays to accumulate.

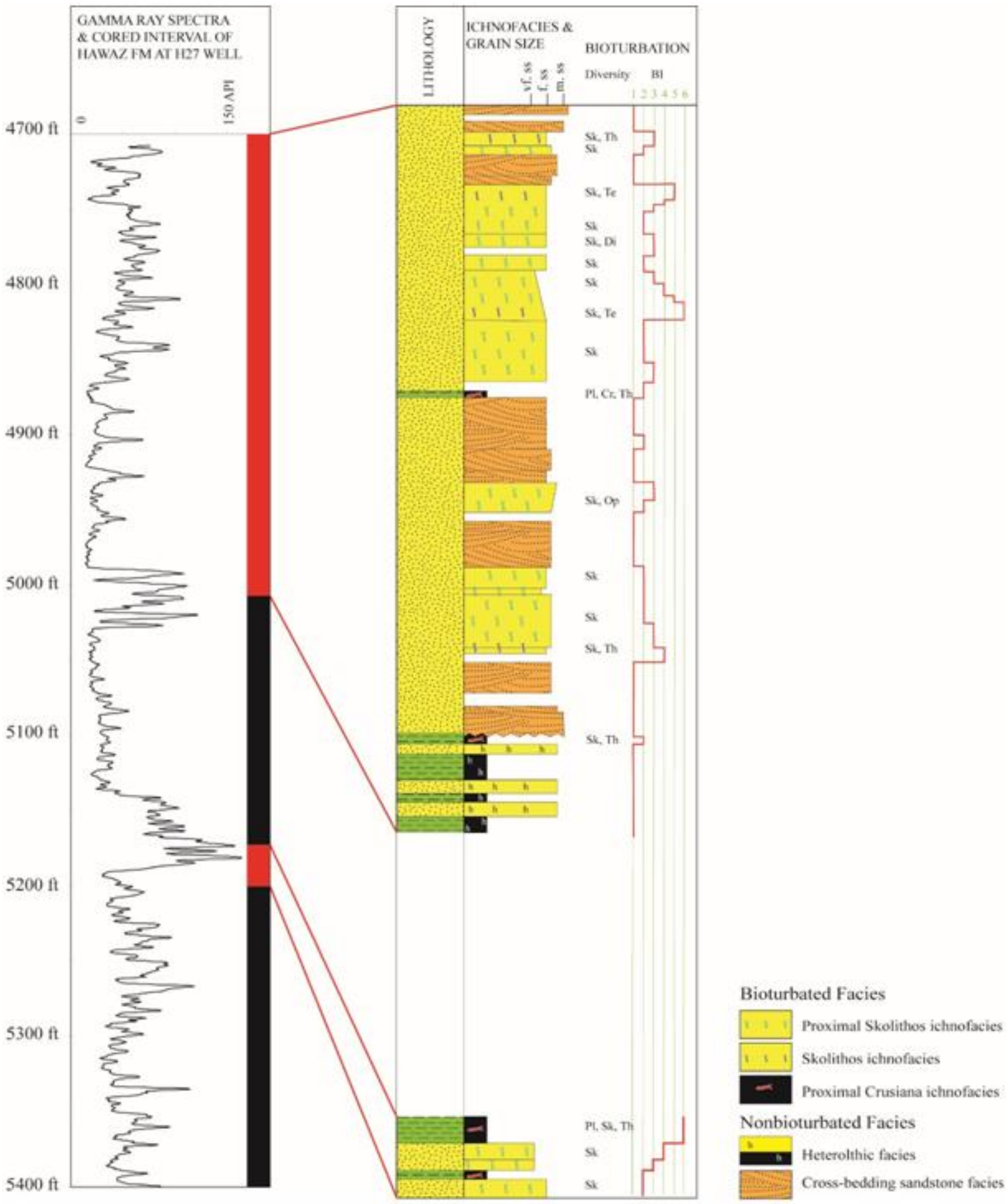

Figure 2: Description summary of Hawaz core at H27-well as bioturbated and nonbioturbated facies. BI = Bioturbation Index, Sk= *skolithos*, Th =*Thalassinoides*, Pl = *Planolites*, Op = *Ophiomorpha*, Di = *Diplocraterion*, Cr = *Cruziana*, and Te = *Teichichnus*

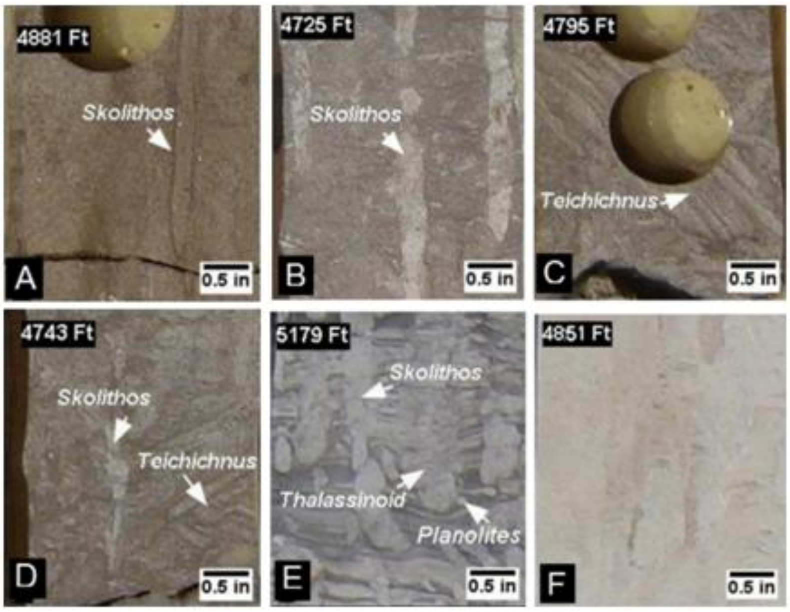

Figure 3: Photo of slabbed core samples showing *Skolithos* filled with brown (A) and white sands (B) or within a white sand (F) from proximal *Skolithos* ichnofacies. *Teichichnus* and *Skolithos* from *Skolithos* ichnofacies (C and D). *Thalassinoid*, *Planolites*, and *Skolithos* from *Cruziana* ichnofacies (E).

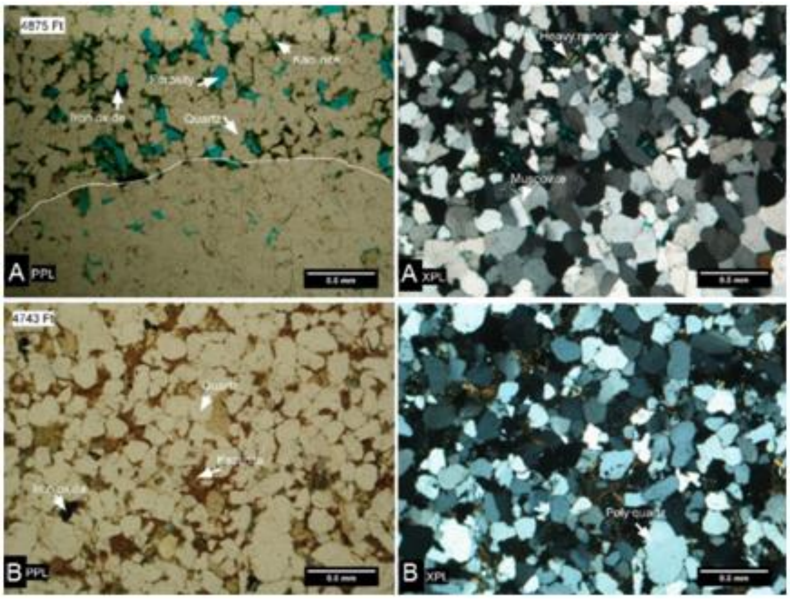

Figure 4: Microphotograph of a thin section showed the grain type, matrix, and porosity of Hawaz Formation. (A) Proximal *Skolithos* ichnofacies, the white line indicates the approximate extent of the *Skolithos* ichnogenus (B) *Skolithos* ichnofacies. PPL = plane-polarized light XPL = cross-polarized light.

4.1.2 *Skolithos* Ichnofacies

Description

Vertical to semi-vertical *Skolithos* borrows are common and abundant in these facies. Other ichnogenera such as *Teichichnus*, *Planolites*, and *Thalassinoides* were detected in these facies, as shown in Figure 3 (C and D). *Skolithos* ichnofacies is mostly dirty, brown, mottled, massive, and very fine-to fine-grained sandstone. In addition to abundant *Skolithos* borrows, frequent Stylolite digenetic structures have been found within the facies. The rate of bioturbation within these facies is moderate to intense, ranging from 3 to 6 on the bioturbation index (see Figure 2).

Based on the modal analysis of these facies, the sandstone was classed as quartz arenite and texturally identified as sub-mature sandstone. The content of feldspar, mica, and heavy minerals increased as well. The intergranular porosity of *Skolithos* ichnofacies in the examined samples was 6%. The *Skolithos* sandstone ichnofacies have a high matrix content facies (about 15%; Table 2 and Figure 4 B).

Table 1: The main grain mineral components, matrix, and porosity of the studied samples from the H-27 well showed quartz arenite composition for most sandstone samples. Also, the porosity of the cross-bedding and most proximal *Skolithos* ichnofacies were high as compared to the *Skolithos* and heterolithic facies.

Depth	Facies	Quartz	Feldspar	Lithic Fragments	Mica	Heavy minerals	Matrix	Porosity%
4895'	Cross-bedding	68	1	0	2	2	6	21
4910'	Cross-bedding	68	0.5	0	1	0.5	5	25
4975'	Cross-bedding	72	0.5	0	0.5	0	1	26
4995'	Heterolithic	35	8	25	15	2	10	5
4834'	Proximal *Skolithos*	63	10	0	5	2	15	5
4875'	Proximal *Skolithos*	68	2	1	4	1	5	20
4940'	Proximal *Skolithos*	70	0.5	0	2	0.5	2	25
4743'	*Skolithos*	70	3	0	5	1	15	6

Interpretation

In comparison to the proximal *Skolithos* ichnofacies, the *Skolithos* ichnofacies are considered as deeper and calmer facies. The presence of fine grain as a matrix, such as mud or silt, indicates these facies were deposited within the intermediate shoreface environment. The presence of shale layers in this facies suggests that the deposition environment of this facies was calm. The shape of the vertical borrows in the *Skolithos* ichnofacies is characterized for deposit-feeding organisms and interpreted as dwelling borrows in the upper part of the facies, whereas Teichichnus' downward substrate shift was most likely caused by a deepening event (Rodrguez-Tovar & Uchman, 2010). Furthermore, the intensity and diversity of ichnofossils may be increased due to the quietness of water energy or the preservation potential of the traces.

4.1.3 Proximal *Cruziana* ichnofacies.

Description

Cruziana ichnofacies frequently exhibits and associated with a good preservation on the surface sedimentary structures planes as well as surface trace fossils. These ichnofacies have black to brown tone bands of laminated shale. These bands are also intercalated with tiny laminations of very fine-grained sandstone and siltstone. The facies are characterized by intensive to moderate bioturbation; the degree of bioturbation within these facies ranges from 2 to 3 on the bioturbation index scale (see Figure 3 E). *Cruziana* trace fossils were more prevalent in fine-grained sandstone and siltstone, whereas *Skolithos* and *Thalassinoides* ichnofossils were more limited to shale band layers.

Interpretation

Cruziana ichnofacies is a shallow marine environment that is deep enough to be below fair wave weather base but above storm weather wave base (Pemberton et al., 2012). *Cruziana* trace fossils have been discovered in both marine and freshwater strata. Shallow horizontal troughs and tunnels with locomotion and feeding traces, especially *Cruziana*-Trilobite feeding traces, are typical ichnofossils. These facies can be attributed to the lower shoreface and/or the transition to offshore settings based on grain size, primary sedimentary structure, and trace fossil richness. The persistence of horizontal traces suggested a state below the fair wave base. As a result, deposit feeders predominate, with a little contribution from suspension and graze feeders. Storm episodes were inferred from the silty and sandy-grained sediments.

4.2. Nonbioturbated facies

The Nonbioturbated facies consists of cross-bedding sandstone and heterolithic facies. These ichnofacies were deposited in a variety of environments, ranging from proximal fluvial-tidal channels to the transitional shoreface-offshore setting.

4.2.1 Cross-bedded Sandstone Facies

Description

The Hawaz Formation's sandstone cross-bedded facies are fine-to medium-grained sandstone (Figure 5 A, B, and C). The sandstones are well-sorted and brown in color. It is classified lithologically into massive and cross-bedded strata. Within these facies, there are two forms of cross-bedding stratification: planer and trough bedding stratification. Mud clasts were found on occasion within the massive sandstone layers (see Figure 5 D). The facies are distinguished by very low to nonexistent bioturbation activities, with degree of bioturbation ranging from 0 to 1 on the bioturbation scale. The quartz accounted for more than 68% of the total count and had a rounded to sub-rounded form (Figure 6 A; Table 2). With a broken surface and evidence of grain alteration, the feldspar content reached up to 2%. Mica and heavy minerals were the minor grain components of the cross-bedding sandstone. As a result, the cross-bedding sandstone is classified as quartz arenite. These sandstone facies have been categorized as supper-mature sandstone based on visual assessment of grain sorting, matrix, and grain morphology. The intergranular porosity was very high, ranging from 21 to 26%. Within the facies, rarer stylolite diagenetic characteristics can be observed.

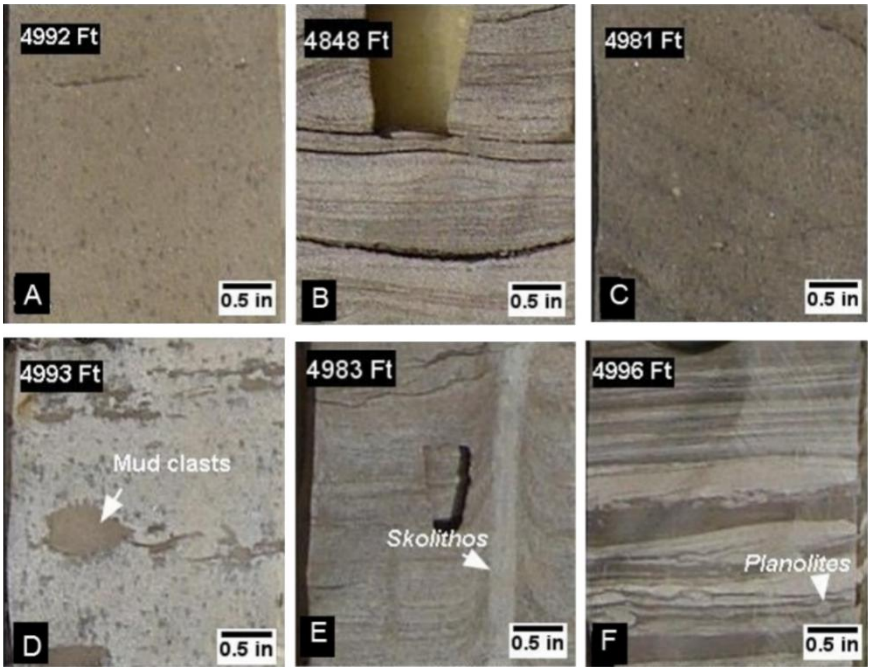

Figure 5: Massive bedding (A), cross-bedding (B), low-angle cross-stratification (C), mud clast (D), and continuous shifting substrate of *Skolithos* (E) and Planolites at heterolithic facies (F)

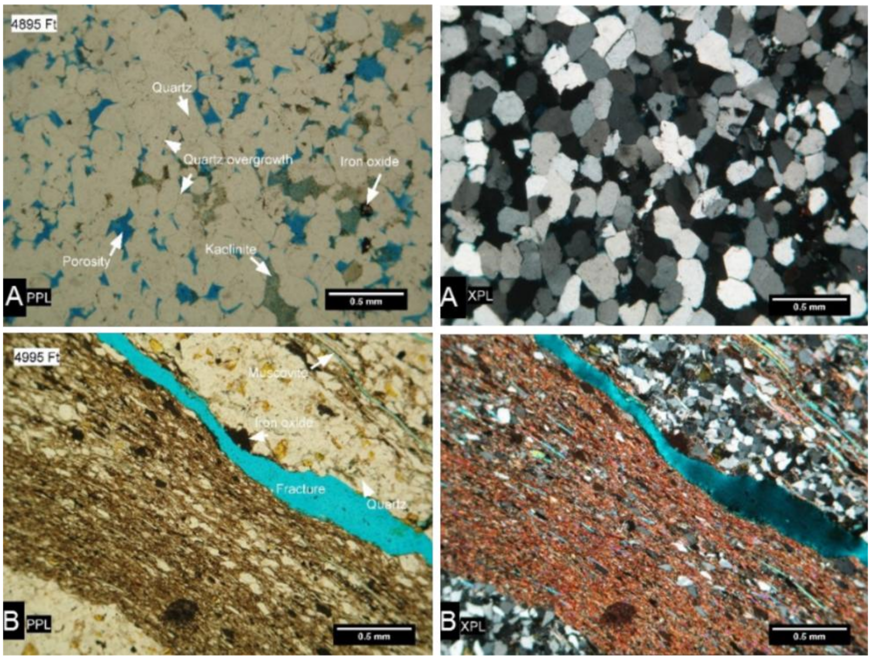

Figure 6: Microphotograph of a thin section showed the grain type, matrix, and porosity of Hawaz Formation (A) Cross-bedding sandstone facies, (B) heterolithic sand-shale facies. PPL = plane-polarized light XPL = cross-polarized light

Interpretation

The low BI, as well as the variety of trace fossils, imply severe environmental conditions and/or a limited preservation capability of traces (Pemberton et al., 2012). The substrate shift implies a quick upward migration of the trace-maker in unstable environmental settings (Figure 5E). The occurrence of cross-bedding structures in these facies with relatively high textural maturity suggests high-energy environment conditions. Dunes or ripple migration movements can cause planer and trough cross-bedding stratification. Mud clasts were also formed by a tidal inlet, which featured channel erosion at the facies' base (Uhlir, Akers, & Vondra, 1988).

4.2.2. Heterolithic Facies.

Description

Heterolithic facies comprised of two or three alternating lithotypes, the most common of which are sand and mud. The facies is composed of intercalated laminated very fine-to fine-grained sandstone and dark brown shale layers. The flaser, load-deformation, ripple marks, and lamination structures are all associated to the sandstone (Figure 5 F). These facies are notable for their extremely rare bioturbation characteristics. The most prevalent ichnogenera identified in heterolithic facies are *Thalassinoides* and *Planolites* (Figure 5F), and the estimated bioturbation index in the Heterolithic facies is between 0 and 3. Only one slide from this ichnofacies was studied. The lithic fragments and mica components were much greater than the other investigated ichnofacies, with 25% and 15%, respectively (Figure 6 B; Table 2). Quartz, on the other hand, has the lowest (about 35%) among the other examined facies. These grains ranged from subangular to angular, whereas mica grains were elongated angular in shape. The fractural porosity measured up to 0.4 mm wide.

Interpretation

The presence of flaser and ripple marks, as well as the alternating of distinct lithotype laminations, which define the heterolithic facies, allow us to interpret these facies as shoreface facies with other materials supplied by streams on a regular basis. The load-deformation structures suggested aggressive sand sedimentation on unconsolidated clay, whereas the relatively low bioturbation intensity suggested an unsuitable substrate for the trace-makers.

4.3 Ichno-sedimentological model of Hawaz Formation

In 1967, Seilacher established the concept of ichnofacies. According to Pemberton (1992) and Pemberton, Frey, Ranger, and MacEachern (1992), this ichnofacies concept explains how trace-makers adjust to the substrate consistency, food supply, hydrodynamic energy, salinity, sedimentation rate, erosion, turbidity, temperature, and oxygen levels. The sandy, siliciclastic Hawaz Formation substrate has been suggested with a number of ichnofacies based on the results of this study. These ichnofacies often represent the actions of the trace-maker and the degree of preservation of the traces. These ichnofacies correspond to a certain siliciclastic habitat boundary, as seen in Figure 7. The suggested ichnofacies of the Hawaz sandstone are thought to cover the backshore-foreshore regime and the fair-weather wave base (FWWB), according to the findings of this study. These ichnofacies also correspond to a siliciclastic substrate between *Psilonichnus* and *Cruziana* ichnofacies.

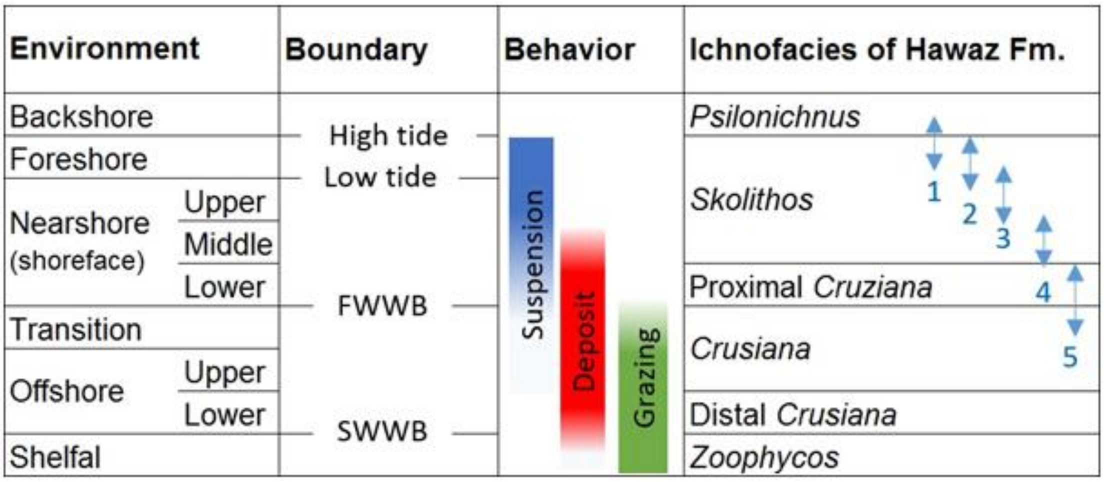

Figure 7: Vertical association of the ichnofacies and their relation to the Hawaz Formation's depositional environments adopted and modified from Pemberton (1992). 1 = Cross-bedding facies, 2 = Heterolithic facies, 3 = proximal *Skolithos* ichnofacies, 4 = *Skolithos* ichnofacies, and 5 = *Cruziana* ichnofacies. FWWB = Fair-weather wave base, SWWB = Storm-weather wave base

5.Reservoir Quality and HawazIchnofacies

Diagenesis is the term used to describe all physical and chemical processes that happen to sediments and sedimentary rocks nearly after deposition and before metamorphism, or in other word, during the period between deposition and weathering. Diagenesis processes are categorized into three groups: eodiagenesis, mesodiagenetic, and telodiagenesis. Rock characteristics like porosity, permeability, and the degree of lithification are gradually affected by diagenetic processes. The quality of the Hawaz reservoir was significantly impacted by kaolinization, pyrite precipitation, and mechanical compaction during the eodiagenesis, claim Abouessa and Morad (2009). The reservoir quality was also more negatively impacted by mesodiagenetic dickitization, illitization, chemical compaction, quartz overgrowth, and siderite precipitation.

In Hawaz Formation, however, throughout the eodiagenesis process, the bioturbation plays a major influence in the reservoir porosity and permeability. The abundance of bioturbation of the Hawaz sandstone demonstrates the fundamental relationship between the reservoir characteristics and the rate of bioturbation. The cross-bedding facies has demonstrated that the higher textural maturation of sandstone is associated with low authigenic and/or endogenic clay concentrations, degree of sorting, sphericity, and roundness. The porosity-permeability plots of each Hawaz Formation sample under investigation reveal a minor variation in porosity among the sandstone strata (A porosity of between 11% and 20% is possible; Figure 8). The permeability measurements, however, show a significant range of variation. According to the porosity-permeability plots, the permeability of the dense bioturbate dichnofacies of the Hawaz Formation decreased significantly, (ranging from 0.1 mD to 6 mD), while the permeability of the nonbioturbated ichnofacies ranged from 88 to 948 mD (see Figure 8).

The worst case scenario for the destruction of reservoir permeability, according to Abercrombie, Hutcheon et al. (1994), can occur during mesodiagenesis as a result of the breakdown of smectite into illite (pore-lining clay) and the precipitation of dissolved silica as quartz overgrowth to block the empty reservoir pores. Based on our instigations the only places that would enrich with clay precipitations are the quieter environments associated with the *Skolithos* ichnofacies. In Figure 3 A, the *Skolithos* vertical borrows have been filled by cleaner sand grains that were ultimately cemented completely by silica overgrowth. The substrate of the *Skolithos*' trace-maker might be enhanced to be suitable to live, despite the concerning the mud content as compared to the surrounding area where the pore was filled by clays. Later, during the mesodiagenesis, the cleaner *Skolithos* vertical borrows become the favorable passage to the silica-rich fluids, which would precipitate there when its solubility decreases.

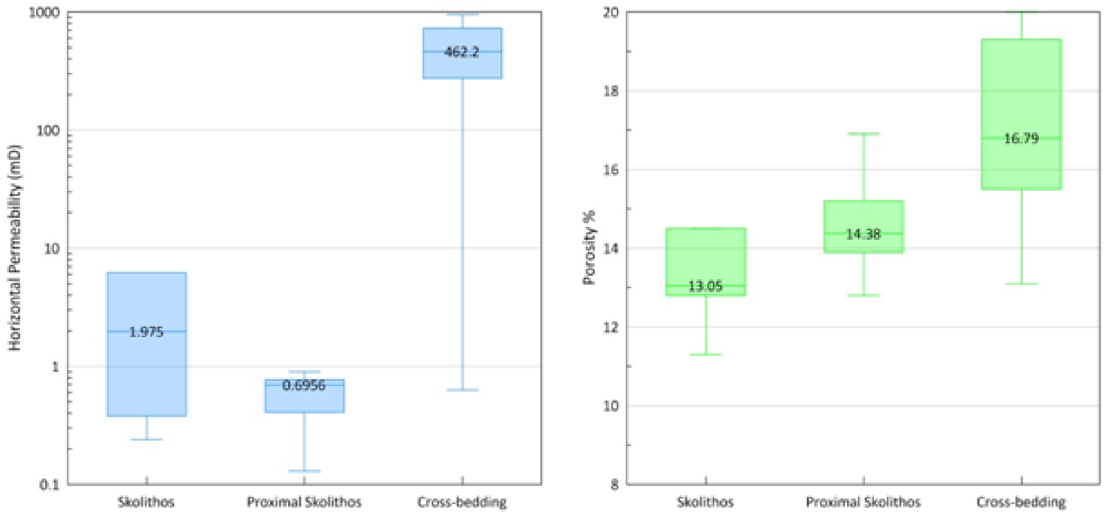

Figure 8: Porosity and permeability plot of the core plugs collected from the cross-bedding facies, proximal *Skolithos* ichnofacies, and *Skolithos* ichnofacies. The number inside the box is the mean of the data; the box top and bottom are the quartile 75% and quartile 25%, respectively; and the top and the bottom line are the max and min, respectively

6.Conclusion

To determine the reservoir quality at the H-27 well, NC115 block in the research region in the Murzuq Basin SW Libya, the ichnofacies of the Hawaz Formation were examined. This study's facies analysis allowed the examined Hawaz Formations to be lithologically separated into the two primary facies of bioturbated and nonbioturbatedlithofacies. The nonbioturbated facies are sandstone crossbedding and heterolithic facies, whereas the bioturbated facies are the proximal *Skolithos*, *Skolithos*, and *Cruziana* ichnofacies. These ichnofacies have been deposited at broad depositional settings from the proximal fluvial-tidal channels to the transitional shoreface-offshore environment.

The sandstone was enumerated as quartz arenite and showed a similarity in porosity (up to 25%) for both cross-bedding and proximal *Skolithos ichnofacies*. Also, the measured porosity from core plugs was around 10 to 20%. However, the nonbioturbated facies was impermeable (up to 6 mD) as compared to the cross-bedding facies, which ranged between 88 and 948 mD. These ichnofacies have been deposited in a variety of depositional environments, including the transitional shoreface-offshore environment and proximal fluvial-tidal channels.

This interstation is strongly supported by the facies' high textural maturity and rarity of nonbioturbation. In contrast to the bioturbated sandstone facies, which exhibits a striking drop in permeability of around 6 mD at its maximum, the cross-bedding sandstone has exceptional permeability of up to 950 mD. Both types of sandstone were impacted by the mesodiagenetic processes, which ultimately served as a key factor in the reservoir quality's most detrimental effects.

The intensity and diversity of bioturbation, as well as the formation of authigenic silica and clay minerals in the depositional environment's quiet conditions, had an impact on the reservoir quality beforehand.

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