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Sedimentological and Depositional Environment Architecture Lower Paleozoic of Hawaz Formation, Murzuq basin, Libya.

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Abstract
The present study focuses on the vertically stacked pattern of the Hawaz Formation in Murzuq Basin, west Libya. It is based on the conventional cores analysis and wireline log interpretation from wells T01, T02, T03 and T04. The Hawaz sandstones is considered the main reservoir target in block NC-186. The Paleozoic Hawaz Formation represents the Middle Ordovician Paleozoic age. Consisting of up to 95% sandstones it's classified in four lithofacies (H1-H4) based on sedimentary textures, sedimentary structure and biogenic features. Hawaz Formation has been deposited in shallow marine environments affected by wave and storm actions in variable energy regimes as the relative sea-level rose. The Hawaz sandstone occasionally invaded by thin beds of shale denoting in low energy marine setting characterized by slow rates of sedimentation whereas clean sandstone suggests a relatively high energy regime. Vertical stacking patterns of sandstone reservoir followed by shale beds forming coarsening upward units as changes in sea level. Also, the presence of trace fossils suggests the deposition in shallow, low-energy marine condition.

Keywords: *Libya, Murzuq, Hawaz Reservoir, Middle Ordovician, Lithofacies.*

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I. Introduction

Murzuq basin is located in SW Libya and forms one of several intracratonic sag basins. The Murzuq basin lies between the Sahara shield in the south and was separated from the Tethys Ocean by the Gargaf arch (Selley,1976; Bellini and Massa,1980). It is located between three prominent tectonic elements: Al Gargaf uplift in the north, Tibesti-Haruj uplift in the east and the Precambrian Hoggar in the south which extends into Algeria and Niger (Figs. 1A). The present-day maximum sedimentary thickness in the Murzuq basin is about 4000 m (Davidson et al., 2000). Its elliptical in shape, 800x800 Km^2, covers an area of over 350,000 km^2. It is a large intracratonic sag basin located in the North African Platform, which occupies a part of southwest Libya and extends southwards into Niger. In their depocenter, it reaches more than 11,000 feet (3700 m) in depth (Shalbak,2015). The present study is concession of Block NC-186 which is located in the northeast of the Murzuq Basin. The block is located in the northwestern part of the basin, which covers an area of about 8,660 km2, at approximately between latitudes 26° 00' and 27° 00', longitudes 12° 00' and 15° 00' (Fig. 1). Previous studies of the area from many international and local companies resulted from many wells that have been drilled and distributed in the block. Most wells encountered oil in Ordovician and/or Devonian sandstone reservoirs (Swedan, 2003). The present study is based on four wells selected from D Field in NC-186 Block in the basin, which are: T01, T02, T03 and T04 (Fig. 2).

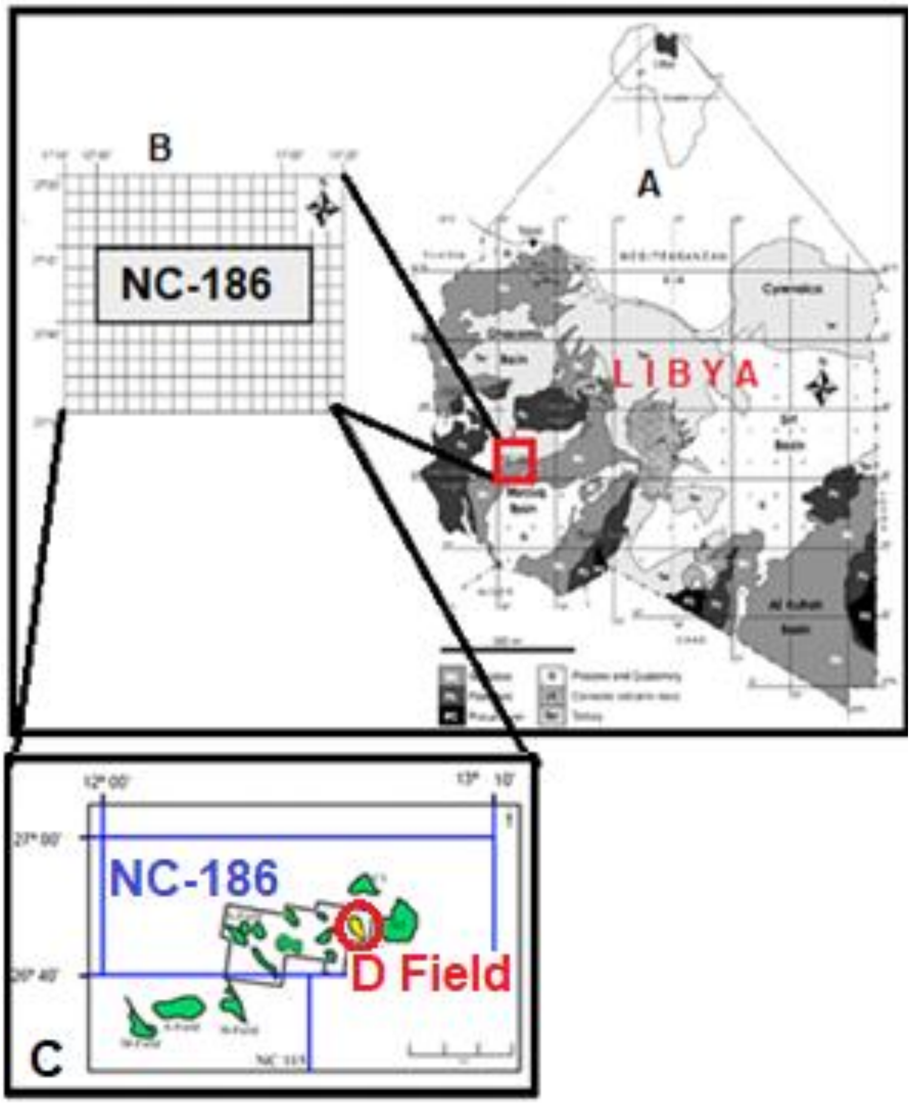

Fig.1 (A) Map of Libya showing the location the study area in NC-186 in the Murzuq Basin (after Ramos et al., 2006). (B) is the location map of NC-186 concessionand (C) location of the study area in D Field (red circle) in NC-186 concession.

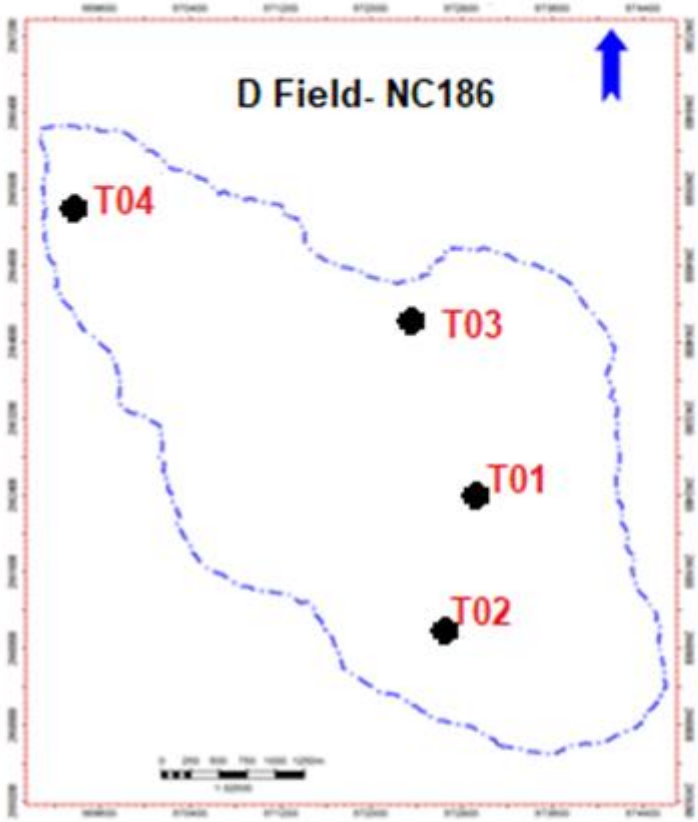

Fig.2. Location map of study selected wells (T01, T02, T03 and T04) in D Field in NC-186.

II. Database and Methodology

The data on which the present study is basedon wireline logs (mainly CAL, GR, FDC, NPHI, DT and resistivity logs) and slabbed core cuts from the sandstone reservoir of Hawaz Formation (Fig. 3). Wells (T01, T02, T03 and T04 in D Field) were reviewed (Fig. 2). Review company reports (published and unpublished). Slabbed core photographs (internal physical structures and biogenic features) are used. Impregnated sandstone thin sections to reveal the reservoir properties were investigated.

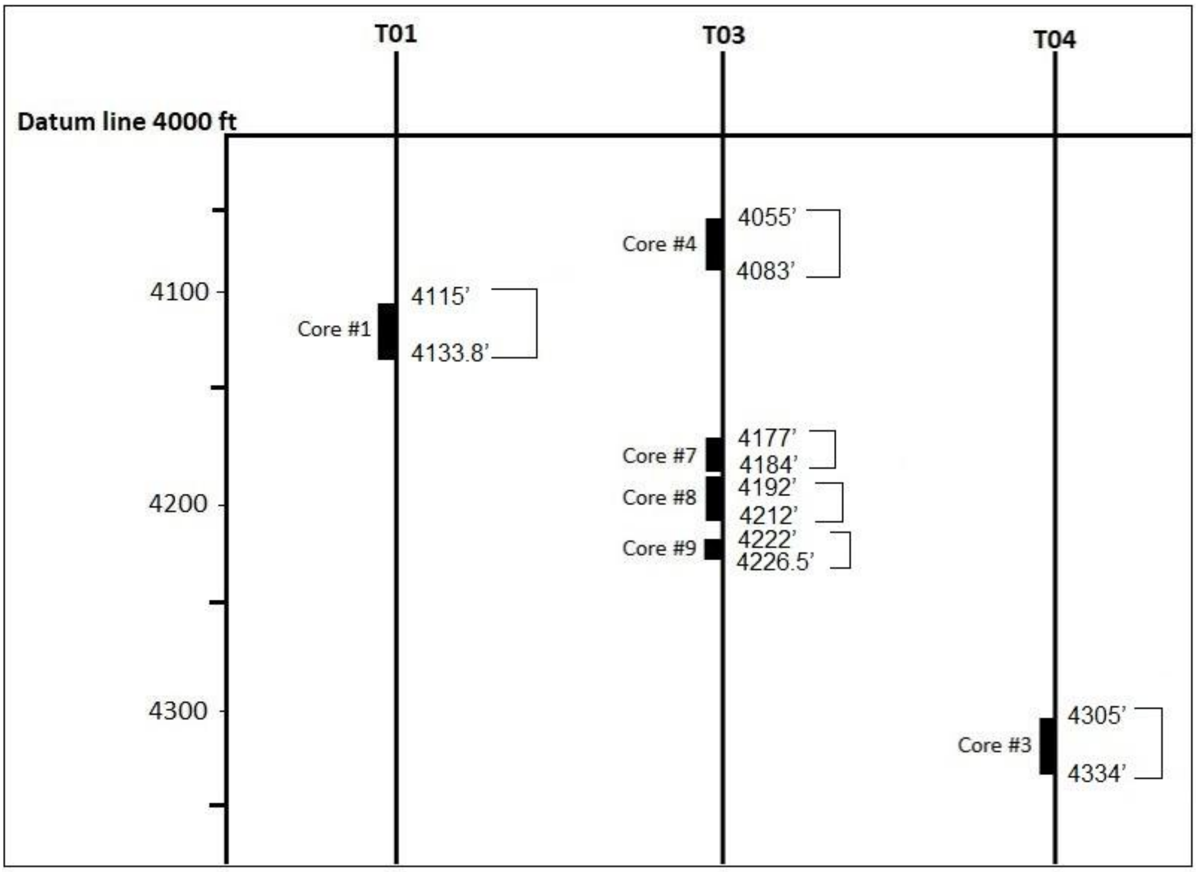

Fig.3 Shows the cut cores in different stratigraphic levels within Hawaz Formation in studied wells (T01, T03 and T04).Core #1 (4115'-4133.8'), Core #3 (4305'-4334'), Core #4 (4055'-4083'), Core #7 (4177'-4184'), Core #8 (4192'-4212'), Core #9 (4222'-4226.5').

General geologic and structural settings

The basin fill extends from the Cambrian to the Carboniferous with some Mesozoic and Cenozoic sediments are also present. Paleocurrent analysis of fluvial Cambro-Ordovician and Mesozoic sediments delineates a northerly paleoslope over the Gargaf arch (Selley,1976). Caledonian, Hercynian and Alpine tectonic events affected this basin evolution, especially Caledonian and Hercynian Orogenies (Mohamed, et.al., 2016). The major sedimentation phase in these basins lasted from the Permianor (latest Carboniferous) to the Jurassic.
The Murzuq basin is a good example of a cratonic basin (Selley,1976). It was affected by late Hercynian movements towards the end of Visean times and was totally emergent by the end of Baskirian times. Subsidence took place in late Silurian and early Devonian times. Paleocurrent analysis of fluvial Cambro-Ordovician and Mesozoic sediments delineates a northerly palaeo-slope over the Gargaf arch (Selley,1976). The Cambrian to upper Devonian succession is characterized by fluvial, estuarine-deltaic and shallow-marine deposits, whereas the lower to middle Carboniferous is dominated by open marine shales with sandstones and limestones. Ordovician sandstones of the Mamuniyat Formation (Upper Ordovician) constitute the known reservoirs in this basin.

General Tectonic framework

Libya is located on the Mediterranean foreland of the African shield, a foreland that has been the site of the deposition of vast blankets of continental debris interrupted by several marine incursions (Conant and Goudarzi, 1967). Tectonically Libya is affected by two sets of faults, which are thought to parallel the rift system in the Gulf of Suez and east Africa (Conant and Goudarzi ,1967). The geology of Libya can be divided into four depositional basins separated by major anticlinal swells (Fig. 4). These basins, of intracratonic type, have been affected by the Palaeozoic Caledonian and Hercynian Orogenies (Bellini and Massa ,1980). The Gargaf arch, Tibisti-AI Haruj uplift and Nafusa uplift represent the events that formed the structural and tectonic features in the south and northwest of Libya (Fig. 4). The sub-horizontal or gently dipping strata is faulted and the faults are most frequently parallel to the axis.

Fig. 4. Map of structure and tectonic sedimentary basins of Libya showing the location of the study area (red color) within Murzuq Basin.

Stratigraphic setting

The stratigraphic column of Murzuq basin ranges from the Pre-Cambrian to the Quaternary (Fig. 5). The maximum thickness in the basin center does not exceed 4000m (Mohammed, 2016). The Ordovician Hawaz Formation lies conformably over the Ash Shabiyat Formation. Both formations are cut by an erosive surface recognizable in outcrop and subsurface (Aziz,2000; Khoja et al., 2000). This surface is related to a glacial period lasting from Caradocian to Upper Ashgillian times. Hawaz formation has been described by Pierobon (1991) as typically consisting of cross-bedded, quartzitic sandstone with kaolinitic and thin shaley intercalations. The formation thickness ranges from 50 m (at Dor Al Qussah) to 300 m in outcrops and 30 to 230 m in the subsurface (Mohamed, 2016). Palynological studies of this formation strongly indicate a Middle Ordovician (Llanvirnian- Llandeilian) age for the whole of the Hawaz Formation (Mohammed, 2016).

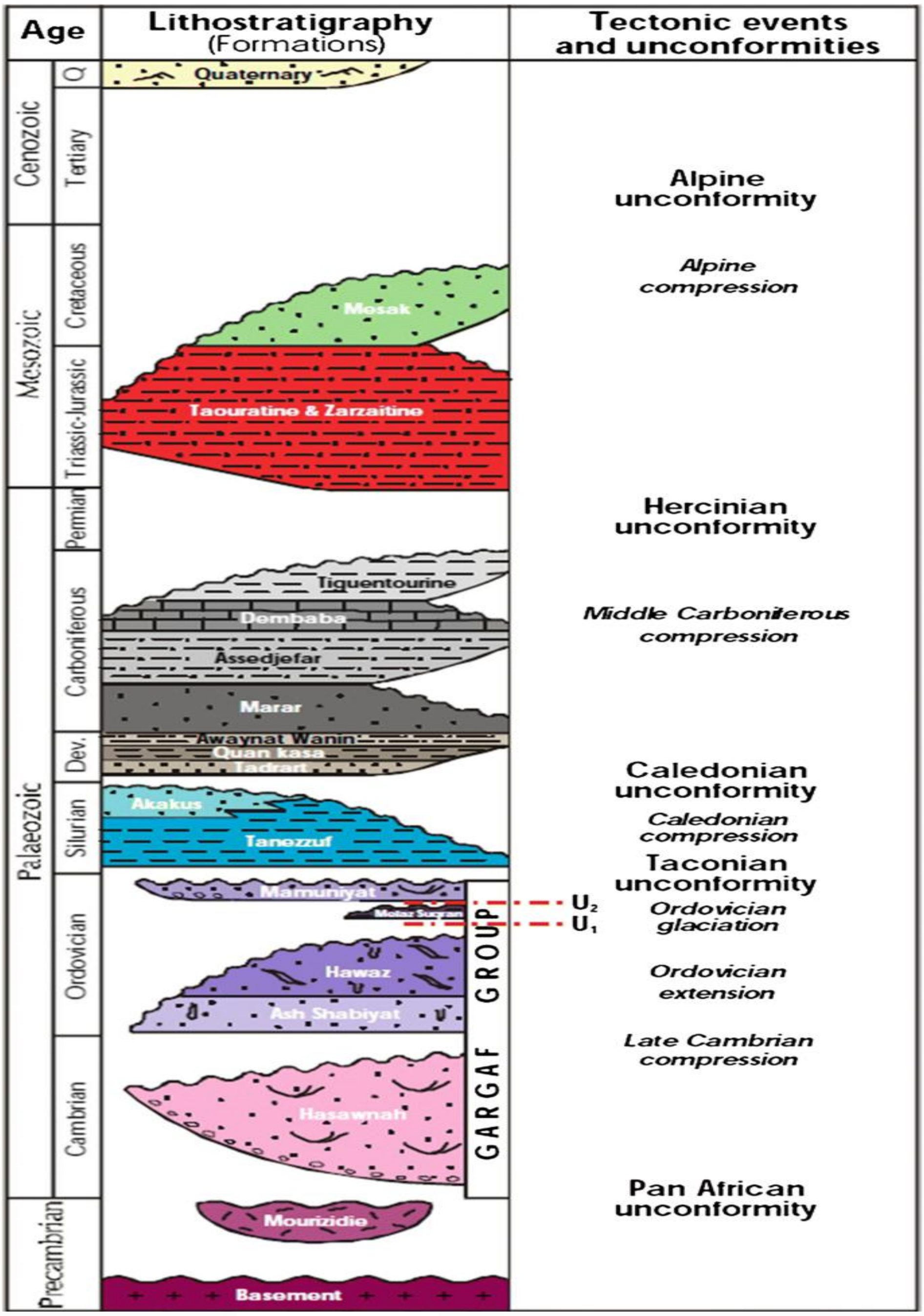

Fig.5 Stratigraphic section in the D Field in NC-186 Concession in Murzuq Basin (after Davidson et al., 2000 and modified by Mohamed, 2016).

The age of the study formations in these wells is Ordovician, Silurian, Devonian and Carboniferous age. In the present study, we will focusonOrdovician and Silurian formations in the study wells (Fig. 5 and Table1).

Table 1. Stratigraphic column of Palaeozoic (Cambro Ordovician) of the study area and illustrated the formations and it is age (From Respsol Oil Operation (ROO) and Institute Research Center (IRC)).

Era	Period / Subperiod Series	Epoch		Age	Main tectonic event	ROO Formations based on (IRC)
Paleozoic	Silurian	Lower	Llandovery	439.0	TaconIc	Tanezzuft
	OrdovIcIan	Upper	Ashgillian	443.1		Mamuniyat
						Melez Shuqran
			Caradocian	463.9		
		Middle	Llanv. / Lland.	476.1	Late Pan African	Hawaz
		Lower	Arenig	493.0		Achebyat
			Tremadoc	510.0		

III. Discussion

Sedimentary Facies

Lithofacies types were classified on the basis of bedding, composition, texture, biogenic features and sedimentary structures. This will support the sandstone reservoirs characteristics of Hawaz Formation through of the understanding the depositional environments and rock type varieties in the study area. It has been carried out on available slabbed cores and has focused mainly on lithofacies analysis, and interpretation of the core succession allowing four lithofacies type recognized based on core and electric log data from wells T01, T02, T03 and T04. These lithofacies were recognized as:

Lithofacies (H1) Small to large scale cross-bedded sandstone (H2) Burrowed sandstone, (H3) Planar and Low angle lamination and (H4) Sandy and Muddy heterolithics (Table.3). All core depths are in feet.

Description and Interpretation of Lithofacies Types

Each lithofacies is described and interpreted as follows:

1. Lithofacies (H1): Small to large-scale cross-bedded sandstones

Description

This lithofacies consists of up to 95% clean, fine to medium-grained sandstones present in cores # 7, 8 and the upper part of 9 (Figs. 6 & 7). They are very light grey to light olive grey, (light yellowish brown to yellowish brown) in color. Pyrite and argillaceous matter are rarely encountered. Scarred mudstone clasts are recorded in the lithofacies. The sedimentary structures are small to large-scale cross-bedding with mud drapes (Fig. 6). In addition, planar lamination and ripple cross-lamination are also present. Generally, bioturbation in (H1) is characterized by absent to weak with less than 5% (Fig. 7). Burrows, if present in the lithofacies are short about 5 mm long mostly horizontal and mainly Planolites burrows (Bishop et al.,2003).

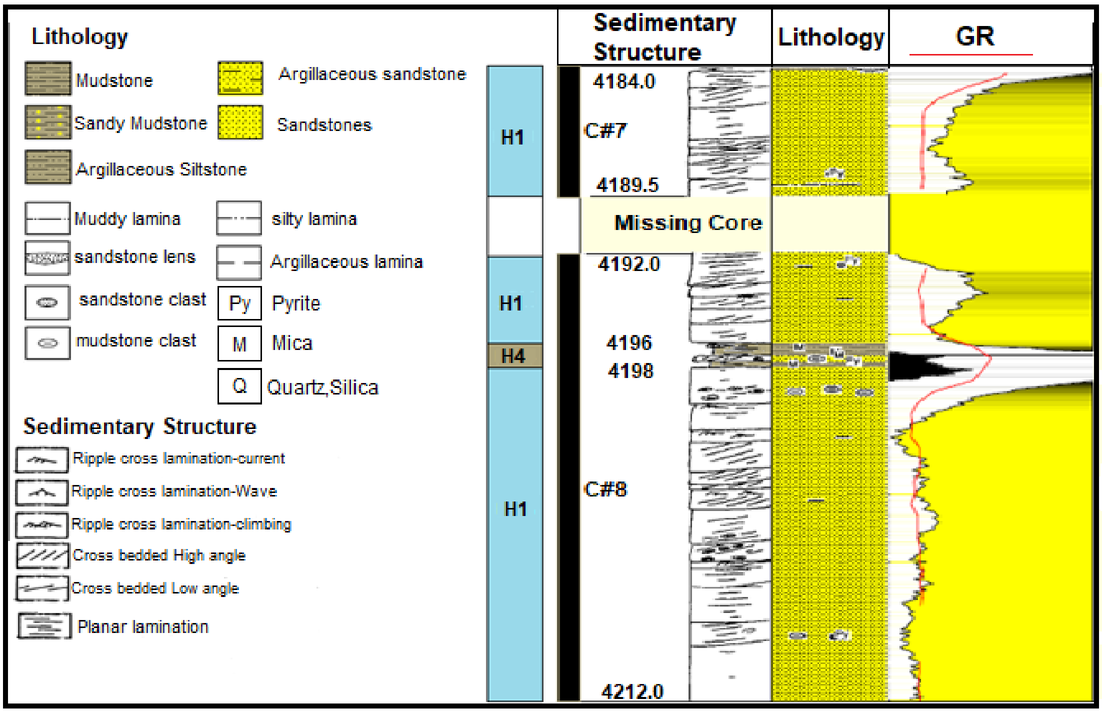

Fig.6.Sedimentological log of two cores interval; Core #7 (4184'-4189.5') and C#8 (4192'-4212') in lithofacies H1 well T03. All depthsare in feet.

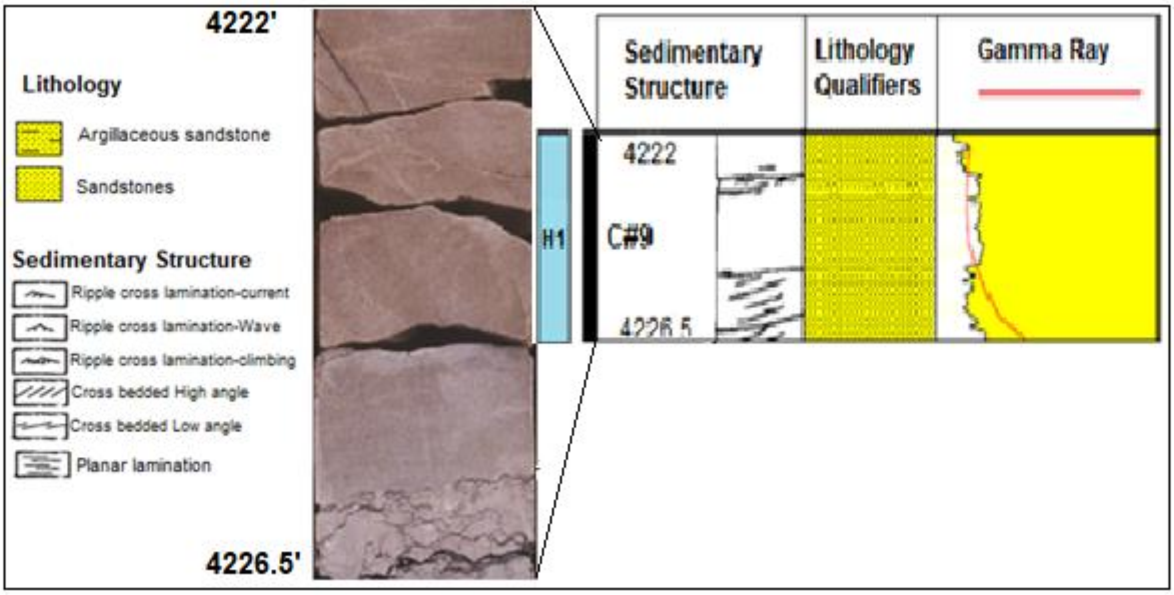

Fig.7. Sedimentological log of lithofacies H1 from the upper part of Core #9 (4222'-4226.5') in well T03. Slabbed core photograph at depth (4226.5') shows mainly clean sandstone and lowermost part have seen sedimentary structures sandstone. All depth in feet.

Interpretation

The clean sandstone of this lithofacies suggests a relatively high energy regime in which fines were carried off in suspension (Bishop et al, 2003). The lithofacies generally consists of cross-bedding and may represent beach environments. Ripples cross lamination deposited under the influence of unidirectional current flow. The currents were sufficiently powerful to erode previously deposited mud drapes. The mud drapes in the lithofacies represent fluvio-deltaic influenceddepositionalconditions (Bishop et al, 2003). These fluvio-deltaic sediments were deposited on a shoreface setting with no evidence of an erosion surface between them (may be due to gradual, low-energy progradation of the depositional system) forming a coarsening-upward unit. This was followed by a return to transgressive shelf conditions as the relative sea-level rose (Burki,1998). Planar lamination and/or parallel-laminated sand is the dominant physical sedimentary structure formed in the nearshore facies (Howard and Reineck,1981). The mudstone clasts are usually restricted to the distal parts of basin-floor fans(Talling et al., 2004; Hodgson et al., 2009; Kane and Pontén, 2012; Grundvåg et al., 2014; Kane et al., 2017; Spychala et al., 2017). Pyrite generally is usually interpreted as late diagenetic (Raiswell,1982; Longstaffe,1989). The presence Planolithes as traces suggest the deposition in shallow, low-energy marine condition (Seilacher,1967; Driese et. al.,1981).Planolithes are typically developed below normal fair-weather wave base in well sorted sands and silts in relatively quiet water conditions.

Lithofacies (H2): Burrowed sandstone
Description
This lithofacies consists mainly of fine-grained sandstones (Figs. 8, 10 and 12). Sandstones are characterized by light to moderate grey color. They are moderately argillaceous with abundant of disseminated fine-grained micaceous material. Rare small pyrite nodules are observed. Less common sedimentary structures are present in form of wave ripple cross lamination and irregular lamination in non-bioturbated interval. The lithofacies is strongly bioturbated, which has destroyed the bedding and homogenized the sediments. On the other hand, bioturbation is observed in most of the lithofacies, and it makes up from 90% to 95 % (Figs. 9, 11 and 13). High diversity of ichnofauna composed of Teichichnus, Thalassinoides, Siphonichnus and indeterminate burrows. Burrows mainly are vertical and horizontal where Skolithos, Siphonichnus burrows are dominated (Figs. 9, 11 & 13).

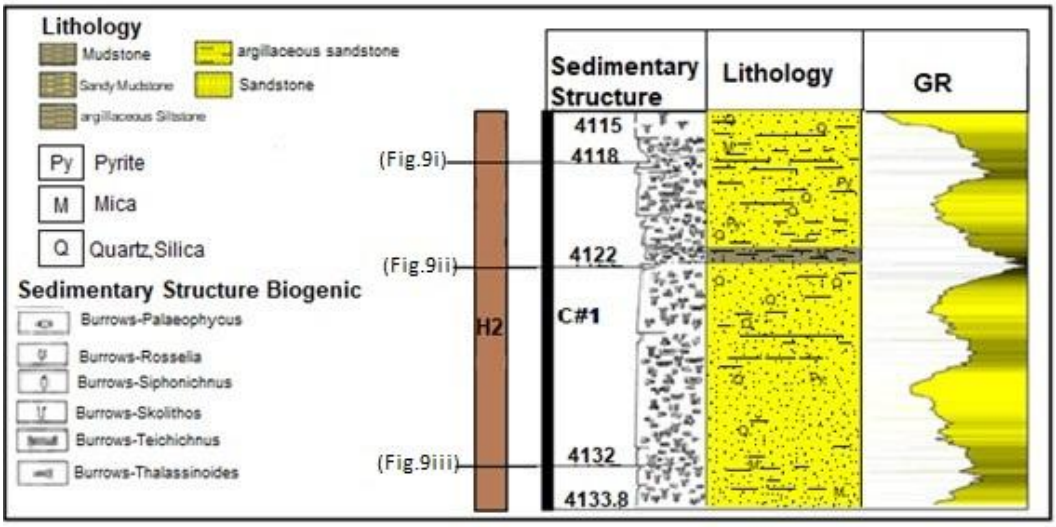

Fig.8.Sedimentological log of core #1 (4115’-4133.8’) showing lithofacies H2, well T01.

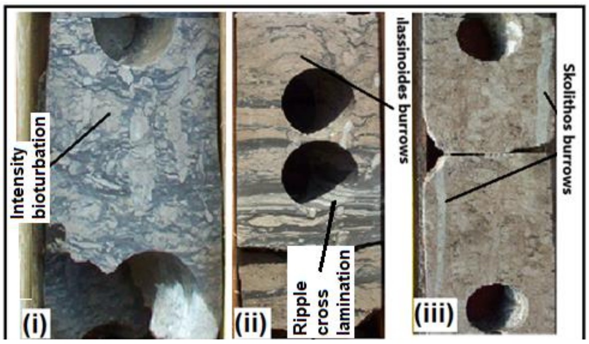

Fig.9.Slabbed core photographs of lithofacies H2 Showing (i) intensely bioturbated (Note the burrows have obliterated most of the original sedimentary structures), (ii) display the remnant sedimentary structure of ripple cross lamination due to minor occurrences of burrows and (iii) Skolithos burrows (deep vertical). (See Fig.7 for samples location).

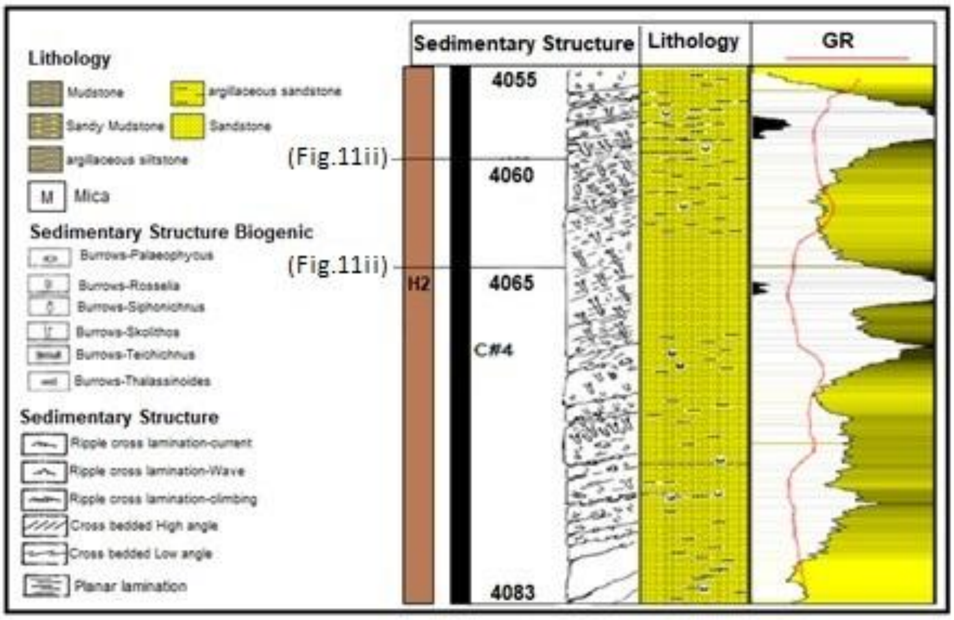

Fig.10.Sedimentological log of core #4 (4055'-4083') showing lithofacies (H2), well T03.

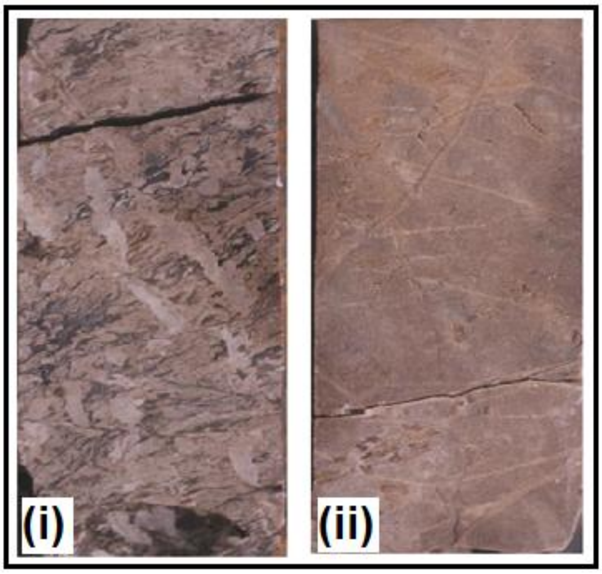

Fig.11. Slabbed core photographs of lithofacies (H2) showing (i) the intense bioturbation and scattered burrows. (ii) clean sandstone with less bioturbation and visible marks of sedimentary structure (see Fig.9 for location).

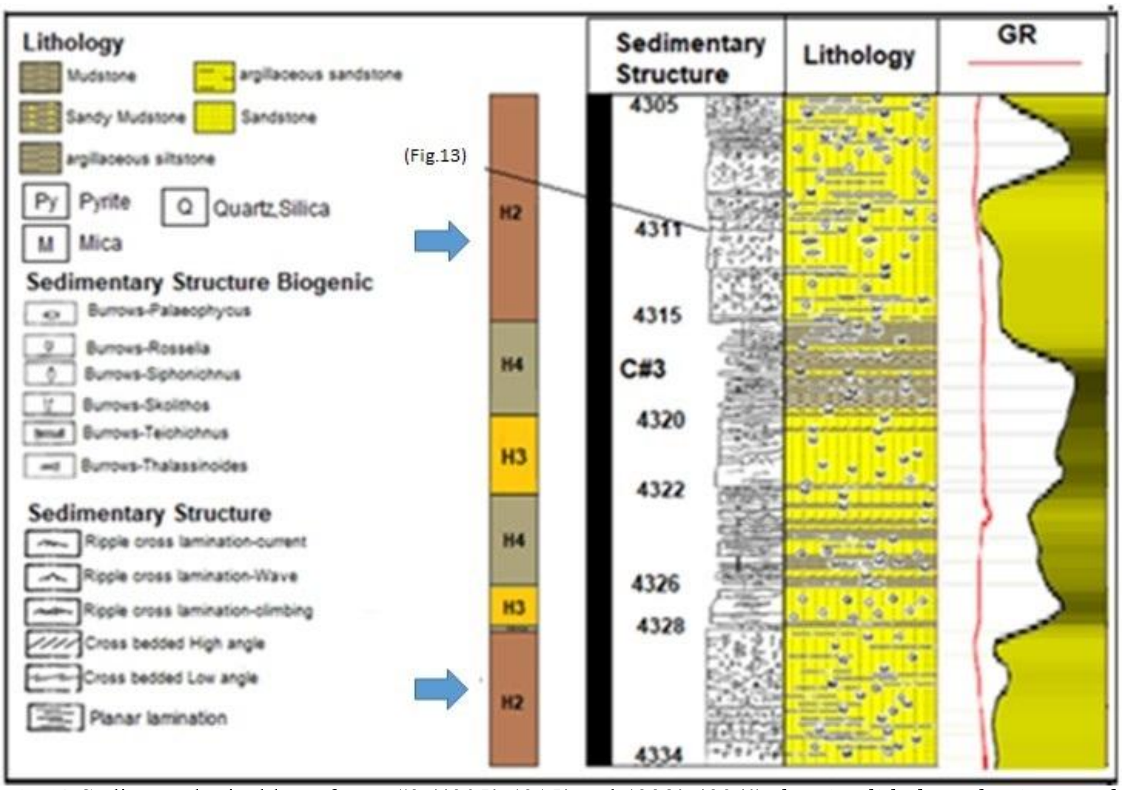

Fig.12.Sedimentological log of core #3 (4305'-4315' and 4328'-4334') showing lithology dominant and structures distribution in lithofacies H2 (arrows) in wellT04.

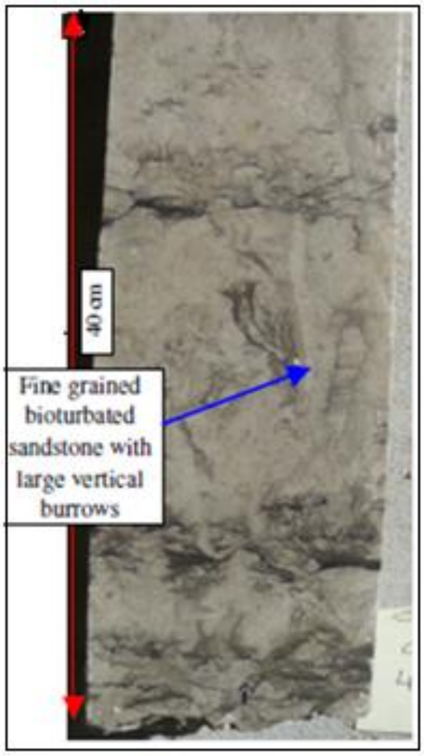

Fig.13. Slabbed core photograph of Lithofacies (H2) showing bioturbation and homogenized sediments. See deep vertical burrows (Skolithos)

(See Fig.12 for sample location).

Interpretation

This lithofacies (H2) is characterized by fine grained sandstone, where the finer sediments deposited during calm water imply deposition in an offshore quieter water shelf setting (Burki,1998). The sedimentary structures observed, such as ripples and irregular laminae (Fig.11. (ii)), suggest sedimentation under oscillatory waves or possibly wave reworking (Howard and Nelson,1982). Quartz cement is an important cement in sandstones and this cement is suggested to be sourced from pressure solution (Heald,1955; Rittenhouse,1971; Houseknecht,1984,1988; James et al.,1986; Stone and Siever,1996). The presence of mica in a non-plastic soil can have a pronounced effect on its density, this is due principally to the particle shape of the micas. Stylolites that are generally not orientated parallel to bedding are believed to have formed as a result of tectonic compression (Railbeck and Andrew,1995). The argillaceous content and high-density ichnofauna imply that deposition occurred in a moderately low energy marine setting characterized by generally slow rates of sedimentation environment (Churchill and McDougall,2003; Bishop et al,2003). 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 (Alkhalas,2005). Bioturbation is most likely to be abundant where rate of sedimentation is low (Allen,1965). Bioturbation increases away from the shore as water depths increase and sediment becomes finer-grained (Burki,1998) (Figs.11 (i) and 9). These trace fossils are indicative of slow but continuous sedimentation.

Lithofacies (H3): Low angle planar laminated and current ripple lamination sandstone
Description

The lithofacies consists of (90-95 %) very fine to fine grained, well sorted and commonly micaceous sandstone (Fig. 14). It is varying in color encountered from very light grey to light olive grey to very light olive grey sandstone. The color of argillaceous sandstone is medium dark grey. Sandstone interbedded with thin beds of argillaceous mudstone (Fig. 14). This lithofacies is characterized by low angle planar lamination and wave and mud drapes current ripple, climbing mega ripple cross lamination. The sandstone locally shows prominent hummocky cross-stratification, defined by mud drapes in lithofacies. Bioturbation are weak about 5-10% represented in Skolithos and Planolites trace fossils (Fig. 15).

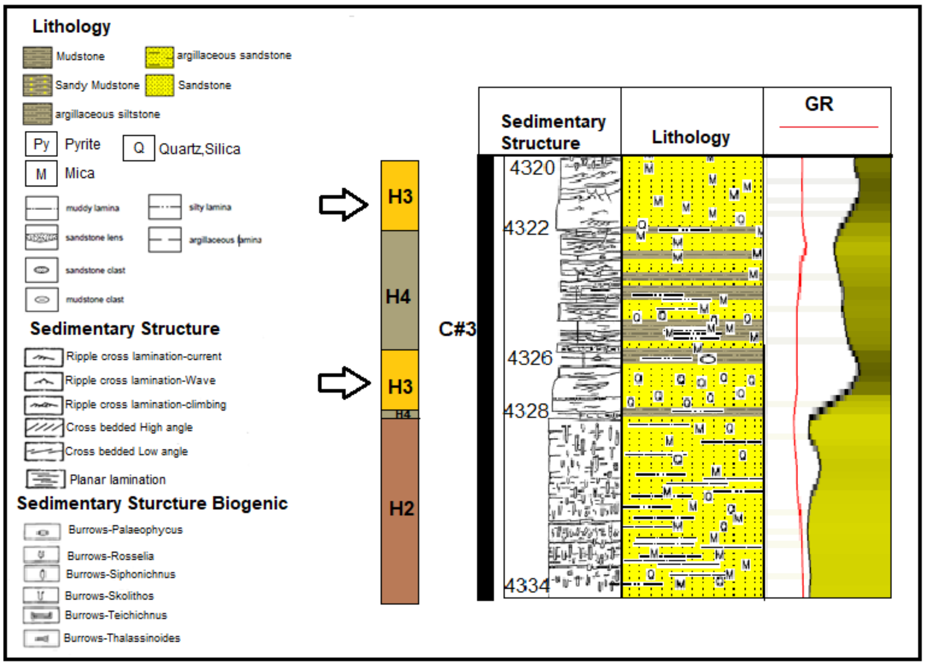

Fig.14.Sedimentological log of core #3 (4320’-4322’ and 4326’-4328’), showing lithofacies H3 (arrow) in well T04

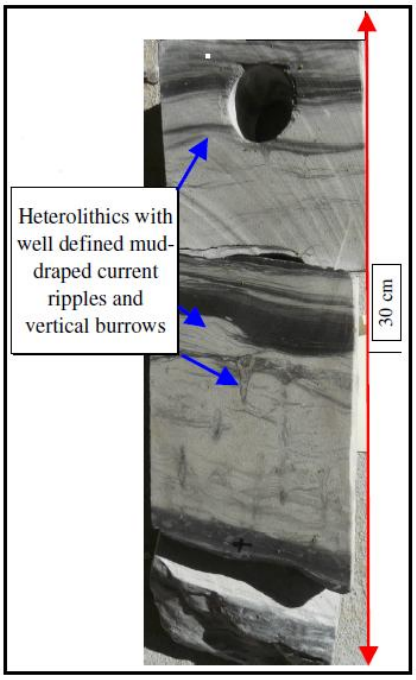

Fig.15. Slabbed core photograph from core #3 at depth 4320’ and 30 cm long showing current ripples with mud drapes and vertical burrows (Skolithos) (blue arrows) in lithofacies (H3), well T04.

Interpretation

Different colors with commonly grey colors suggest deposition under more reducing conditions or records reducing pore water (Reineck and Singh,1973). Parallel-laminated sandstone, may be the product of either lower or upper flow regime, plane-bed conditions (Burki,1998). Parallel lamination and low-angle cross-stratification, interpreted to represent hummocky cross-stratification, suggest deposition by storm events below fair-weather wave-base (Harms et al., 1975; Hamblin and Walker,1979; Dott and Bourgeois, 1982). The planar-laminated to low-angle cross-stratified facies typically shows fine lamination that is geometrically arranged in bed sets having horizontal to low-angle cross-stratification (Grotzinger et al.,2005). The low angle planar lamination also is interpreted as reflecting deposition from subtidal sand sheets or low relief sand bars (Bishop et al., 2003). The Mega ripples are dominantly transverse aeolian bedforms that can form when wind-driven saltating grains impact upon and drive coarser grains in creep (Bagnold,1941; Sharp,1963; Fryberger et al.,1992). The fine sand is transported both in suspension and traction, when flow velocity was less than 0.5 m/s (Baas,1999). Thin ripple laminated sandstone beds indicate deposition by low-energy waves and currents. The depositional structures, especially the small-scale hummocky cross-stratification, together with the presence of Skolithos and Planolites trace fossils, are supportive for the shallow marine environment (Dott and Bourgeois,1982; Dumas and Arnott, 2006; McCave,1985; Basilici et al., 2012).

Lithofacies (H4): Sandy and Muddy heterolithics

Description

The lithofacies consists of about (20-30%) very fine to fine grained, well sorted sandstone. The sandstones varying in color encountered from very light grey to light olive grey to very light olive grey. The lithofacies consists (70-80%) of dominated micaceous mudstone interbedded with micaceous argillaceous siltstone. The mudstone and argillaceous siltstone are medium dark grey. The sandstone is characterized with current and wave ripples with mud-draped, small-scale cross-bedding and planar lamination (Figs. 16& 18). Pyrite are rare and present as nodule (Fig. 17). The mudstone and argillaceous siltstone display planar lamination and lenticular bedding (current and wave rippled sand lenses), shrinkage cracks (Figs. 16& 17). Burrows are scattered within lithofacies sediments some of them indeterminate burrows.

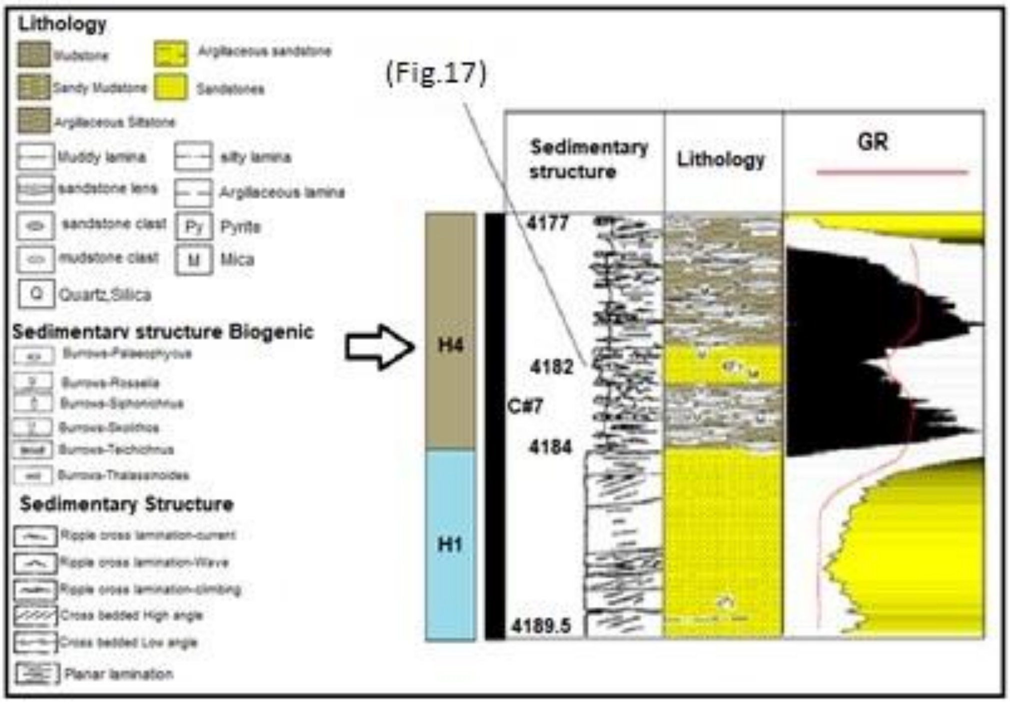

Fig.16.Sedimentological log of core #7, showing lithofacies H4(4177'-4184')in well T03. Lithofacies consist of mainly mudstone invaded with sandstone bed.

Fig.17.Slabbed core photograph of lithofacies (H4) showing visible marks of sedimentary structure, wave and current ripple lamination, planar lamination with sharp contacts. Spherical pyrite nodule at the top (see Fig 12 for location).

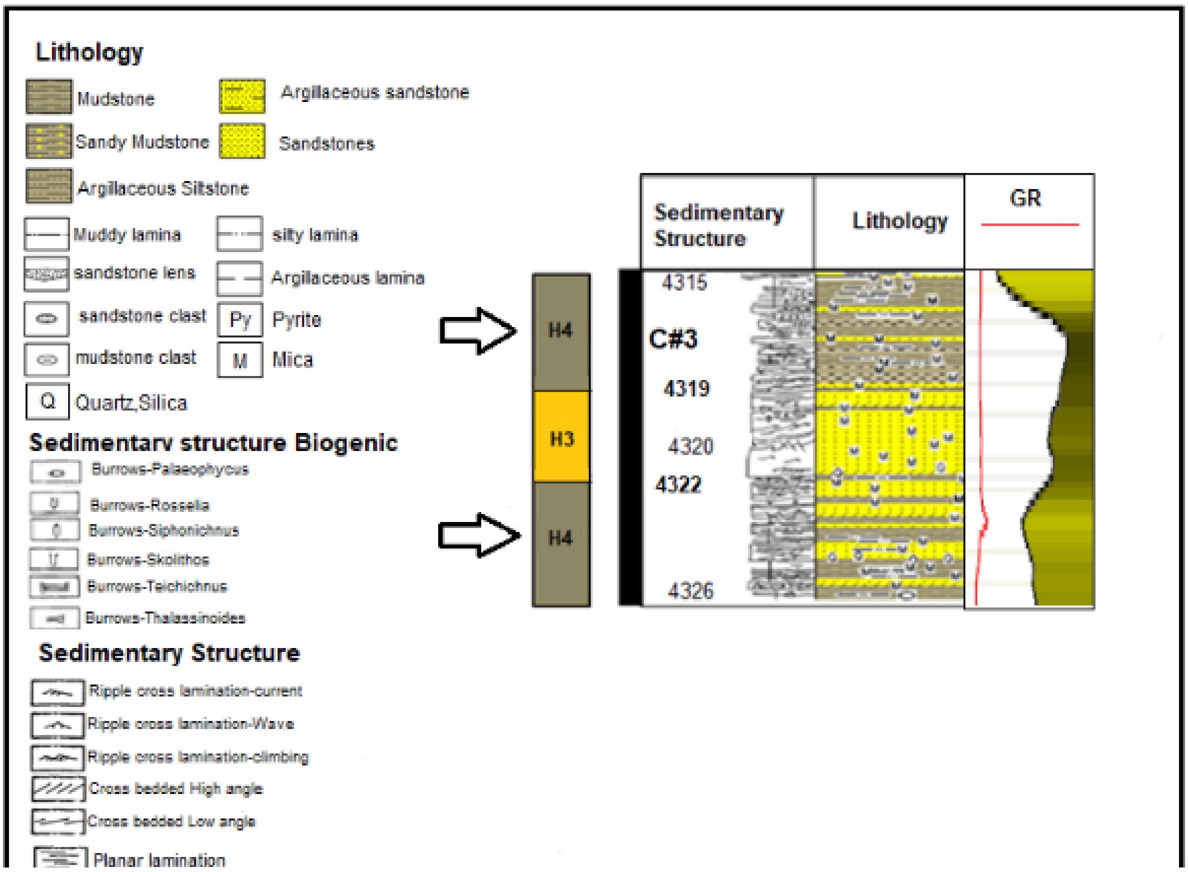

Fig.18.Sedimentological log of core #3 (arrows), showing lithofacies H4 (4315'-4319') and (4322'-4326') in well T04. The upper one mainly dominates by mudstone interbedded with thin sandstone beds whereas the lower are increases sandstone on the expensed decrease mudstone sediments.

Interpretation

The lithofacies consists of laminations are composed of clay and silt, with smaller amounts of very fine-grained sand in the heterolithics sediment, all deposited from suspension (Pedersen,1985). it's characterized by varicolored heterolithics sediments. Grey colors suggest deposition under more reducing conditions (Reineck and Singh,1973). Pyrite nodules can form under these same reducing conditions (Fig.17), Hoefs (1997) pointed out that pyrite may be reflecting precipitation from H2S originating from bacterial reduction of marine-derived sulfate in a relatively open system. The interbedding of argillaceous siltstone and very fine to fine grained sandstone suggests fluctuating energy conditions in an overall low energy setting (Alkhalas,2005). The heterolithics mudstone and sandstone sediments include several exclusive features of tidal deposits, including mud drapes and couplets within flasers, wavy, and lenticular laminae indicating ebb-flood currents with intervening slack water suspension deposition and reactivation surfaces indicating fluctuating flow velocities (Nio and Yang,1991). The sandstone beds/lenses represent higher energy pulses in an otherwise low energy setting. Under the quiet, low energy conditions mud settled out of suspension and in the high energy regime, sand was moved by both unidirectional and oscillatory (wave-generated) flows (Bishop et al.,2003). Planar lamination and/or parallel-laminated sand is the dominant physical sedimentary structure formed in the nearshore facies (Howard and Reineck,1981). The muds form very thin beds, with limited lateral extent. The shrinkage cracks are interpreted as syneresis cracks rather than desiccation cracks, so there is no reason to suppose that the sediments were subaerially exposed (Bishop et al.,2003). Burrows occur H4 are predominately horizontal, and filled with light grey siltstone or very fine sandstone. These trace fossils are characteristic of an open-marine environment and alternating energy conditions (Howard and Reineck,1981; Frey and Pemberton,1984).

IV. Conclusions

The Hawaz Formation represents the onset of the first major Palaeozoic marine transgression in the area. It consists of alternating fine to medium grained, often quarzitic, sandstones with silty shales, characterized by the presence of vertical tubes of the trace fossil mainly (Skolithos). The Hawaz Formation corresponds to an alternation of energy setting. On the hand,sandstones of the Hawaz Formation were deposited in shallow marine environments. In general, this study is resulted in the classified the sandstone into four main lithofacies characterized by variable sedimentary structures and different trace fossils with addition to shale interbedded that enhance the deposition setting of Hawaz Formation in presence of sea level changes.

Acknowledgement

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