

Petrography, Diagenesis and Paragenesis of Wadi Halfa Oolitic Ironstone Formation, North Sudan

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ABSTRACT

Utilizing petrography, diagenesis and paragenesis are the major step to study the sediments of Wadi Halfa Oolitic Ironstone Formation for their origin and economic potential. Petrographical analysis of Wadi Halfa Oolitic Ironstone Formation were carried out depending on the investigation of six vertical lithofacies profiles from the region of Wadi Halfa. The petrographic classification of sandstone samples of Wadi Halfa Oolitic Ironstone Formation according to mineral composition (quartz, lithic fragments, and feldspars) are classified as quartzarenite 66.7%, sub lithic arenite 20.9% and subarkose 12.5%. The provenance of the sandstone revealed that all sample were derived mainly from interior stable craton. The stable craton offered good environments for detrital constitution to be recycled and transported for relatively long-distance. The present study adopted an intergranular pressure solution (IGV) diagram for IGV values more than 50 percent for all studied samples indicating that more of their original porosity has been destroyed cementation rather than by compaction processes for most samples.

Keywords: Petrography, Diagenesis, Paragenesis, Wadi Halfa, Lithofacies and Intergranular pressure solution (IGV)

INTRODUCTION

Based on paleontological and stratigraphical studies [1] adopted the term Wadi Halfa Oolitic Ironstone Formation of Upper Carboniferous Permo-Triassic Upper Jurassic age.

The Wadi Halfa Oolitic Ironstone Formation occupied the area around Wadi Halfa and Argeen near the Nubian Lake in the extremely northern Sudan bordering south Egypt.

The Nubian sandstone succession in the study area is represented by the Wadi Halfa Oolitic Ironstone Formation ranges in thickness from a few to a maximum of 500 meters. It is composed of loose to highly consolidated beds of sandstones, siltstone, mudstones, oolitic ironstone, barite concretions and pedogenic facies.

Six vertical lithofacies sections were chosen for detailed studies based on the variations of composition, grain size, color, sorting, primary sedimentary structures and palaeocurrent direction.

The main objectives of the present research are to study the petrography, diagenesis and paragenesis of the Wadi Halfa Oolitic Ironstone Formation to give a base information of the petrographical data of the selected formation.

GEOLOGY OF THE STUDY AREA

The study area is located east of the Sudanese section of Lake Nasser (Nubia Lake), near the bordering area between Sudan and Egypt. The study area bounded between latitudes ($21^{\circ} 50'$ N) and longitudes ($31^{\circ} 18'$ E) as shown in Figure 1.

Wadi Halfa Oolitic Ironstone Formation is composed of yellowish, brownish to whitish fine, medium to coarse grained sandstone layers that are intercalated with oolitic ironstone and barite concretions. The main primary structures of this formation are bedding planes including planer and trough cross-bedded sandstone, joints, caves, holes and honeycomb structures. [2] The thickness of oolitic ironstone ranging from 20 to 80 cm thick that representing one to three layers. The colors of oolitic ironstone vary from reddish, brownish, yellowish and black.

The lithofacies of Wadi Halfa Oolitic Ironstone Formation contain sediments of fluvial, glacial, fluvioglacial, and shallow marine sediments. It includes trough cross bedded sandstone, planner cross bedded sandstone, horizontally stratified sandstone, fine mudstone facies, massive mudstone facies, rippled sandstone facies and horizontally shallow marine sandstone facies and barite concretion facies [3].

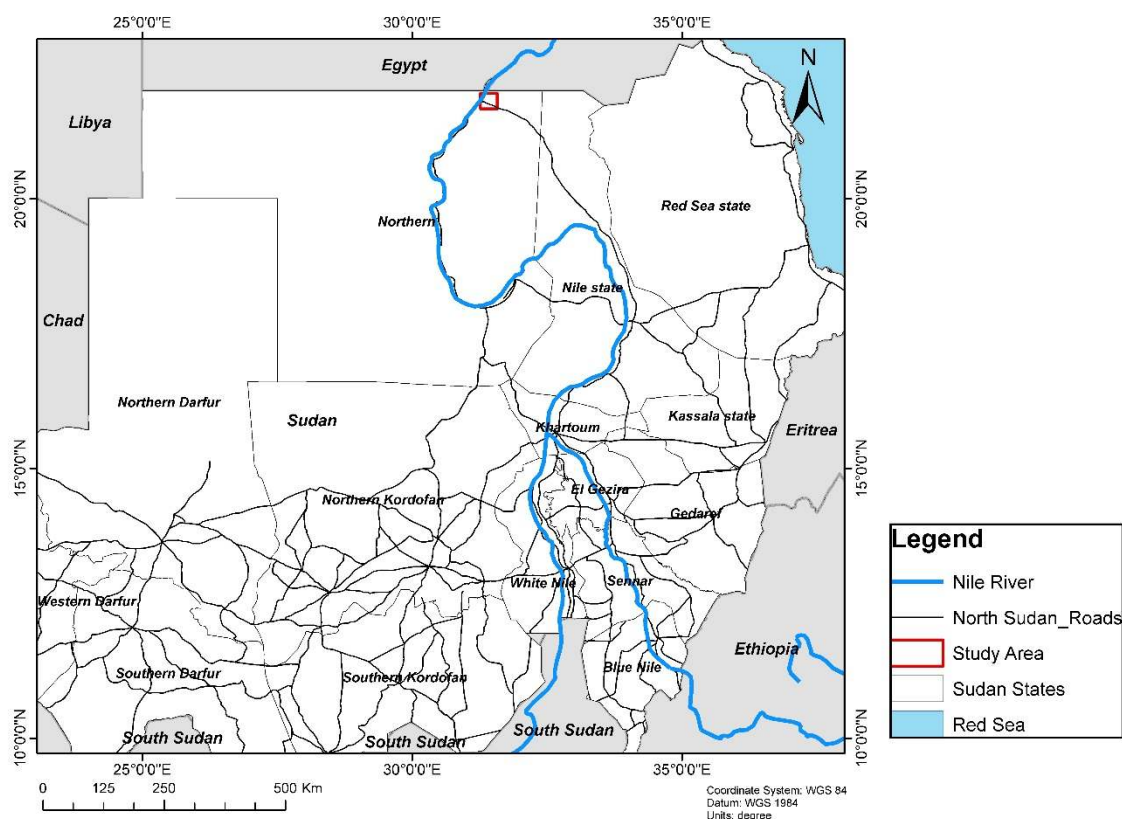


Figure 1. Location map of the study area

Sampling and Methodology

The carefully selection representative six vertical sections (vertical lithofacies associations) of Wadi Halfa Oolitic Ironstone Formation were examined, each section was photographed and documented, described and classified into several lithological units.

A total of thirty samples were thin sectioned. The petrographic characteristics were determined using polarized microscope (PL) and counted by point counting to determine the rock constituents and the different porosity types using methods suggested by [4].

Scanning electron microscope (SEM) was also used to identify minerals and textures. Clay minerals were studied by X-ray diffraction (XRD).

RESULTS AND DISCUSSION

Field Observations

Six vertical stratigraphic sections around Wadi Halfa were measured, each section was studied and described in detail. Figure 2.

During field observations more eight facies were recorded include trough cross-bedded sandstone, planner cross bedded sandstone, horizontal stratified sandstone, horizontally shallow marine sandstone, fine mudstone facies, massive mudstone facies, massive conglomerate facies and rippled sandstone.

The lithofacies associations include trough cross-bedded sandstone facies, planar cross-bedded sandstone facies and horizontally stratified sandstone facies forming channel fill deposits. The facies indicating the fluvial origin of these clastic sediments. Figure 3.

Section two characterized by more than five facies, these facies association of oolitic ironstone, bioturbation in addition to presence of trace fossils like *Planolites Sp.*, *Rhizocorallium Sp.*, and *Skolithos sp.*, indicate shallow marine origin of near shore bars and shore face deposits intercalated with fluvial continents sediments contain of *Paleoweichselia aff. Defrancei Sp.* *Calamites Sp.*, *aff. Sigillaria Sp.*, *Lepidodendron imprint* as shown in Figure 4 and Figure 5.



Figure 2. The lithofacies associations of the first profile (P1)

- [1] Trough cross-bedded sandstone facies (*St*).
- [2] Massive sandstone facies (*Sm*).
- [3] Caves and holes (Honeycomb weathering) in sandstone layers. [4] Planar-cross bedded Sandstone facies (*Sp*)



Figure 3. The facies association in profile two (P2) contain *St*, *Sp*, *Gm*, and oolitic ironstone.



Figure 4. Fossil evidences of shallow and near shore marine environment Upper Carboniferous, Wadi Halfa, North Sudan [1] Indeterminate worm burrows. [2] *Calamites* (*Sp*). [3] *Rhizocorallium* (*Sp*). [4] *Planolites* (*Sp*). [5] Oolitic Ironstone contains *Skolithos* (*Sp*). [6] Ripple cross – laminated sandstone facies (*Sr*).

Sandstone Petrography

The detrital framework grains of sandstone of Wadi Halfa Oolitic Ironstone Formation are composed of monocrystalline, polycrystalline quartz followed by feldspars, lithic fragments, opaques (iron oxides), clays, carbonates, micas and heavy minerals. Table 1.

The percentage of total particles are determined by point counting includes detrital grains such as quartz, feldspars, rock fragments, micas and heavy minerals. Chemically precipitated cements such as carbonates, iron oxides and barites and as well as clay matrix.

Different porosity types also counted and determined. The roundness of grains and contact types between them have been detected and measured.

Detrital Framework Minerals

Quartz: Quartz grains are the dominating framework grain in the studied thin sections in all selected samples from Wadi Halfa Oolitic Ironstone Formation. The percentage of quartz ranging from 63.49 to 98.80% with an average 81.13%. They are monocrystalline (Qm) 85.95 %, polycrystalline (Qp) 14.03 % and tectonic quartz (Qt) 0.2% quartz grains. The polycrystalline quartz grains relatively increasing in coarse grains.

Feldspars: Most of the feldspar grains the studied samples are twinned microcline whereas the plagioclase is in minor amounts. The percentage of feldspars of studied samples ranging from 0.41 to 12.00% with average 6.21%

Rock Fragment: The percentage of rock fragments of studied samples ranging from 0.52 to 15.20% with average 7.86%

Micas: The average of micas in studied samples 1.09% and the percentage from 0.33 to 1.84%.

Heavy Minerals: A low amount of heavy minerals was recorded in the studied samples of Wadi Halfa Oolitic Ironstone Formation most of them are zircon, tourmaline and rutile ranging from 0.33 to 4.35% with average 2.34%

The detrital framework grains are showed in Figure 5 and 6.

Cement and Cementation Fabrics

Carbonates: The percentage of carbonates in studied samples were measured and calculated by point counting techniques ranges from 0.56 to 19.47% with average 10.02% as cement in a lot of samples. Calcite is the main type of carbonate found in studied thin sections figure.

Table 1. The petrographic point counting results of the studied samples from Wadi Halfa Oolitic Ironstone Formation

Number	Samples	Textural Data					Detrital Grains						Cement/Matrix				Pores	
		Roundness	G.Contact				Quartz		Feldspars	Rock Frag.	Heavy M.	Micas	Iron Oxides	Carbonates	Clays	Others	Intergranul.	Oversized
			Point C.	Conca.-C	Over G.	Straight	Mono	Poly										
1	P11	A-SA	4	0	0	0	43	5	0	2	0	0	16	0	4	0	25	5
2	P12	SA-SR	1	0	1	0	69	1	1	4	0	0	8	3	4	0	9	2
3	P13	SA-SR	2	1	0	0	64	0	0	0	0	0	6	0	16	0	12	2
4	P14	SA-SR	6	2	0	1	63	1	0	1	0	0	12	0	0	0	12	0
5	P15	A-SA	7	8	1	0	64	0	0	0	1	0	10	0	14	0	12	0
6	P21	SA-SR	3	1	2	0	67	0	2	1	1	0	19	6	0	0	4	0
7	P22	R-SR	4	1	0	0	61	0	2	1	1	1	16	2	2	0	11	3
8	P23	SA-SR	4	1	3	0	55	1	4	1	0	0	10	9	0	0	20	0
9	P31	A-SA	5	0	3	0	63	4	1	1	1	0	5	0	13	1	11	0
10	P32	SA-SR	6	4	0	0	67	2	4	1	0	0	14	0	6	0	5	0
11	P33	A-SA	6	3	1	0	59	3	3	1	0	0	14	0	16	0	5	0
12	P41	A-SA	2	2	4	1	50	8	2	1	0	0	5	9	1	0	18	7
13	P42	SA-SR	5	3	0	0	61	0	2	4	1	1	0	6	2	0	23	0
14	P43	A-SA	2	0	0	0	40	3	1	2	0	0	37	0	1	0	16	0
15	P44	A-SA	21	4	0	0	57	1	1	1	0	0	17	1	1	0	15	6
16	P45	A-SA	3	0	0	1	59	1	0	1	1	0	21	0	21	0	8	0
17	P46	SA-SR	4	1	2	0	61	0	2	1	2	1	14	8	0	0	11	0
18	P51	R-SR	4	1	1	1	56	10	0	2	0	0	5	0	4	1	16	6
19	P52	R-SR	3	1	1	1	60	4	1	1	1	1	29	3	0	0	0	0
20	P55	SA-SR	5	0	0	0	50	0	1	0	0	0	49	0	0	0	0	0

2 1	P56	SA-SR	8	0	0	0	6 2	0	0	3	1	0	3	0	3	0	2 1	7
2 2	P61	A-SA	5	0	0	0	6 9	1	3	0	1	0	7	2	8	0	8	0
2 3	P63	SA-SR	3	0	0	1	6 5	1	3	1	0	0	8	0	1 1	0	1 0	1
2 4	P65	SA-SR	1	0	0	0	6 1	2	2	0	0	0	1 9	1 1	2	0	2	0

G. contact grain contact **P.C:** Point contact, **C.C:** Concavo-convex, **St:** Straight and **O.G:** Overgrowth).

Roundness of quartz grains A-SA: Angular to sub angular, **R-SR:** Rounded to sub rounded and **SA -SR:** Sub angular to sub rounded) **H.M:** Heavy minerals.

Iron Oxides: Most studied thin sections contain iron oxides, the amounts ranging from 3.75 to 24.81% averaging 14.16 %. It is one of the principal cementing materials.

Clay Minerals: Clay minerals are common in sandstones as matrix or cement constituents in many samples. Based on optical and SEM characteristics, the interpreted clay mineral assemblage is usually dominated by kaolinite with minor illite, montmorillonite and chlorite. The cementation fabrics are showed in Figure 7, 8 and 9.

Pores and Porosity

The studied samples are characterized by different types of pores. They can be divided into three categories: i) pores between sand grains (intergranular pores); ii) pores larger than normal intergranular pores and comparable to the size of sand grains (oversized); and iii) intra granular pores (pores within grains).

Most of studied samples exhibits medium to high porosity. The porosity of studied samples of Wadi Halfa Oolitic Ironstone Formation ranging from 4.33 _to 36.46% averaging of 20.40%

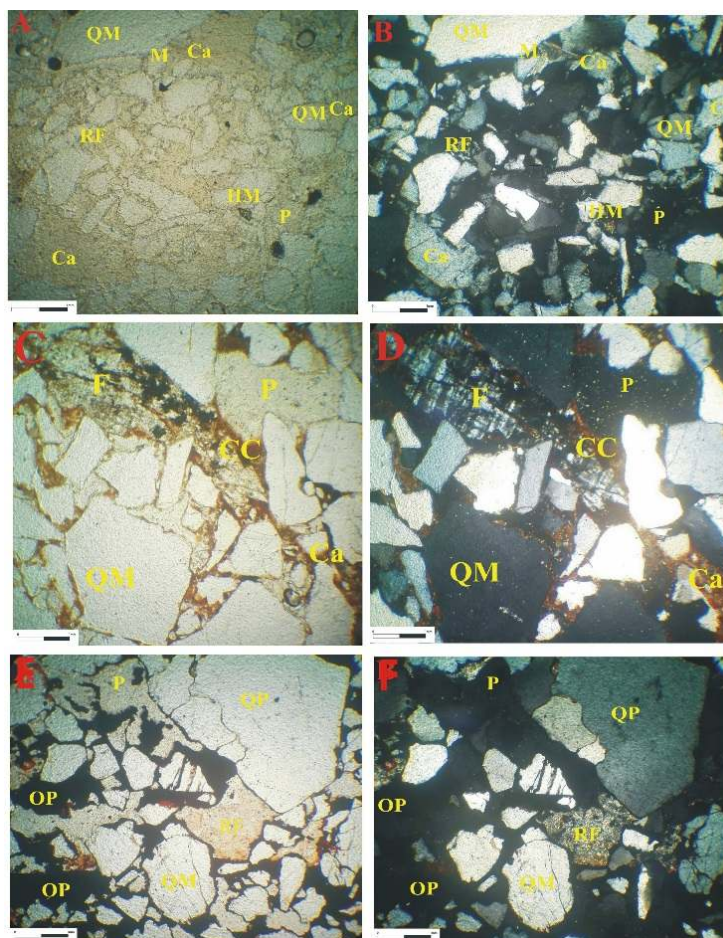


Figure 5. [A] P.N and [B] C.N photomicrograph of samples from different profiles shows: moderately sorted angular to sub angular quartz grains, cemented by iron oxides the contact between grains is point contact. Clays occurred as matrix. Twinning microcline feldspars in the middle (red arrows). [C] P.N and [D] C.N sample from profile two shows angular to sub angular monocrystalline quartz grains cemented by iron oxides and carbonates. Well-developed twinned of plagioclase feldspars. Flakes of mica occurred (red arrow). [E] P.N and [F] C.N sample profile three shows sub angular to sub rounded monocrystalline quartz grains, (black cycle) shows the straight contact between grains. Clays occurred as matrix. Intergranular porosity between grains. QM: Monocrystalline, M: Micas, P: Pores, RF: Rock fragments

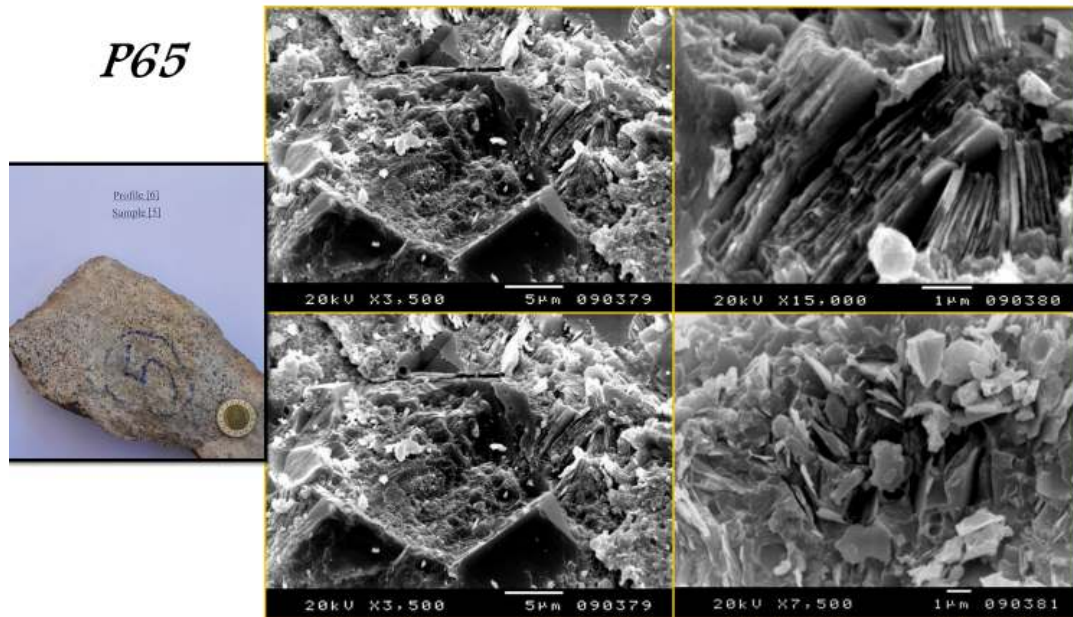


Figure 6. SEM micrograph showing quartz overgrowth and clay matrix between grains of sample P65.

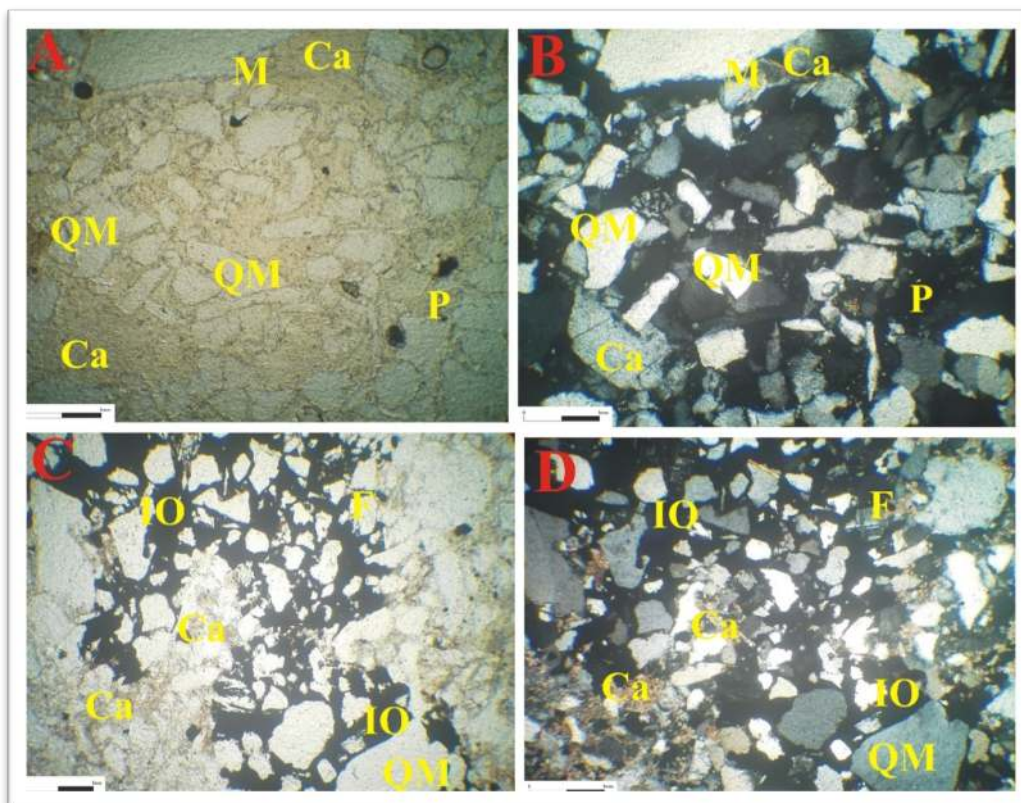


Figure 7. [A] P.N and [B] C.N Photomicrograph of sample four shows a poorly sorted angular to sub angular monocrystalline quartz grains, the contact between grains are straight and concavo-convex, calcite is the main cementing material, intergranular and oversized porosity recorded

[C] P.N and [D] C.N Sample from profile six ferruginous sandstone six shows moderately rounded to sub rounded monocrystalline quartz grains, two types of cementing materials occurred iron oxides (opaques) and carbonates, twined microcline occurred. QM: Monocrystalline quartz grains, P: Pores, Ca: Carbonate cement, M: Micas, F: Feldspars, and IO Iron oxide (opaques).

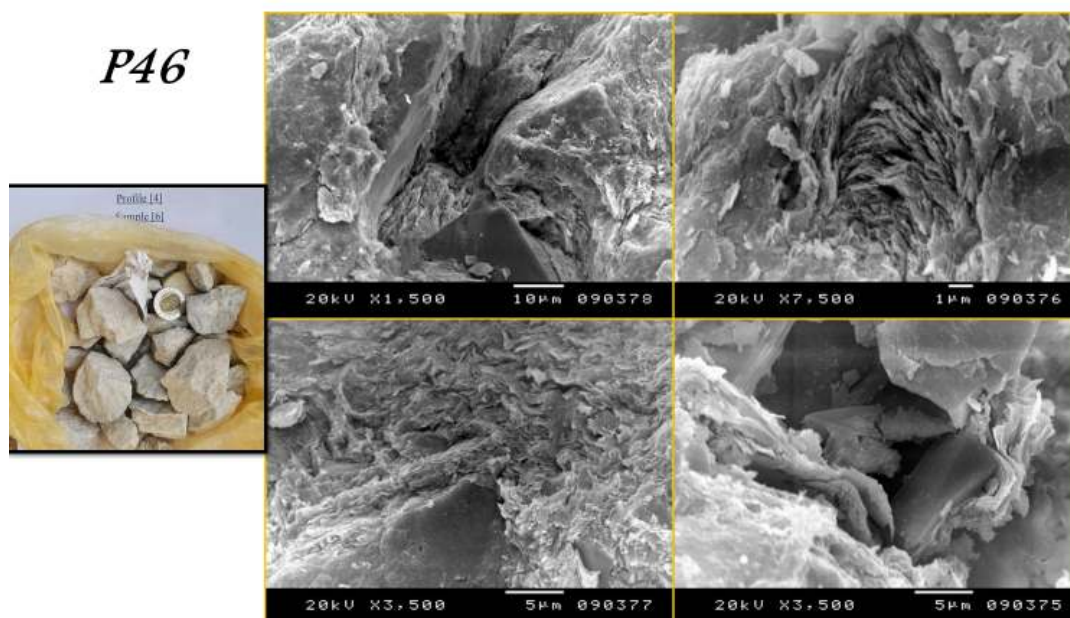


Figure 8. Scanning electron micrograph of different types of clay minerals found in most studied samples: Authigenic kaolinite within pores, well developed pseudo-hexagonal plates profile four and photomicrograph of nontronite clay minerals (Smectite, montmorillonite groups) found in sample from profile four.

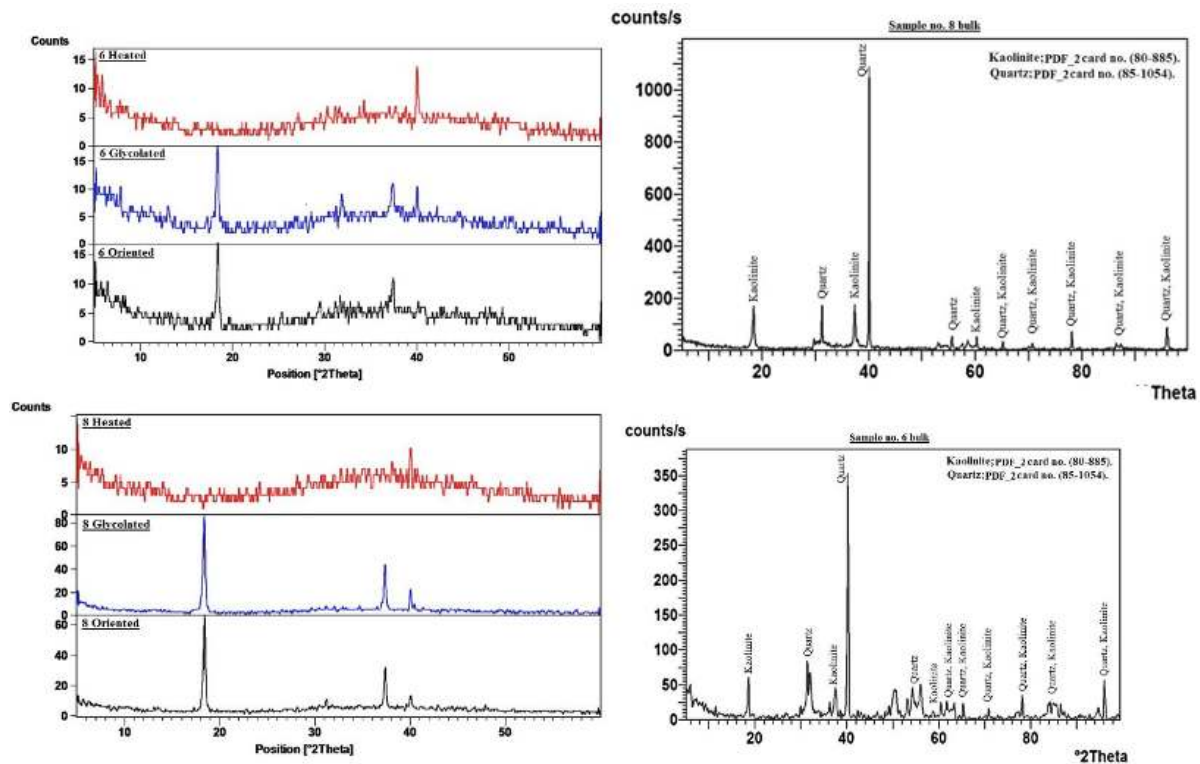


Figure 9. x ray diffraction results of the selected samples

Sandstone Classification and provenance

For classifying the studied sandstones, according to [5] and [6] quartz, feldspars and lithic fragments (QFL) scheme Figures 10 and 11 the percentage of quartz, feldspar and lithic fragments were calculated to 100%.

The classification of sandstone samples of Wadi Halfa Oolitic Ironstone Formation is classified into three main subfacies: 1) Quartzarenite subfacies 66.7 %; it is characterized by more than 95 % of quartz grains and less amounts of lithic fragment and feldspars 5%. 2) Sub lithic arenite subfacies 20.9%; which characterized by more than 5 % of lithic fragment. 3) Subarkose subfacies 12.5%; characterized by more than 5 % of feldspars as shown in Table 2.

The following marks were concluded:

1) The sandstone of this formation is a mature quartzarenite characterized by a lesser content of feldspars and low content of rock fragments.

The predominance of sub angular to sub rounded monocrystalline quartz grains over the polycrystalline ones indicate the igneous origin of the sediments where the angular to sub angular composite quartz grains (polycrystalline) indicate medium to high grade metamorphic origin of the sediments. 2) The texturally immature, moderately sorted, medium to coarse grained subarkose sandstone indicate the fluvial origin of sediments. This is supported by the evidences observed during the field work. 3) The feldspars content was greater at time of deposition preserved in the samples are microclines that indicate granitic origin. 4) The contact between grains indicates to degree of compaction from point contact, straight to suture contact

between grains. 5) Hematite is found in most samples as dominant cementing material in sandstone of Wadi Halfa Oolitic Ironstone Formation which shows oxidizing environment.

The percentages of the different grains were plotted on a triangular diagram, which was used to interpret their provenance and tectonic setting of [4].

For the provenance a triangular plot of monocrystalline quartz, feldspars and lithic fragments [QmFLt] (Qm monocrystalline, F total feldspars and Lt total lithic fragments) takes into account the monocrystalline quartz grains, the feldspars and the lithic fragments were drawn revealed that all sample were derived mainly from interior stable craton. The stable craton offered good environments for detrital constitution to be recycled and transported for relatively long-distance Figure 12.

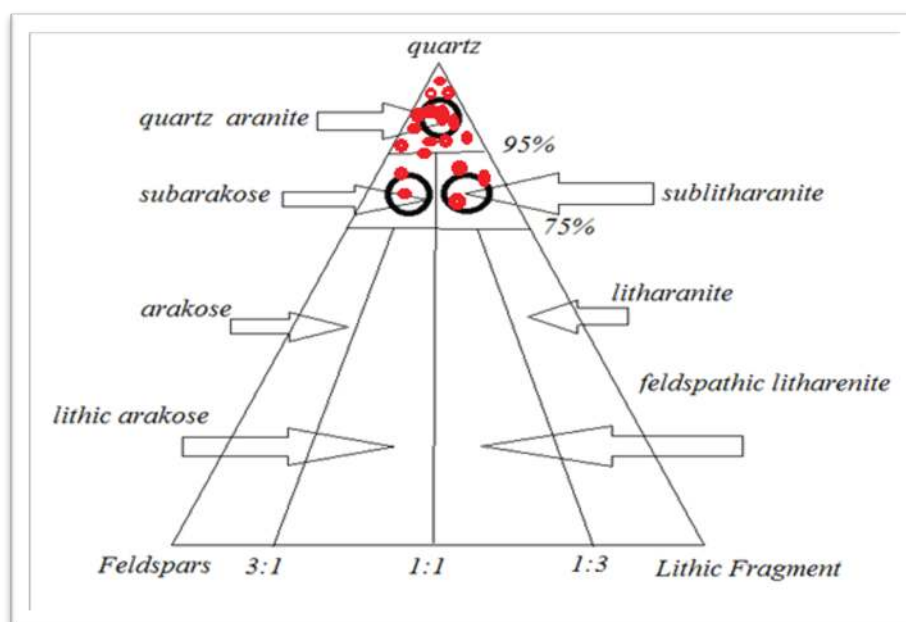


Figure 10. QFR triangular classification plot of different sandstone samples from the WHOI Formation

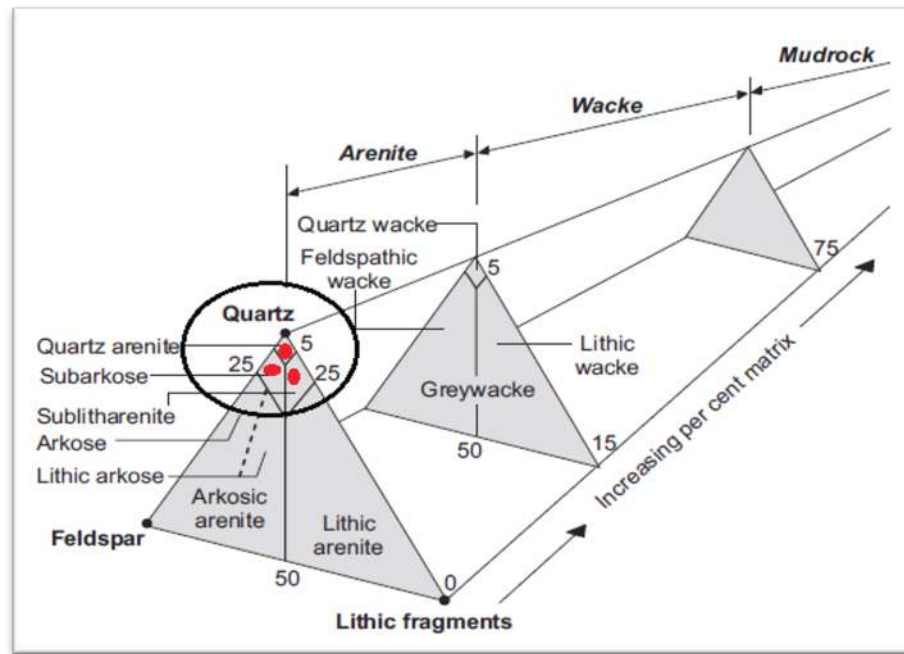


Figure 11. (QFL) scheme diagram for classification of sandstone of studied samples after [5]

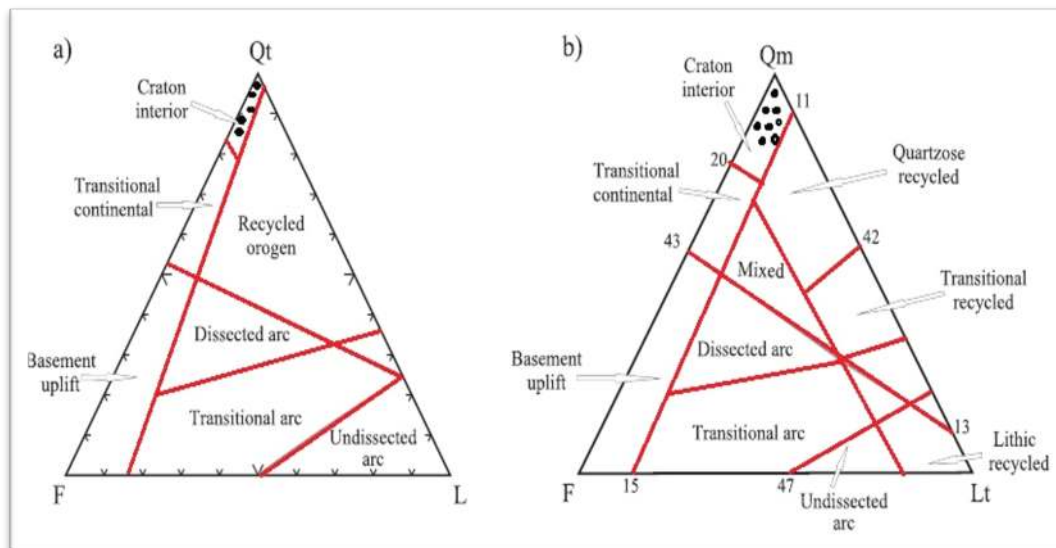


Figure 12. Plotting of the ternary diagram results for different provenance terrains of [6]

Other Features (Oolitic Ironstone)

The oolitic ironstone occurs in profile two. It is represented by one to three layers with thickness values from 20 to 80 cm. The colors of oolitic ironstone vary from reddish, brownish, yellowish and black. The oolites are moderately to well sorted, rounded to sub rounded and showed concentric hematitic layers structure yellowish, brownish to dark brown ooids under polarized microscope figures 13 and 14

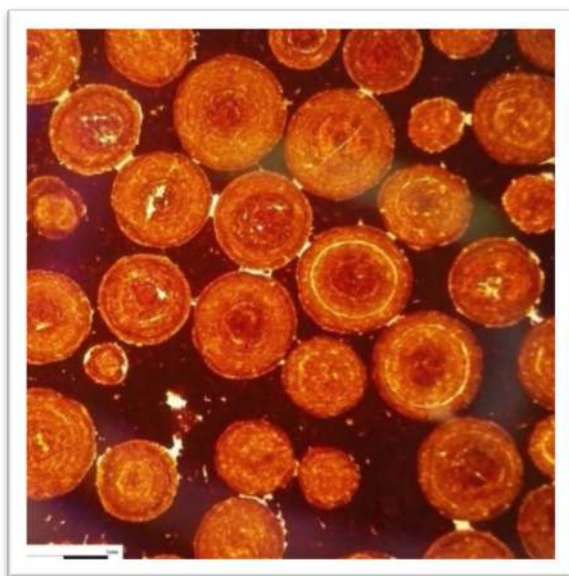


Figure 13. Microscopic photograph shows moderately to well sorted, rounded to sub rounded concentric hematitic ooids. Yellowish, brownish to dark brown oolitic ironstone

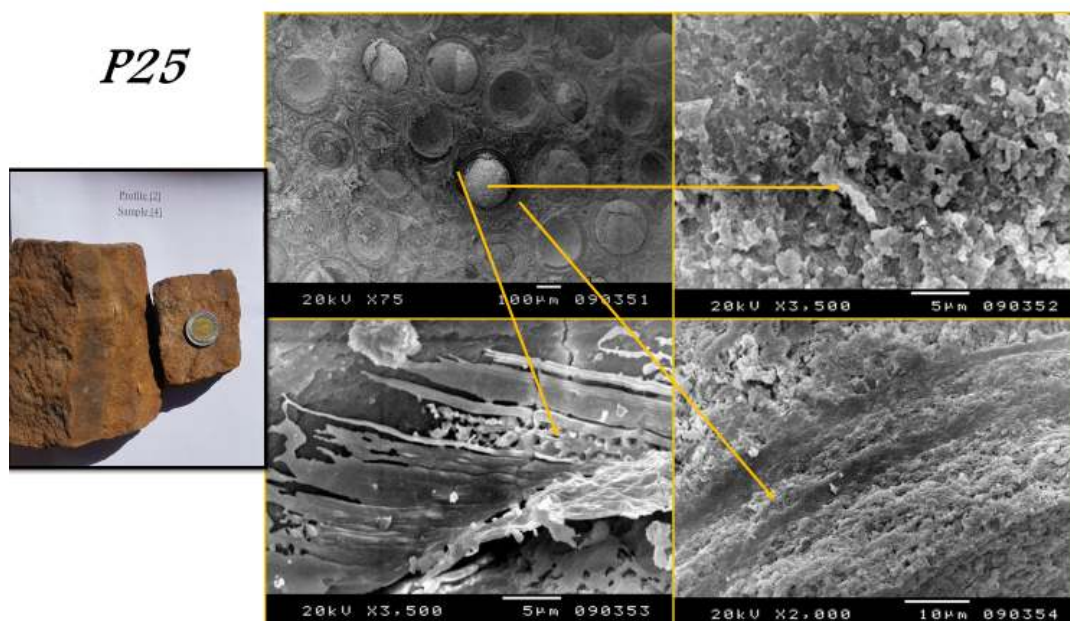


Figure 14. Scanning electron microscope micrograph of different part of oolitic ironstone shows the well-rounded concentric hematitic ooids with alternate berthierine and hematite rich sheaths and the iron oxide cement between concentric hematitic ooids

Paragenesis of the Wadi Halfa Oolitic Ironstone Formation

The present research has adopted [7] method of assessing the relative importance of compactional processes and cementation to the reduction of porosity in studied sandstones by plotting intergranular volume (IGV) versus cement to give an evidence about the paragenesis. At the depositional surface, well-sorted sands have an IGV (porosity) of about 40 percent. That IGV can only be reduced by compactional processes; mechanical compaction can possibly

reduce the IGV to about 30 percent, and any further reduction can only be attained by chemical compaction, of which intergranular pressure solution is the most important specific process [Intergranular porosity = IGV – Cement] IGV values less than 40 percent are the result of mechanical and chemical compaction [7].

Data points are broadly scattered across the diagram, indicating that more of their original porosity has been destroyed cementation than by compaction processes for most samples. These evidences seen by the detailed thin section microscopic study.

The initial porosity (50%) illustrate early diagenetic by cementation and mechanical compaction to reach porosity of (15 – 25) for profiles one, three and six as shown in Figure 15 these evidence suggested by the contact between grains started by straight, concavo-convex, and sutured respectively reveals the compaction paragenesis processes during deposition period. The original porosity destroyed by mechanical compaction to reach porosity 5%.

For profile two and five (fluvial and marine origin of sediments) data points are broadly scattered across the diagram, indicating that more of their original porosity has been destroyed cementation than by compaction processes.

For profile four including barite concretions data points indicating that more of their original porosity has been destroyed cementation than by compaction processes. Intergranular volume (IGV) versus volume of cement showing that the intergranular porosity has been reduced mainly due to cementation for barite concretion and by mechanical compaction for other samples.

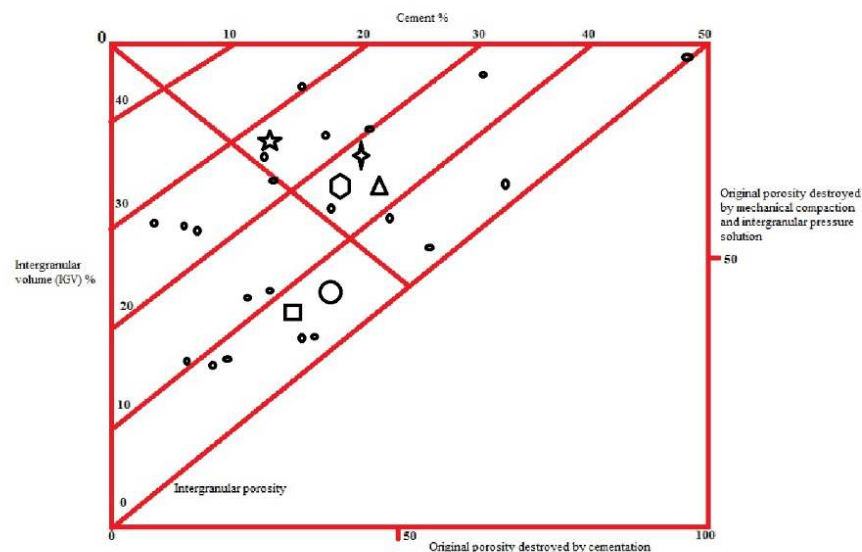


Figure 15. Intergranular volume (IGV) versus volume of cement of all studied samples

CONCLUSION

Based on the results of the field and laboratory study of Wadi Halfa Oolitic Ironstone Formation; the following conclusions have been summarized:

- 1) The Late Carboniferous Permo-Triassic Lower Jurassic Wadi Halfa Oolitic Ironstone Formation covers large area of more than 500 km², and consists of thick alternating beds of shale, siltstone and sandstone and marked by a thin key bed of oolitic ironstone and barite concretions.
- 2) Based on the field observations of six vertical profiles; it has found that the Wadi Halfa Oolitic Ironstone Formation is composed of fluvial, fluvio-marine and shallow marine sediments which characterized the following lithofacies (trough cross bedded sandstone, planner cross bedded sandstone, horizontally stratified sandstone, fine mudstone facies, massive mudstone facies, rippled sandstone facies and horizontally shallow marine sandstone facies. These facies contain a pattern of joints, caves and holes "honeycomb structures". Profile two characterized by intercalation of two to three layers of oolitic ironstone with different thickness. Profile four characterized by more than two layers of sandstone facies contain barite concretions of different size and shape.
- 3) Petrographically, the detrital framework grains of sandstone of Wadi Halfa Oolitic Ironstone Formation are composed of monocrystalline, polycrystalline quartz followed by feldspars, lithic fragments, opaques (iron oxides), clays, carbonates, micas and heavy minerals. The petrographic classification of sandstone samples of Wadi Halfa Oolitic Ironstone Formation according to mineral composition (quartz, lithic fragments, and feldspars) are classified as quartzarenite 66.7%, sub lithic arenite 20.9% and subarkose 12.5%. The present study adopted an intergranular pressure solution (IGV) diagram for IGV values more than 50 percent for all studied samples indicating that more of their original porosity has been destroyed cementation rather than by compaction processes for most samples. The clay mineral analysis indicates that the sediments of Wadi Halfa Oolitic Ironstone Formation are dominated by kaolinite.
- 4) The present study adopted scanning electron microscope of all selected samples which shows different stages of the development of quartz overgrowth in Wadi Halfa Oolitic Ironstone Formation. It shows different types of clay minerals occurred within pores.

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