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Wadi Halfa Oolitic Ironstone Formation, Wadi Halfa and Argein Areas, North Sudan

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***Abstract*—**In present study, a large deposit of oolitic iron ore of Late Carboniferous-Permotriassic-Lower Jurassic age was discovered in Wadi Halfa and Argein areas, North Sudan. It seems that the iron ore mineralization exists in the west and east bank of the River Nile of the study area that are found on the Egyptian-Sudanese border. The Carboniferous-Lower Jurassic age strata were covered by 67 sections and each section has been examined and carefully described. The iron-ore in Wadi Halfa occurs as oolitic ironstone and contained two horizons: (A) horizon and (B) horizon. Only horizon (A) was observed in southern Argein area. The texture of the ore is variable depending on the volume of the component. In thin sections, the average of the ooids was ranged between 90%-80%. The matrix varies between 10%-20% by volume and detritus quartz in other component my reach up to 30% by volume in sandy massive ore. Ooids size ranges from 0.2mm-1.00 mm on average in very coarse ooids may attend up to 1 mm in size. The matrix around the ooids is dominated by iron hydroxide, carbonate, fine, and amorphous silica. The probable ore reserve estimate of 1.234 billion at a head grade of 41.29% Fe for the Wadi Halfa Oolitic Ironstone Formation. The iron ore shows higher content of phosphorus ranges from 6.15% to 0.16%, with mean 1.45%. The new technology Hatch–Ironstone Chloride Segregation (HICS) can be used to produce commercial-quality of iron and reduce phosphorus and silica to acceptable levels for steel industry. The presence of infrastructures in addition to the presence of massive quantities of iron ore would make exploitation economically.

Keywords—HICS, Late Carboniferous age, Oolitic iron ore, phosphorus.

I. Introduction

SUDAN is a far-flung country; but still virgin and rich in natural resource materials which represent a strong base for development. These primary materials consist of oil, minerals (gold and rare metals), and dimensional or ornamental stones. This study is focusing on oolitic ironstone deposits. The study area is located in extreme Northern of Sudan (Fig. 1). The area is including Wadi Halfa and Argein areas. The area is covered with Paleozoic and Mesozoic sedimentary strata which extend to the north into Egypt. The area is accessible by railways (Port Sudan-Atbara- Wadi Halfa, Khartoum-Atbara-Wadi Halfa) an asphalted road (Khartoum-Dongola-Elselem-Wadi Halfa) and Ship {from Aswan (Egypt) to Wadi Halfa (Sudan)}.

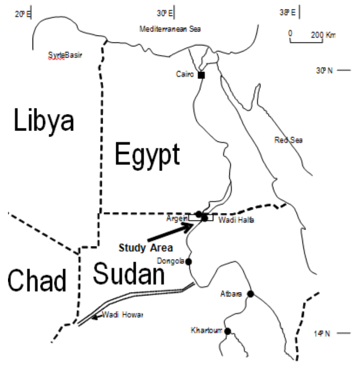

Fig. 1 The location of the study area

The landscape of the study area is made up of huge plains interrupted by escarpments and plateaus of oolitic ironstone and clastic sedimentary rocks. The study area lies in the desert climate region which is characterized by very high-temperatures in the afternoons and low-temperatures in the mid-nights. A small number of foxes and other desert animals survive in the increasing aridity of the region.

The first sedimentological studies of the North and Northwestern Sudan were published by [1]–[17].

The primary aim of this study is to characterize the Paleozoic and Mesozoic Strata of Northern Sudan in terms of facies types, depositional environment and emphasis on oolitic iron ore mineralization, quality and quantity. The study involved both field and laboratory investigations. In the field, the facies analysis of strata is based on sedimentary profiles. Each profile has been examined and described in term of all facies aspects. The examination and description involved fresh color, weathering color, sedimentary structures, paleocurrent direction, fossils, and iron ore content. The laboratory work based on analysis of oolitic ironstone samples which were collected from the profiles.

II. Regional Geology and Tectonic setting

Pre-existing shear zones and their rejuvenation in general have controlled the structural evolution in the Sudan and NE Africa by plate motion through time [3], [6]. During Precambrian period, the high grade poly metamorphic and granitoids west of the Nile (Fig. 2) are part of the pre-Pan-African; while the Basement east of the Nile comprises the

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Pan-African meta-volcanic, meta-sedimentary ophiolite and related granitoids assemblage of Nubian shield. But the rocks of the late Archean occur in a limited Basement Complex in the surrounding of Jebel Uweinat [6]. Thus, the Pan-African tectono-thermal event was dominated during the Precambrian. During the late Proterozoic, the Central African Shear Zone was initiated and can be traced from Cameroon, through Central Africa, Chad, to North Kordofan in Central Sudan; and probably further into the Red Sea in NE Sudan Fig. 2; thus, representing one of the major shear zones of lithosphere weakness in Africa [6]. The structural pattern in NE Africa plate during Paleozoic-Mesozoic shows that the African continent; was generally in a state of extension from the Early Mesozoic until the recent time. This beginning with the break of Gondwana in the Permotriassic and resulting in African continental margins and several of intra-continental rift basins, these basins are located mainly in older (Late Proterozoic) shear zones [18]. In the NE Africa the structural pattern during Cambrian and Carboniferous time was controlled by large NNW-SSE striking shear zones, which are generally wide graben and small horst block, such as Kufra basin (in Libya) and Dakhla basin (Fig. 2). In the Late Carboniferous, the collision of Gondwana with North Continent initiated ENE structures by re-opening of pre-existing zone, and rising magma caused uplift in Jebel Uweinat area. During this period extensive basins were developed and filled gradually with fluvial sandstone and conglomerate of Permotriassic to Lower Jurassic age (Lakia Formation). The structural regime controlling sedimentation and basin differentiation since the Late Carboniferous continued until Early to Middle Jurassic [6]. The extensional tectonics related to the differential opening of the Atlantic and the Indian Ocean, lead to the formation of Central and Southern Sudanese rift basins; such as Southern Sudan rift, White Nile rift, Blue Nile rift, Atbara basin and Humar basin. These rift basins are considered as part of the Central African rift system [19]. The sedimentation in this period had been restricted in the Blue Nile basin and in Northwest Sudan, as marked by Gilf Kebir Formation. The Early Cretaceous period was marked by the continuation of the development of the central and southern interior rift basins [7]. During the Late Cretaceous the differentiation of the NE African plate increased, indicating the beginning of the Red Sea rifting and this period was marked by the sedimentation of Wadi Howar, Kababish and Jebel Abyad Formations in NW Sudan [4]–[6]. Two pairs of E-W trending uplifts and troughs, which include: (1) The Third Cataract Arch/Selima-Toshka Trough and (2) the Gebel Uweinat-Bir Safsaf-Aswan Uplift/Kom Ombo graben [20] (Fig. 2). These Two pairs of E-W trending uplifts and troughs have been active since early-Mesozoic time; and led to the formation of the Nubian Swell in southern Egypt and northern Sudan [20] (Fig. 2). Nubian Swell is defined as 500 km wide zone of uplifted Neoproterozoic crystalline basement and Paleozoic sediments and parallel troughs extend west ward for more than 800km from the flank of the Red Sea Hills [20]. During the Cenozoic time (Pleistocene), the area between southern Egypt and North Sudan has been uplifted [20].

In north Sudan and south Egypt, the sedimentary strata within the basins appear to be controlled by the reactivated NNW-SSE, NE-SW, E-W and N-S trending structures [4], [6], [20]. In the North, and NW Sudan and SW Egypt, the Paleozoic-Mesozoic sediments consists mainly of fluvial and glacial strata intercalated with deltaic and shallow marine sequences [4], [8]–[17]. Reference [4] divided the so called "Nubian Strata" of NW Sudan and SW Egypt to three cycles and more than 20 formations. Reference [5] concluded that the term "Nubian Sandstone" is unjustified form both the sedimentological and stratigraphical points of view. This is because the term "Nubian" has been used in NE Africa to describe strata of different ages and environments. The subdivisions of these formations are based on stratigraphical and Paleontological evidence, fieldwork and fits logically in the regional framework:

- The Lower cycle expands from Cambrian to Lower Carboniferous age and consists of Karkur Talh, Um Ras, Tadrat and Wadi Malik Formations.
- The Middle cycle expands from the Upper Carboniferous To Lower Jurassic age and consists of Northern Wadi Malik and Lakia Formations.
- The Upper cycle expands from Upper Jurassic to Tertiary age and consists of Gilf Kebir, Wadi Howar, Kababish and Jebel Abyad Formations.

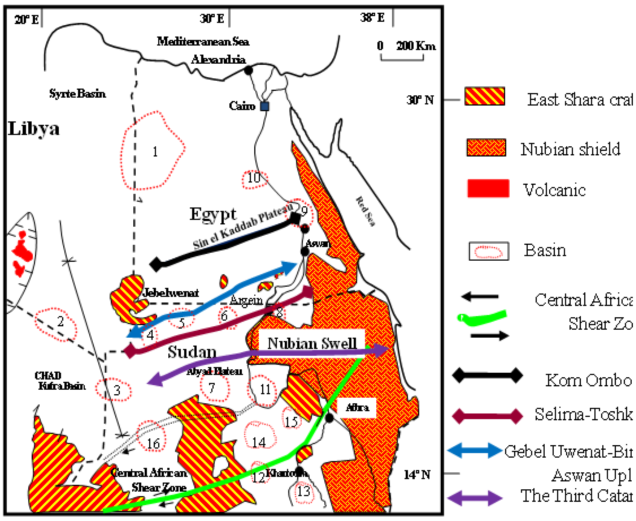

Fig. 2 The Intracratonic basins configuration in North East Africa (Modified after [7], [17], [20], [21]) (1=DakhlaBasin, 2=Kufra Basin, 3=Murdi Depression, 4=Mourdi (Karb Eltoum Basin), 5= Misaha Trough, 6=Selima Basin, 7= Abyad Basin, 8= Nile or Gabgaba Basin (Wadi Halfa Basin), 9=Kom Ombo Basin, 10=Asyut Basin, 11 =Deba Basin, 12= Bagbag Basin, 13= Khartoum Basin, 14= Humar Basin, 15= Gilif Basin), 16= Wadi Howar)

III. Wadi Halfa Oolitic Ironstone Formation

A. Type Section of Wadi Halfa Oolitic Ironstone Formation

This formation has thickness up to 89 m and covers large area of more than 500 km^2 (Fig. 3) (N 21° 51′ 44.9", E 31° 21′ 53.2").

B. Type Locality of Wadi Halfa Oolitic Ironstone Formation

Wadi Halfa Oolitic Ironstone Formation is located in Wadi Halfa City near the Nubian Lake in the extremely northern Sudan bordering south Egypt. The type locality of Wadi Halfa Oolitic Ironstone Formation is about three km north Wadi Halfa market.

C. Naming of Wadi Halfa Oolitic Ironstone Formation

The Wadi Halfa Oolitic Ironstone Formation is a geological formation consists of thick alternating beds of shale, siltstone, and sandstone and marked by thin key bed of oolitic ironstone. The Wadi Halfa Oolitic Ironstone Formation was named based on Wadi Halfa City and by marked key bed of oolitic ironstone.

D. Age of Wadi Halfa Oolitic Ironstone Formation

The Wadi Halfa Oolitic Ironstone Formation is a geological formation dates back to 175 million years ago and covering the Late Carboniferous-Permotriassic-Lower Jurassic age. The Wadi Halfa Oolitic Ironstone Formation is found in Wadi Halfa area extremely northern Sudan. As its name suggests, it consists mainly of sandstone and Oolitic ironstone. The age assignment is based on the presence of plant fossils aff. *Sigillaria* sp., *Sigillaria* aff. *boblayi, Rhodea* aff. *lontzenensis,* aff. *Walchia* sp., *Paleoweichselia* aff. *defrancei, Calamites* sp., and *Pterophyllum nubiense, Pecopteridae* aff. *Paleoweichselia,* aff. *Ginkgoites*, aff. Coniferales. Marine sediments were indicated by the presence of ichnofossils e.g. *Arthrophycus* sp., *Rhizocorallium* sp., *Skolithos* sp.

E. Facies Description of Wadi Halfa Oolitic Ironstone Formation

Total of (67) sections have been described and analyzed in the study area, covering the strata of Upper Carboniferous to Lower Jurassic age. The main objectives of this study are to characterize the facies types, thickness of Oolitic ironstone and overburden. Ten facies have been recognized: St, Sp, Sh, Fl, Fm, Sr, Shm$_1$, Shm$_2$, F0i and Fd. Trough cross–bedded sandstone facies (St) is composed mainly of medium to very coarse grained sandstone with some pebbles. Planar cross-bedded sandstone facies (Sp) consists of medium to coarse grained moderately sorted sandstone, yellowish to brownish. Horizontally stratified sandstone facies (Sh) facies is distinguished by flat, parallel lamination, with parting lineation occurring on bedding planes, very fine to very coarse. Fine laminated mudstone facies (Fl) is composed mainly of brown, white, and grey fine laminated mudstone. Massive mudstone facies (Fm) is composed mainly of red, white, and grey mudstone. Rippled sandstone facies (Sr) consists of fine to medium sandstone containing ripple marks. Horizontally stratified shallow marine sandstone (Shm$_1$) is composed of medium to coarse brownish sandstone. Horizontally stratified shallowmarine sandstone (Shm$_2$) is composed of medium to coarse brownish sandstone. Shallow marine Oolitic ironstone facies (Foi) is recorded in Argein and Wadi Halfa areas. This facies is represented by one to three layers with thickness (20 – 100 cm) in Wadi Halfa and only one layer in Argein with variable thickness (15-50 cm).

Oolitic ironstones beds extend laterally for more than30 km and containing *Skolithos* sp., *Rhizocorallium* sp., cockade texture and having density more than 3 g/cm3. Glacial sediments (Fd) are found in the all sections with thickness of several meters. Three facies types of glacial sediments have been recognized: 1) Diamictites facies, 2) Dropstone facies, and 3) Platy fragments of silicified sandstone like a disk shape facies. Diamictites facies overlay the herringbone cross stratification facies at Argein area. It composed mainly of rock fragments of yellowish to brownish sandstone, Ferruginous sandstone and quartz pebbles. The size of the fragments range from 2mm to 70 cm embedded in a matrix of sand silt and clay. This diamictites facies was hitherto thought to be either of Late Ordovician-Early Silurian or of Late Carboniferous-Early Permian age. Dropstones facies are composed laminated siltstone deformed by the impact of large dropstones falling onto sedimentary surface. Platy fragments of silicified sandstone like a disk shape facies are found in hummocky cross bedded sandstone. Thus, the lithofacies types which are found in Wadi Halfa Oolitic Ironstone Formation might interpret as tillites, glaciofluvial-glaciolacustrine to marine depositional environments.

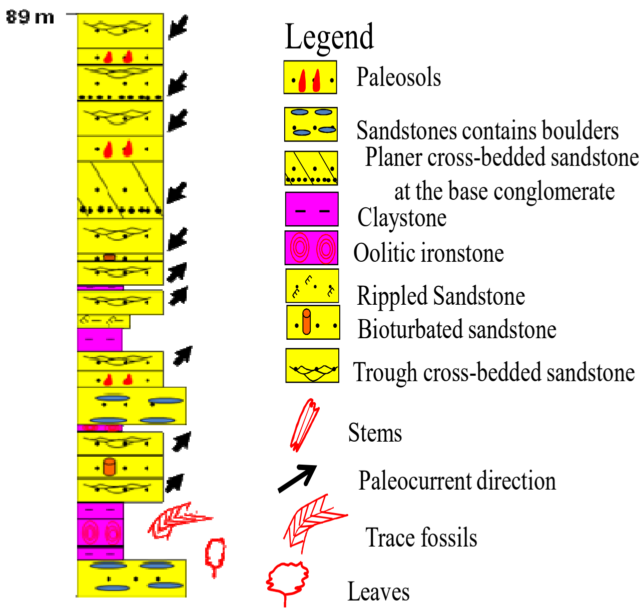

Fig. 3 Llithofacies of Wadi Halfa Oolitic Ironstone Formation

IV. Iron Mineralization

The studies of oolitic ironore in Sudan and south Egypt were published by [2], [14], [16], [22]–[34]. The iron mineralization occurs in east and west of the River Nile (Wadi Halfa and Argein areas), near border between Sudan and Egypt. The iron-ore is bounded by latitude 21 ° 59' N -21° 39' N and longitude 31° 54' E-31° 00' E. The mineralization is invariably confined to the Wadi Halfa Oolitic Ironstone Formation of Late Carboniferous-Permotriassic to Lower Jurassic age. The iron-ore of Wadi Halfa occurs as oolitic ironstone and contains two horizons: a lower and upper referred to in this study as (A) horizon and (B) horizon, respectively (Figs. 4 and 5). The "A" horizon is composed of one band of iron-ore with an average thickness ranging from 100 cm to 20 cm.

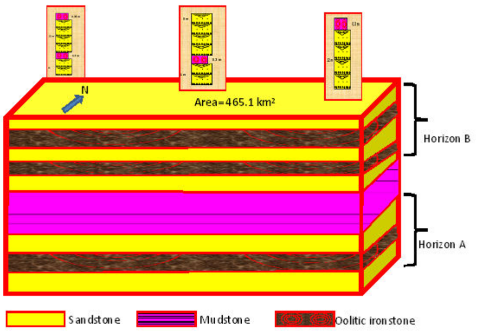

Fig. 4 The iron-ore of Wadi Halfa occurs as oolitic ironstone and contains two horizons: (A) horizon and (B) horizon

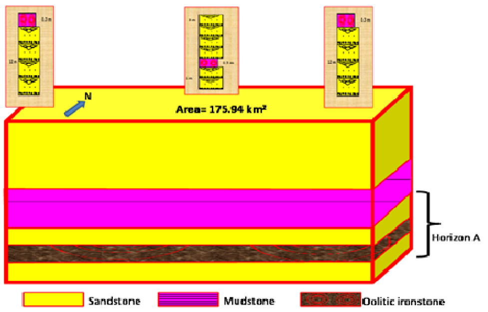

Fig. 5 Oolitic ironstone of Argein occurs as one horizon (A)

The "B" horizon is of wider extent and is represented by either one, two or three bands of iron ore varying in thickness from 20 cm to about 100 cm. The majorities' thicknesses of this band range between 30 cm to 50 cm. The "A" and "B" horizons are separated from each other by layers of mudstone ranging in thickness from 2.00 m to about 4 m. The overburden above the ore varies from 0 to about 30 m. The majority of the overburden thicknesses range between 1-3 m. The iron-ore bands are often associated with ferruginous sandstones and clays. Transitions from ferruginous sandstone to oolitic iron-ore are often encountered. The iron mineralization of Argein occurs as one horizon (A). The "A" horizon is composed of one band of iron-ore with an average thickness ranging from 100 cm to 20 cm). In most of the locality, the thickness of this band ranges between 30 cm to 50 cm. The overburden above the ore also varies from 0 to about 30 m. The majorities overburden thicknesses range between 1-3 m. The iron-ore bands are often associated with ferruginous sandstones and clays. Transitions from ferruginous sandstone to oolitic iron-ore are also often encountered similar to that of Wadi Halfa.

V. Petrology and Mineralogy Analysis

As already mention the oolitic iron ore of Wadi Halfa and Argein area occurs as thin beds and lenses within the sedimentary units of Wadi Halfa Basin (Gabgaba or El Nile Basin) and Selima Basin. A number of representative thin section and polish surfaces have been prepared and studied under microscope. The oolitic ironstone facies consists entirely of closely spaced (grain–supported) ferruginous Ooids with less abundant detritus quartz grains and ferruginous clay materials. In thin sections, the shape of the Ooids varies from well rounded concentric to oval and lensoidal (Fig. 6 (a)). The lensoidal and oval ooids show evidence for elastic deformation probably during diagenesis and later cataclastic deformation indicated by later fractures affecting both of the ooids and the matrix, filled with goethite (Fig. 6 (b)). The colors of oolitic ironstone vary from reddish, brownish, yellowish, and purple to black. The oolites can be seen by an unaided eye with diameters less than 2 mm. Ooids comprised between 90-80 % by volume of the oolitic ore. The ooids are composed of concentric zones of iron oxide and hydroxide. The matrix around the ooids is dominated by iron hydroxide, carbonate, fine and amorphous silica with other materials. Although hematite, goethite and limonite are the main ore minerals components, detritus magnetite and pyrite have been observed in some samples (Figs 6. (c)-(f)). The presence of detritus magnetite and pyrite may indicate a proximal source area of basement rich in these minerals which is likely to be the neighboring juvenile Pan African Units.

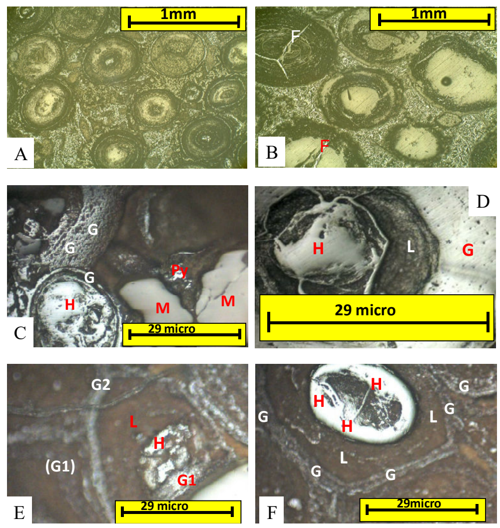

Fig. 6 (a) Ooids with different shapes and composition (circular ooid, oval ooid and lensoidal ooid); (b): Ooids with late fractures (f); (c): Ooid with hematite core (h), goethite rime (g), and magnetite detritus grains (m), pyrite (py); (d): Ooid with hematite core (h), goethite rime (g), and limonite rime (l); (e): Oval ooid with hematite core (h), goethite rime (g1), posdaigentic goethite fracture filling (g2), limonite (l); (f): Lensoidal ooid with hematite core (h), goethite rime (g), limonite rime (l)

VI. Geochemical Results

Twenty nine representative samples from Wadi Halfa and Argein have been analyzed (GRAS Lab., OMAC Lab.).The chemical analyses include full geochemical assay results of elements for each sample taken in the Ores (Tables I).

TABLE I
THE CHEMICAL ANALYSIS RESULTS OF THE ORE FOR WADI HALFA AND ARGEIN AREAS

Elements	SiO_2	Al_2O_3	CaO	Cr_2O_3	Fe_2O_3 OMAC	Fe_2O_3 G.R.A.S	Fe G.R.A.S	K2O	MgO	MnO	Na_2O	P_2O_5	S	TiO_2	LOI at 1000C	Ba	Tm	V	W	Y	Yb	Zr
Highest Value	57.88 %	8.88 %	9.29 %	0.032 %	77.76 %	81.00 %	56.6 %	0.69 %	0.71 %	3.7 %	1.48 %	6.15 %	1.55 %	1.05 %	15.66 %	3295.7 ppm	1.2 ppm	843.7 ppm	23.1 ppm	103.3 ppm	7.7 ppm	387 pm
Lowest Value	2.03 %	2.12 %	0.01 %	0.005 %	28.52 %	32.25 %	22.56 %	<0.01 %	<0.01 %	0.016 %	0.01 %	0.16 %	0.05 %	0.04 %	2.72 %	93.5 ppm	0.1 ppm	54.7 ppm	<0.5 ppm	10 ppm	1.0 ppm	20 ppm
Mean	29.95 %	5.5 %	4.65 %	0.013 %	57.41 %	59.04 %	41.29 %	0.35 %	0.36 %	1.56 %	0.75 %	1.45 %	0.18 %	0.17 %	9.19 %	1694.6 ppm	0.65 pm	476.4 ppm	11.8 ppm	56.65 ppm	4.35 pm	204 pm

G.R.A.S= Geological Research Authority of Sudan, Lab analysis
OMAC= Ireland Lab analysis

The analysis results of the representative samples indicate that the quality of the ore is good and compare well with similar oolitic iron ores, with average grade above 58% Fe_2O_3. The oolitic ores would need to be upgraded prior to shipment. The metallurgical process shows that the phosphorus is high, and it can be reduced but it is expensive. The new technology Hatch–Ironstone Chloride Segregation (HICS) can be used to produce commercial-quality of iron and reduce phosphorus and silica to acceptable levels for steel industry [35], [36]. The estimated geological reserve is about 1.234 billion tons at 41.29% Fe (Table II). The development of infra structures and presence of huge quantity of iron ore would make exploitation of the iron ore economic.

TABLE II
SHOWING GEOLOGICAL RESERVE ESTIMATION

Wadi Halfa and Argein	Geological Reserve Estimation Million tons
This study	1234
[23]	441-882
[25]	250

VII. CONCLUSIONS

Sudan is a far-flung country but still virgin and rich in oolitic ironstone especially in Northern State. The areas investigated have been regionally mapped to 1:75.000. Four units have been recognized: (1) Basement unit (2) Ordovician-Silurian-Devonian unit (3) Upper Carboniferous (Pennsylvanian)-Permotriassic to Lower Jurassic unit (hosts oolitic ironstone).

Wadi Halfa Oolitic Ironstone Formation which hosts iron mineralization was characterized by high sea level, accompanied by a major transgression on northern Sudan and southern Egypt, which leaded to the deposition of Oolitic ironstone in Wadi Halfa and Argein areas.

The iron-ore of Wadi Halfa occurs as oolitic ironstone and contains two horizons: (A) horizon and (B) horizon. Only horizon (A) has been observed in south Argein area perhaps due to deep erosion.

The iron-ore bands have an average thickness ranging from 1 to 0.1 m, the majority of them is ranging in thickness between 0.3 to 0.5 m. The Overburden thickness is between 1-30 m, where the majority of them is ranging between 1-3 m.

The iron ore is more than 80% oolitic with some massive and laminated facies. The most common ore minerals are hematite, goethite, and limonite. Detritus grains of magnetite sometimes with pyrite have been observed. Quartz is main gangue mineral. It appears that, the iron ooids of Wadi Halfa Oolitic Ironstone Formation might have been formed in a sedimentary basin from land-derived iron rich constituents such as Al Bir and Malik Elnasir Areas.

The results of the analysis on representative samples indicate that the quality of the ore is good and compare well with similar oolitic iron ores, with average grade above 58% Fe_2O_3.

The metallurgical process shows that the phosphorus is high, and it can be reduced but it is expensive. The new technology Hatch–Ironstone Chloride Segregation (HICS) can be used to produce commercial-quality of iron and reduce phosphorus and silica to acceptable levels for steel industry.

The estimated geological reserve is about 1234 Million tons at 41.29 %Fe.

The concession area witnesses development in infra structures such as:

- Asphaltic road of Wadi Halfa-Elselem-Dongola-Khartoum.
- Asphaltic road of Wadi Halfa-Elselem-Um Elture-Atbara-Portsudan.
- Asphaltic road of Argein -Dongola-Khartoum.
- Marrowy Dam for energy power supply.
- Railway (Wadi Halfa-Atbara-Portsudan).
- Pipe line of gas From Egypt to Wadi Halfa (proposed).
- Pipe line of gas From Sinar City to Wadi Halfa (proposed).
- These infra structures in additional to nearest of water (Nubian Lake) and huge quantity of oolitic ironstone would make exploitation economic.

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