



## **Barite Concretions in Wadi Halfa Oolitic Ironstone Formation, North Sudan**

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### **Authors' contributions**

*This work was carried out in collaboration among all authors. Author AMAD designed the study and wrote the protocol. Authors RMA and KNS managed and performed the analyses of the study. Author Elamein A. M. managed the literature searches. Author Elsharief A. M. managed the structure of the search. All authors read and approved the final manuscript.*

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### **ABSTRACT**

During our examination of the outcrops of the sedimentary formations in northern Sudan, we found discoidal-shape grains of the heavy mineral, barite in a sandstone of the Wadi Halfa Oolitic Ironstone Formation, which was recorded by all the earlier workers as a reworked sandstone. Petrography-wise, the framework of the sandstone consists of very angular to angular quartz grains, in which monocrystalline grains dominate over polycrystalline grains. Barite is the main cementing material of this sandstone, which occurs as concretions. Barite concretions indicate that more of the original porosity has been destroyed by cementation rather than by compaction processes with the inter-granular porosity being reduced mainly due to cementation. The origin of these concretions, as a cementing material in the sandstone, is ascribed to the reaction of Ba with some soluble sulfate to form the extremely insoluble heavy barite that appears as rounded concretions. The sulfur of the sulfate may be from the hydrothermal fluids related to submarine

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volcanism and/or biogeochemical processes. The deposition of these concretions might have taken place not long after the formation of the sandstone. The source of the barium, however, remains an unsolved problem. Further work is needed to interpret the origin and occurrence of these concretions along the region of Wadi Halfa.

*Keywords: Barite concretions; Wadi Halfa oolitic ironstone; cementation; Sudan.*

## 1. INTRODUCTION

### 1.1 Study Area

THE region of Wadi Halfa is near the border between Sudan and Egypt, and lies to the east of the Lake Nasser in northern Sudan (Fig. 1) with latitudes (21° 50' N) and longitudes (31° 18' E). The Wadi Halfa Oolitic Ironstone Formation (former Nubian Sandstone) covers more than 500 km<sup>2</sup> area, and consists of shale, siltstone and sandstone, and is marked by three beds of oolitic ironstone [1].

### 1.2 Barite Concretions in Wadi Halfa Oolitic Ironstone Formation

During an examination of the outcrops of the Wadi Halfa Oolitic Ironstone Formation in northern Sudan, we found disk-like shaped grains of reworked sediments that were recorded by the previous workers as reworked silicified sandstone. These disk-like shaped, platy

fragments of reworked sandstone were interpreted as tillites and were ascribed to glacio-fluvial or glacio-lacustrine to marine depositional environments [2]. Based on sedimentological studies, [1,3] concludes that these disk-shaped grains of silicified sandstone may indicate glaciation with recycling and reworking of the sediments.

The barite occurrences of different genetic types -- ranging from fissure-fillings in sediments to hydrothermal veins in granitic rocks or associated with copper-zinc-lead-silver mineralization -- have been reported from some places in Sudan, but barite as concretions in sedimentary sequences was not reported hitherto. Barite (BaSO<sub>4</sub>) is the main ore of the element, barium (Ba). It has diverse applications such as in the manufacture of rubber and paper, in radiology for X-ray investigations of the digestive system for reducing radiation in the areas exposed to radiation and as barium- mud in drilling of oil wells.

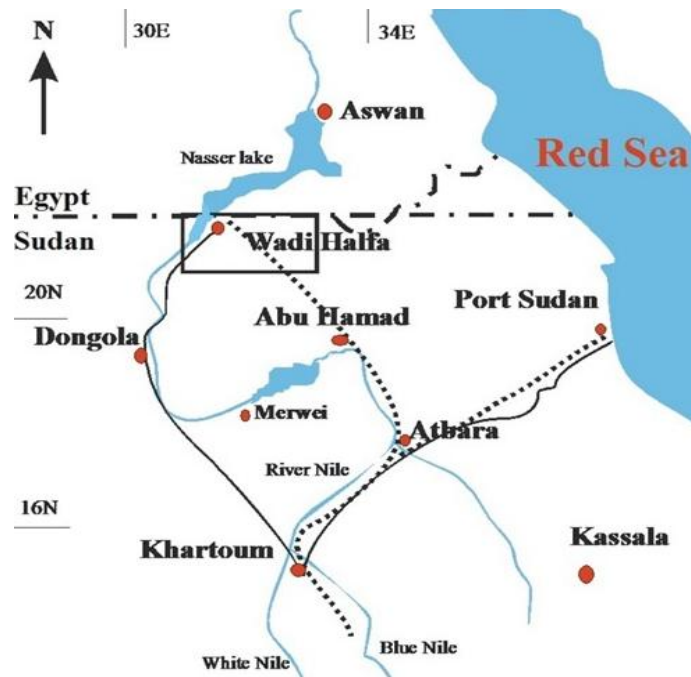


Fig. 1. Location map of study area

## 2. REGIONAL GEOLOGY

### 2.1 Geology of the Study Area

Regional geology of the study area is relatively simple with Precambrian rocks of the Basement complex in the south and the Nubian sandstone in the north. The basement rocks are unconformably overlain by the Paleozoic, Mesozoic and Cenozoic sediments of continental and marine environments. These rocks are unconformably overlain by the Quaternary sediments that include gravel, clays, sandy clays and silt [4]. The Basement complex of northern Sudan comprises three major units: Grey gneisses, metasedimentary group of rocks and a volcano sedimentary sequence. Along the Nile Valley in the northern Sudan between the Bayuada desert and Wadi Halfa area, the basement complex consists of different lithological, structural, tectonic and metamorphic units [5].

The basement complex south of Wadi Halfa are composed of five principal lithologies: a strongly foliated gneissic terrane in the south and west, which is unconformably overlain by a less deformed supracrustal succession, including a succession mainly of mafic metavolcanics, and farther east, a succession of metasediments and predominantly felsic metavolcanics. These three

units were intruded by syntectonic granodiorite and post-tectonic alkali granites [6] (Fig. 2).

The clastic sections in south Egypt and northern Sudan were deposited during a long span of time -- Cambrian to Cretaceous on the northern shelf of the Pan-African Shield. These sediments unconformably overlie the basement complex rocks, and consist mainly of gravel, sandstones, siltstones and mudstones, and contain pedogenic facies and layers of oolitic ironstone [1].

Based on stratigraphical and paleontological evidence, recent sedimentological studies around the Wadi-Halfa and Argeen areas divided the so-called Nubian sandstone of northern Sudan into three units, viz., the Ordovician-Silurian- Devonian unit, Upper Carboniferous Permo-Triassic unit and Jurassic-Cretaceous unit [1] and [2]. These units consist of fluvial, deltaic, glacial, fluvio-glacial and shallow marine sediments and contain layers of oolitic ironstone. The lithofacies of the Wadi Halfa Oolitic Ironstone Formation contain sediments of fluvial, glacial, fluvio-glacial shallow marine sediments include trough cross bedded sandstone, planar cross bedded sandstone, horizontally stratified sandstone, fine mudstone facies, massive mudstone facies, rippled sandstone facies and horizontally shallow marine sandstone facies.

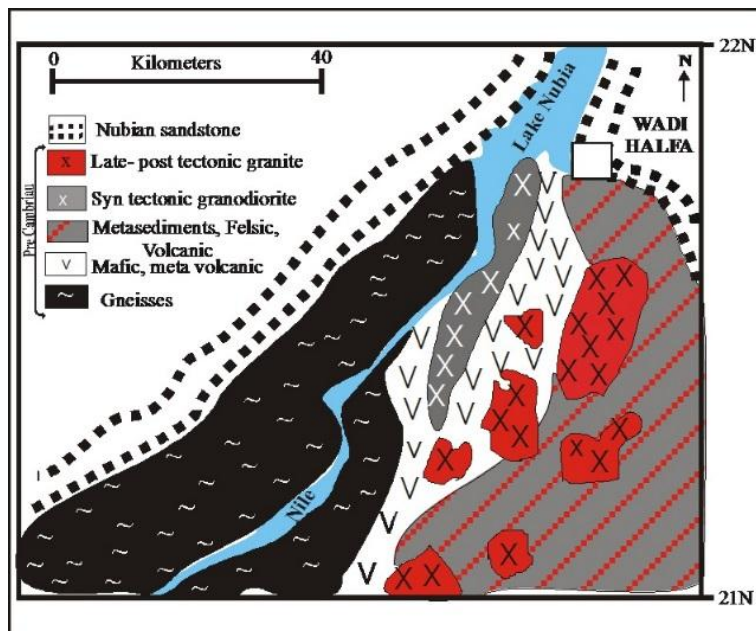


Fig. 2. Sketch map showing the general geological relationships in the basement exposures south of Wadi Halfa (modified after Stern et al., 1994)

## 2.2 Barite Geology

Barite deposits can be divided into the following four main types: bedded-sedimentary; bedded-volcanic; vein, cavity-fill, and metasomatic; and residual. Bedded-sedimentary deposits, which are found in sedimentary rocks with characteristics of high biological productivity during sediment accumulation, are the major sources of barite production [7,8,9]. Barite occurs as concretions as well as cement in sandstone and other sedimentary rocks. The origin of barite in modern sediments is related to volcanism on the sea floor [10]. In the marine sedimentary sequences, these were deposited on or just below the seafloor; they are part of a wider family of deposits known as sedimentary-exhalative (SEDEX) type that are considered to result from interaction of hydrothermal or basin fluids with seawater. These deposits occur in the Proterozoic to Cenozoic host sequences. Most of the barite in the Earth's crust has been formed through mixing of fluids -- one containing Ba, leached from silicate minerals, and the other containing sulphate [11]. Barite can be deposited by the precipitation of hot barium-enriched fluids in faults, joints, bedding planes, breccia zones, solution channels and cavities as a result of fluid mixing or reduced pressure and/or temperature. In some cases, the ore fluid dissolves the surrounding host rocks (especially limestone and dolomite) and barite is deposited in its stead, thus forming replacement deposits. Because of the very low solubility product of barium sulfate, the presence of barite is more to be ascribed to the presence of barium than that of sulfate, since sulfate is almost always present either in the sea water or the typical subsurface brine.

In different countries of the world, several authors [12,13,14,15,16,17,18,19] have contributed on different aspects and occurrences of the barite concretion and sand barite. Occurrences of barite of different genetic types from fissure filling in the sediments to hydrothermal veins in granitic rocks or associated with copper zinc lead silver mineralization have been reported in some places in Sudan but not as concretion in sedimentary sequences.

## 3. METHODS

The methods adopted in the present work are as follows:

### 3.1 Field Work and Sampling

A geological field work was carried out in the area of Number One Railway Station in the Wadi

Halfa Oolitic Ironstone Formation to study the lithology and occurrences of the concretions and other rock types. A total thirty representative samples was collected from different of sections of sedimentary strata for follow-up laboratory studies.

### 3.2 Laboratory Study

Thin sections of thirty representative samples were prepared. Petrographic characteristics of the rocks and their mineralogy were determined, using an Olympus and a Leitz optical microscope, under both the plane polarized (PPL) and crossed nicols (XPL). Modal composition of all the samples was determined, using a point counter by counting 300-500 points per each thin section, as per the method of as per the method of Gazzi-Dickinson [20].

A few representative samples were prepared to study micro-textures of minerals by a Scanning Electron Microscope (SEM), equipped with an energy dispersive X-ray micro-analyzer (SEM-EDAX).

As per the results of petrographic study and SEM analysis, a few samples were studied by X-ray diffraction (XRD) so as to determine the bulk mineral composition.

## 4. RESULTS

### 4.1 Field Investigation

#### 4.1.1 Description of profile A1

Location this section is situated south east of the region of Wadi Halfa near the railway station of number one (Fig. 3).

Latitude [N 21° 44' 47"]

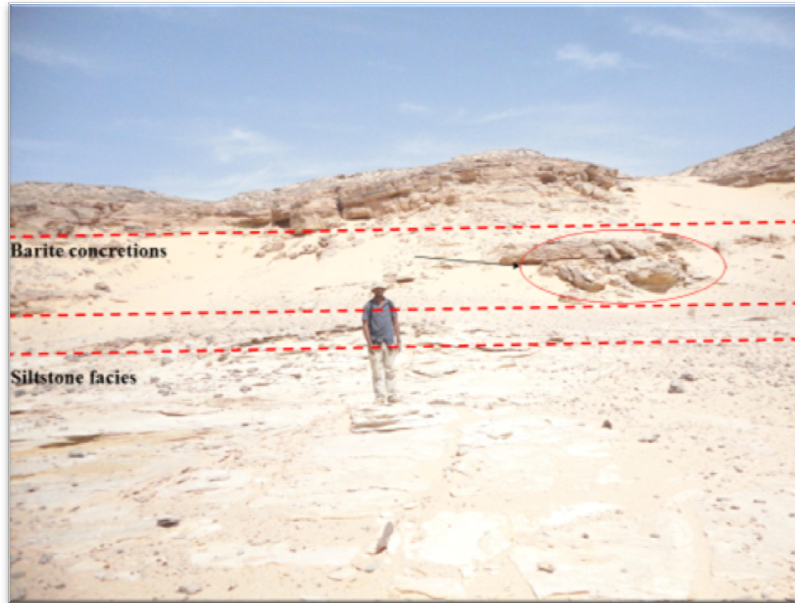
Longitude [E 31° 29' 17.6"].

Thickness of section from the base [50 m];  
Elevation above sea level [215 m].

The lower part consists of fine to medium yellowish sandstone faces overlain by more than two meters of yellowish medium to coarse to fine grained trough cross bedded sandstone facies, overlain by fine to medium grained whitish to greyish sandstone facies. This lower fining upward sequence is overlain by another one sequence consist of poorly sorted yellowish to pinkish coarse grained sandstone contains



discoidal shape grains of heavy gravity sediments; these discoidal shape found penetrating the bedding plane of sandstone the upper part of these sediments equivalent to fine grained sandstone where the lower part equivalent to coarse grained sandstone (Fig. 4).



**Fig. 3. Photographs of the general primary structures and features of the profile A1 shows the yellowish coarse sandstone facies contain discoidal shape of heavy gravity sediments (barite concretion)**



**Fig. 4. Main facies of profile A1 include:**

[1] Planar cross-bedded sandstone facies (Sp).

[2] Honeycomb structure.

[3] Trough cross-bedded sandstone facies (St).

[4] Trough cross-bedded sandstone facies contains discoidal shape of heavy gravity sediments

The discoidal shape of heavy gravity sediments Fig. 5 overlain by another fine to medium yellowish sandstone facies and overlain by ferruginous sandstone facies.

The upper part of this section composed of [20-60 mm] fine to medium grey siltstone facies. The sandstone facies of this profile contain a pattern of caves, holes and honeycomb structure.

#### 4.2 Laboratory Study

Petrography-wise, 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 (Fig. 6). 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, sub lithic arenite and sub-arkose [21]. By using thin section polarized microscope for the discoidal shape of heavy

gravity sediments we found that these sediments are composed of very angular to angular pure quartz grains include monocrystalline quartz grains ranging from 35.1 to 52.3% and polycrystalline quartz grains ranging from 2.0 to 20.9%.

The main cementing material is barite ranging from 39.2 to 44.1% Table 1 and Table 2. Some samples the barite cement penetrate and corroded the quartz grains as shown in Fig. 7.

The discoidal shape of heavy gravity sediments recorded as reworked silicified sandstone in all previous studies and not assigned as barite concretion.

The present research according to above results assigned the barite concretion of those sediments.

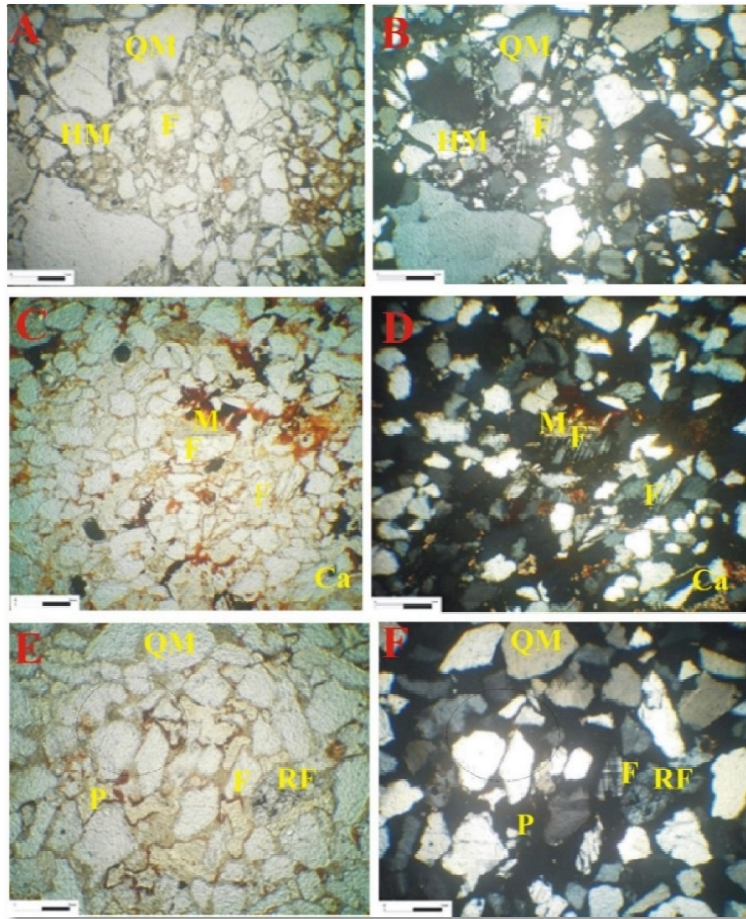
The clay mineral analysis indicates that the sediments of Wadi Halfa Oolitic Ironstone Formation are dominated by kaolinite (Figs. 8 and 9).



Fig. 5. The features of heavy gravity sediments with different size and shape

Table 1. The petrographic point counting results of barite concretion samples from profile A1

Number	Samples	Point contact	Quartz		Feldspar	Barite	Calcite	Heavy M.	Porosity
			Mono	Poly					
1	B1	3	50.8	3.3	0	41.3	0.2	0.5	3.8
2	B2	0	47.4	7.6	0	43.0	0.9	0	1.2
3	B3	0	50.1	1.85	1.6	44.1	0	0	2.1
4	B4	2	52.3	2.0	0.3	43.3	0	0	2.0
5	B5	1	40.5	10.7	0.5	42.9	0	0.2	5.2
6	B6	0	50.1	4.9	0.4	39.2	0	0	3.3
7	B7	0	35.1	20.9	1.2	42.2	0	0	0.6



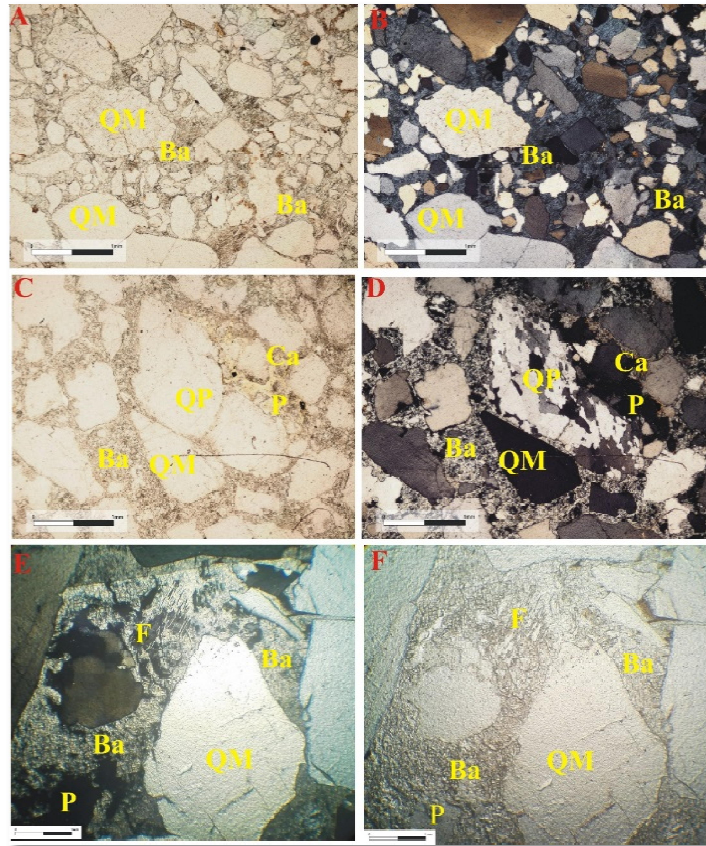
**Fig. 6. [A] P.N and [B] C.N photomicrograph of selected samples shows moderately sorted angular to sub angular quartz grains, cemented by iron oxides, the contact between grains is point contact. Clays occurred as matrix. Twining microcline feldspars in the middle. [C] P.N and [D] C.N shows angular to sub angular monocrystalline quartz grains cemented by iron oxides and carbonates. Well-developed twinned of plagioclase feldspars. Flakes of mica occurred. [E] P.N and [F] C.N shows sub angular to sub rounded monocrystalline quartz grains, the straight contact between grains. Clays occurred as matrix. Intergranular porosity between grains**

*QM: Monocrystalline, M: Micas, P: Pores, RF: Rock fragments*

**Table 2. The percentage of quartz grains, barite cement and pores of barite concretion samples**

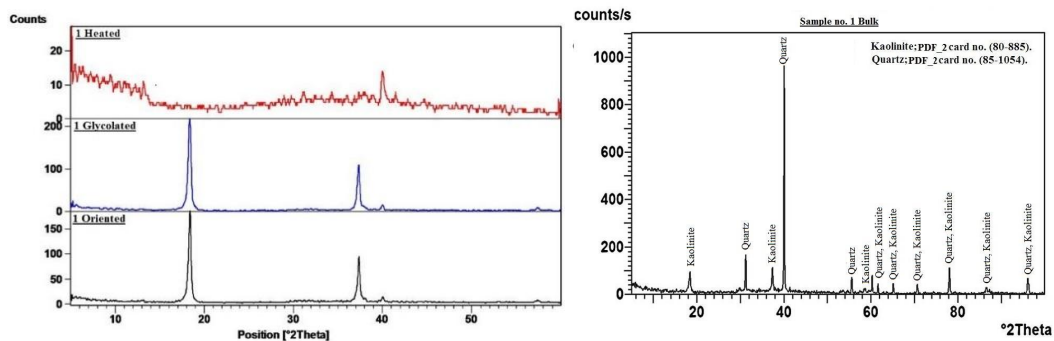
Number	Samples	Grains	Cement	Pores
1	<b>B1</b>	54.6	41.6	3.8
2	<b>B2</b>	55.0	43.9	1.2
3	<b>B3</b>	53.6	44.1	2.1
4	<b>B4</b>	54.6	43.3	2.0
5	<b>B5</b>	51.9	42.9	5.2
6	<b>B6</b>	54.5	41.2	3.3
7	<b>B7</b>	57.2	42.2	0.6
<b>Maximum</b>		57.2	44.1	5.2
<b>Minimum</b>		51.9	41.6	0.6
<b>Average</b>		54.6	42.9	2.9





**Fig. 7. Photomicrograph of different barite concretions shows the major constituent of these concretions showing angular to sub angular monocrystalline quartz polycrystalline quartz grains cemented by barite, no contact between grains**

[A] P.N, [B] C.N, 40X sample (B 1). [C] P.N, [D] C.N, 40X sample (B 2). [E] C.N, [F] P.N, 20X sample (B 3).  
 QM: Monocrystalline, QP: Polycrystalline, Ba: Barite cement, Ca: Carbonates, F: Feldspars, P: Pores



**Fig. 8. X-ray pattern of oriented and powdered shows the majority of kaolinite constituent**

The present research adopted scanning electron microscope of all selected samples which shows different stages of the quartz overgrowth in Wadi Halfa Oolitic Ironstone Formation and it shows

different types of clay minerals occurred within pores as shown in Figs. 10, 11 and 12. Results of SEM-EDAX of barite concretion are shown in Figs. 13 and 14.

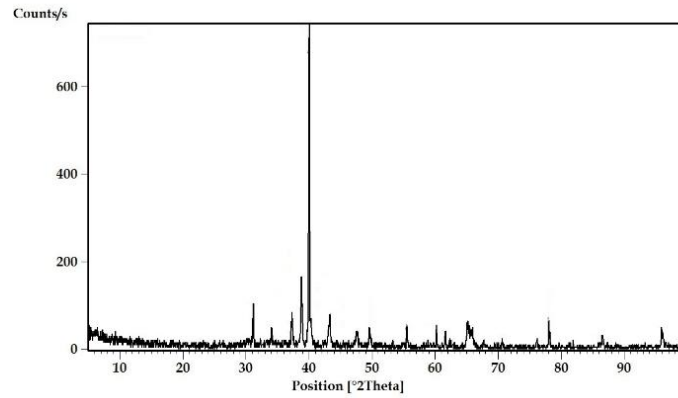


Fig. 9. X- ray pattern of barite concretion sample shows the major peaks of barite

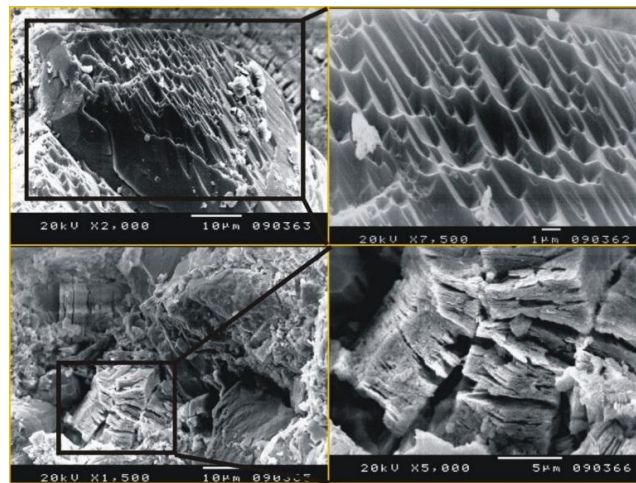


Fig. 10. Scanning electron micrograph shows initial stage of quartz overgrowth forming incomplete crystal faces and kaolinite booklets as pore filling

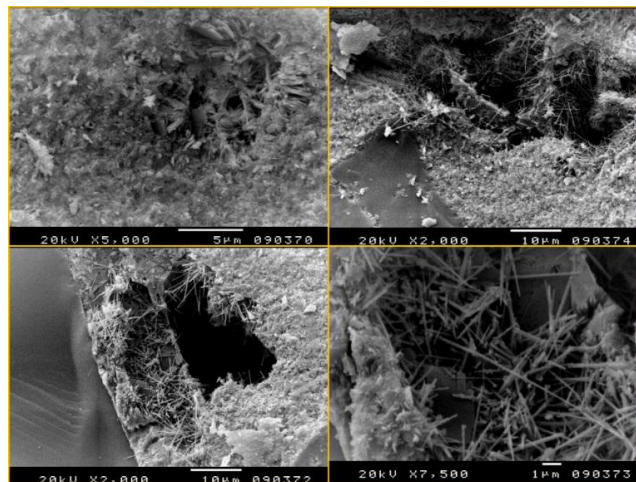
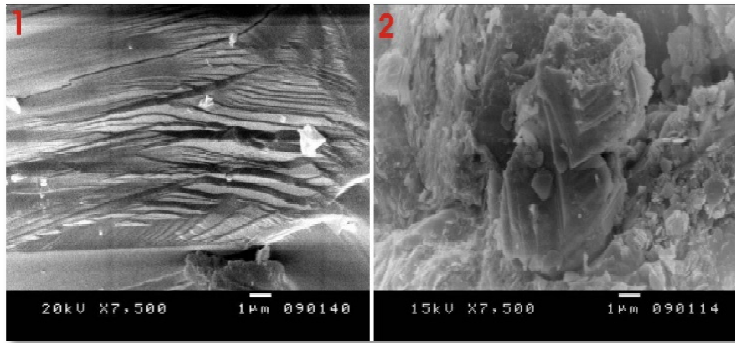
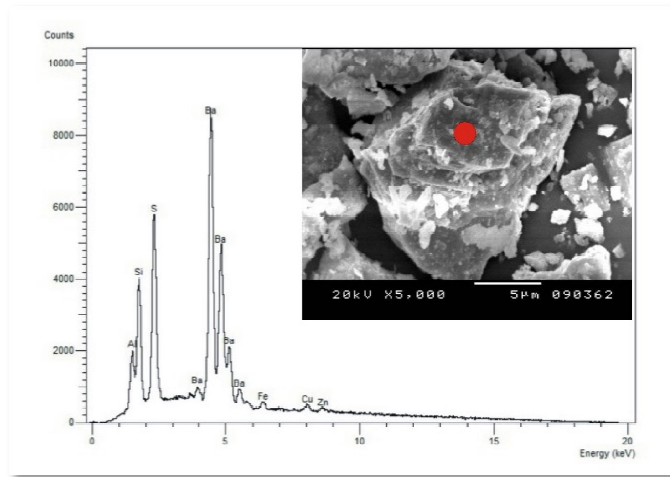


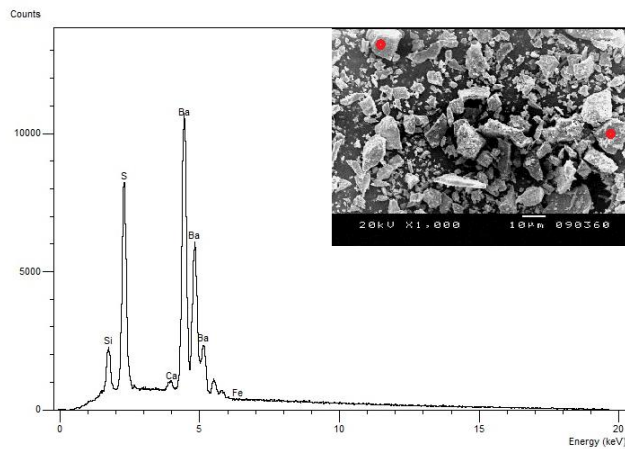
Fig. 11. SEM shows elongated shape of hematitic cement



**Fig. 12. SEM micrograph of barite concretion crystals shows both quartz and barite crystals:**  
(1) Quartz grain surface showing fracture plains with edge abrasion forming arcuate steps and conchoidal.  
(2) A perfect three direction cleavage of barite crystal



**Fig. 13. Scanning electron microscope and EDAX spot analysis (Red cycle) indicating barium sulphate and showed three directions of cleavage of barite. Sample (B2) barite concretion**



**Fig. 14. SEM- EDAX spot analysis (Red cycle) indicating barium sulphate. Sample (B4) barite concretion**



## 5. DISCUSSION

The sandstone of the Wadi Halfa Oolitic Ironstone Formation is a mature quartz arenite, characterized by dominant quartz and less content feldspars and lesser content of rock fragments. The predominance of sub-angular to sub-rounded monocrystalline quartz grains over the polycrystalline ones indicates the igneous origin for the detritus of the sandstone, whereas the angular to sub angular composite quartz grains (polycrystalline) indicate medium to high grade metamorphic origin for smaller part of the detritus in the sandstone. The petrographic features of the sandstone namely textural immaturity, moderate sorting, medium to coarse grain size of the detritus and sub-arkose type, as per classification, all indicate its fluvial origin. This is supported by the evidences observed during the field work. For most studied samples, the fluvial channel-fill deposits of the Wadi Halfa Oolitic Ironstone Formation contain a higher percentage of plagioclase and volcanic rock fragments, so they were derived from a source terrain that included volcanic rocks as well as older sedimentary rocks [1]. Hematite is found in most samples as dominant cementing material in sandstone of Wadi Halfa Oolitic Ironstone Formation, which points to an oxidizing environment.

As per the field investigation, the discoidal shape of barite concretion is penetrating the bedding plane of sandstone, with the upper part of the concretion being equivalent to fine grained sandstone whereas the lower part is equivalent to coarse grained sandstone. The barite recorded in the lower part of Profile A1 penetrates the sandstone layers parallel to bedding planes as concretions of composite grains with discoidal shape and those in other locations in the Wadi Halfa Oolitic Ironstone Formation are as shown in Figs. 4 and 5, given above. Barite occurs as concretions as well as cement. The origin of barite in modern sediments seems to be related to volcanism on the sea floor [9]. This has been deduced from studies of barite formation in modern sediments in the deep ocean; barite appears to be localized with respect to volcanic provinces in the sea. There is also evidence that much of the barite formed in economically workable deposits as well as sandstone cements and concretions are the result of barite precipitation from ascending brines from deeper seated barium containing basement rocks [10]. The present study [14] suggests that the origin of these concretions,

deposited as a cementing material in the sandstone, is due to reaction of Ba with some soluble sulfate to form the extremely insoluble barite ( $\text{BaSO}_4$ ) that occurs in the form of rounded concretions or the crystal aggregates, with the Ba-rich hydrothermal fluids related to submarine volcanism and/or biogeochemical processes. The source of Ba remains an unsolved problem. The time of deposition was probably not long after the formation of the sandstone [14]. This evidence needed more research.

### 5.1 Inter-Granular Volume (IGV)

The present work has followed the method of [22] to assess the relative importance of compactional processes and cementation for the reduction of porosity in studied samples, by plotting inter-granular volume (IGV) against cement to give an evidence about the paragenesis. At the depositional surface, well-sorted sands have an IGV (porosity) of about 40%. That IGV can only be reduced by compactional processes; mechanical compaction can possibly reduce the IGV to about 30% and any further reduction can only be attained by chemical compaction, of which inter-granular pressure solution is the most important specific process [Inter-granular porosity =  $\text{IGV} - \text{Cement}$ ]. IGV values of < 40% are due to mechanical and chemical compaction [22].

The present study adopted an IGV vs. cement diagram Fig. 15, in which all plotted samples (black), including the discoidal shaped barite concretions (red) of Wadi Halfa Oolitic Ironstone Formation point out that > 50% of their porosity was destroyed by cementation. In the Fig. 15, data points are broadly scattered across the diagram, indicating that more of their original porosity has been destroyed by cementation than by compaction processes for most samples. This evidence corroborates the observations made during the microscopic study.

For Profile A1 including barite concretions data points indicate that more of their original porosity has been destroyed by cementation than by compaction processes. The plots in the Fig. 15 indicate that the inter-granular porosity has been reduced mainly due to cementation in case of barite concretions and by mechanical compaction in other samples. The initial porosity (50%) illustrates early diagenesis by cementation to reach porosity of 2 -5 for barite concretions as

shown in Fig. 15. These features suggest that the concretions may be in the early diagenetic stage of original porosity by cementation. This evidences for the barite concretion suggested by

the thin section microscopy in which the barite cement penetrates and corrode the quartz grains as shown in Figs. 7 and 12 mentioned above and Fig. 16 below.

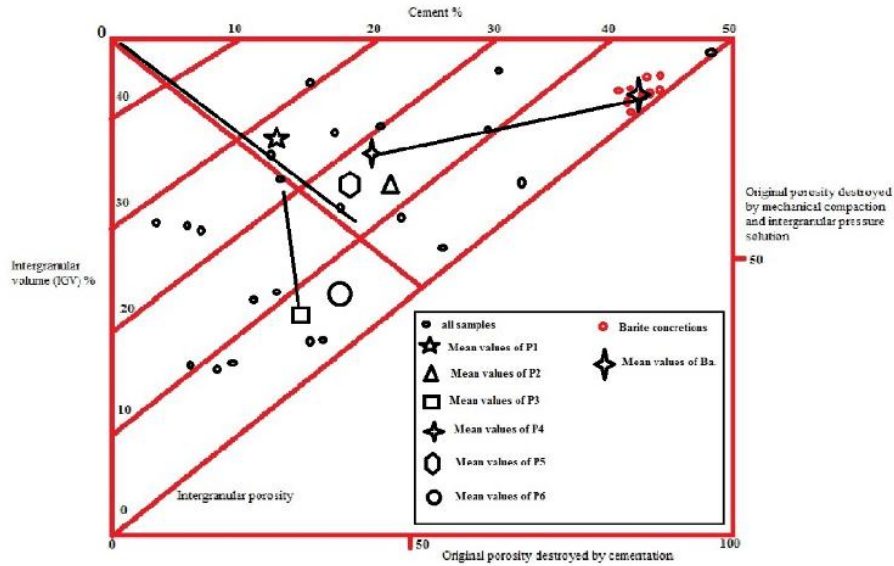


Fig. 15. Intergranular volume (IGV) versus volume of cement diagram of (Houseneckt, 1987) of all studied samples (black cycles) including barite concretions (Red cycles)

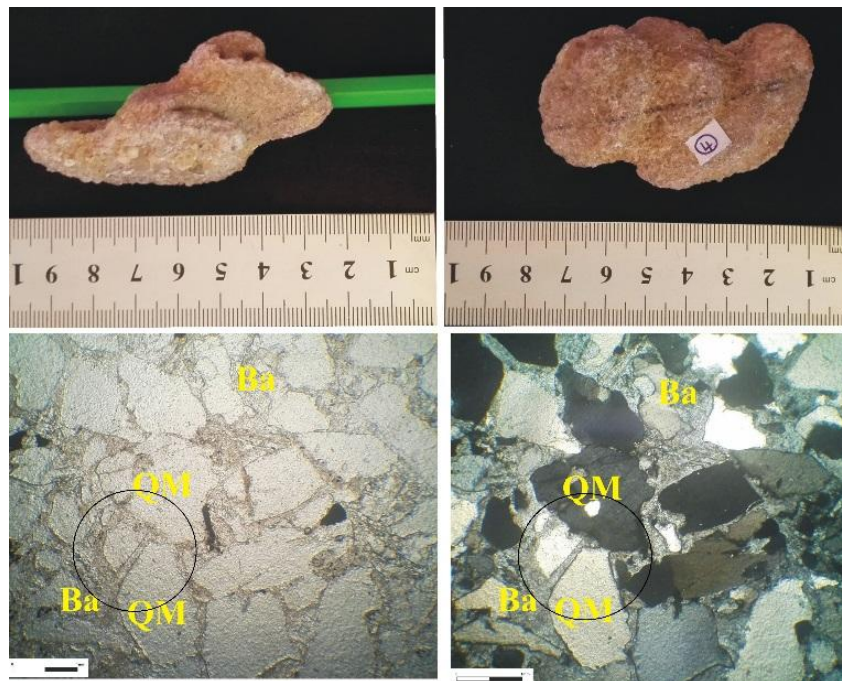


Fig. 16. Photomicrograph of barite concretions shows the major constituent of the concretion. The barite cement penetrating and corroding of barite cement into quartz grains  
 QM monocrystalline, QP polycrystalline, Ba barite cement

## 6. CONCLUSION

The Wadi Halfa Oolitic Ironstone Formation (WHOIF) is a sedimentary formation and belongs to the Nubian Sandstone Formation, located east of the Nubia Lake (the Sudanese section of Lake Nasser) near border between Sudan and Egypt, northern Sudan. Occurrences of barite of different genetic types -- fissure-fillings in the sediments and as hydrothermal veins, associated with copper, zinc, lead and silver mineralization -- have been reported in different places of the world. Barite, in the form of concretions in the sandstone of WHOIF, is reported here for the first time in Sudan. Petrography-wise, the framework grains of the sandstone, containing barite concretions, consist mainly of very angular to angular quartz grains, with mono-crystalline grains dominating over the polycrystalline grains. The main cementing material of the sandstone is barite; in some samples, the barite cement penetrates and corrodes the quartz grains. In the barite concretions, more of the original porosity has been destroyed by cementation than by compaction processes. Plot of the inter-granular volume (IGV) vs. volume of cement shows that the inter-granular porosity was reduced mainly by cementation rather than mechanical compaction.

The present study and [14] suggest that the origin of these concretions is due to deposition of barite as a cementing material in the sandstone, which due to the reaction of Ba with some soluble sulfate to form the extremely insoluble, barite (BaSO<sub>4</sub>). Barite may be formed also from the Ba-rich hydrothermal fluids related to submarine volcanism as well as by biogeochemical processes. Further work is needed to interpret the origin and occurrence of these concretions in the region of Wadi Halfa. If we know the original resource of Ba in this area, it may guide us to find resources of petroleum, gases and other industrial minerals in this area. Also, further work is needed to study the economic aspects of the barite concretions for use in other projects such as in healthcare for radiation reduction while taking X-rays and as an industrial mineral.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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