Journal of Mining and Geology Vol. 58(2) 2022. pp. 57 - 73 0022-2763
© Nigerian Mining and Geosciences Society (NMGS) - Printed in Nigeria.

Typology of Fe-Coated Grains and Diagenetic History of Agbaja Ironstone Formation Exposed at Mount Patti and Koto – Karfi, Southern Bida Basin, Nigeria

Bamidele, T.E.[1], Ojo, O.J.[2] and Adepoju, S.A.[1]

[1]Department of Geology and Mineral Sciences, Kwara State University, Malete, Nigeria.

[2]Department of Geology and Mineral Sciences, Federal University, Oye – Ekiti, Nigeria.

Corresponding E-mail: **toba. bamidele@kwasu. edu. ng**

Abstract

Ooidal ironstones from theMaastrichtian Agbaja Formation, Bida Basin in the north central Nigeria were investigated and sampled around Mount Patti and Koton – Karfi where they formed consistent cap over the older sedimentary sequence. The ironstone samples collected from the outcropping sections were subjected to microscopic and mineralogical studies in order to examine their texture diagenetic history and origin. The ironstone iswell indurated, dark to reddish brown and occurs as oolitic – pisolitic, laminated – massive and concretional lithotypes. The ironstones as well as the associated lithologies are characterized by cross and parallel laminations, ripple marks with burrows of *Thalassinoides* and *Skolithos ichnogenera*. Thin section and Scanning Electron Microscopy images reveal scars on the surface of some Fe – coated grains which is interpreted to have been due to attrition, abrasion and impart during transportation. The main textural components include: true and superficial ooids, oncoids, matrix, pores, lithorelicts and bioturbations with varying level of iron replacement. X – Ray Diffraction result reveal that kaolinite and quartz are the main detrital precursors in the ironstone while goethite, hematite and magnetite form the diagenetic Fe-bearing minerals. Finning upward depositional characteristics, bioturbations, well as broken and scoured surface coated grains suggest a high energy shelf environment with agitated hydrodynamic conditions. Diagenetic processes responsible for the formation of the ironstones include precipitation, replacement, recrystallization and dehydration of Fe-oxide. The study shows that the ironstones are mainly post-depositional in origin with evidences of progressive replacement of the precursor kaolinitic coated grains and groundmass by iron oxide.

Keywords: *Agbaja ironstone, Fe – coated grains, lithorelicts, diagenesis and microfabric*

Introduction

Ooidal ironstones are chemical sedimentary rocks that contain ≥ 15% metallic iron by weight (James, 1966) with >5vol. % coated grains and >15 wt. % iron, which corresponds to 21. 4wt. % Fe_2O_3 (Young, 1989;Petra'nek and Van Houten,1997; Mucke and Fashard, 2005). The origin and nature of ferruginous coated grains,their distribution, occurrence in the Phanerozoic Eon, unique textural and mineralogical compositions, anddepositional characteristics havealways been of research interests (Kimberley, 1994; Maynard, 1986; Petra´nek and Van Houten, 1997). This is because they provide insights to the physical and chemical conditions of sedimentary environments where they are formed and therefore are signi? cant in the palaeoenvironmental reconstruction (Flügel, 2004).

In the southern Bida Basin, ironstones of the Agbaja Formation are widely distributed occurring in Agbaja Plateau, Koton – karfi, Mount Patti, Enegbaki and Bassa Nge (Fig. 1). However, most studies have concentrated on the Agbaja Plateau (Adeleye, 1973; Ladipo et al., 1994; Abimbola, 1997; Abimbola et al., 1999; Mucke*et al.,* 1999; Mucke and Fashard, 2005). Recently, sideritic concretions were reported from Patti Formation (Ojo et al., 2020) in the same basin.

In the present study, ooidal to pisolitic ironstones at Mount Patti, Bassa Nge and Koton-Karfi areas are investigated with a view to further constrain the Maastrichtian paleogeography of Nigeria and Africa. The main objectives are to describe the general characteristics of the ooidal ironstone which include their field, petrographical and mineralogical characteristics, unravel the physical, chemical and biological conditions thatprevailed during deposition of the ironstone. The diagenetic processes through which the ironstone was formed are also examined. This is with a view to provide improved understanding of the enigmatic complexities involved in the, formation of Fe – coated grains and origin of ooidal ironstones and their regional paleogeographic implications.

Location of the Study Area

The study area is located within latitudes $7^0$30' and $8^0$30' N and longitudes $6^0$30' and $7^0$00' E in the southern Bida Basin. The areacovers Mount Patti and Koton – Karfi to the western and northwestern part of the confluence of rivers Niger and Benue in the northcentralNigeria (Fig. 1) and can be accessed through the Lokoja – Abaji – Abuja express way. The study area is part of the several mesas that form the major physiographic features of the Bida Basin.

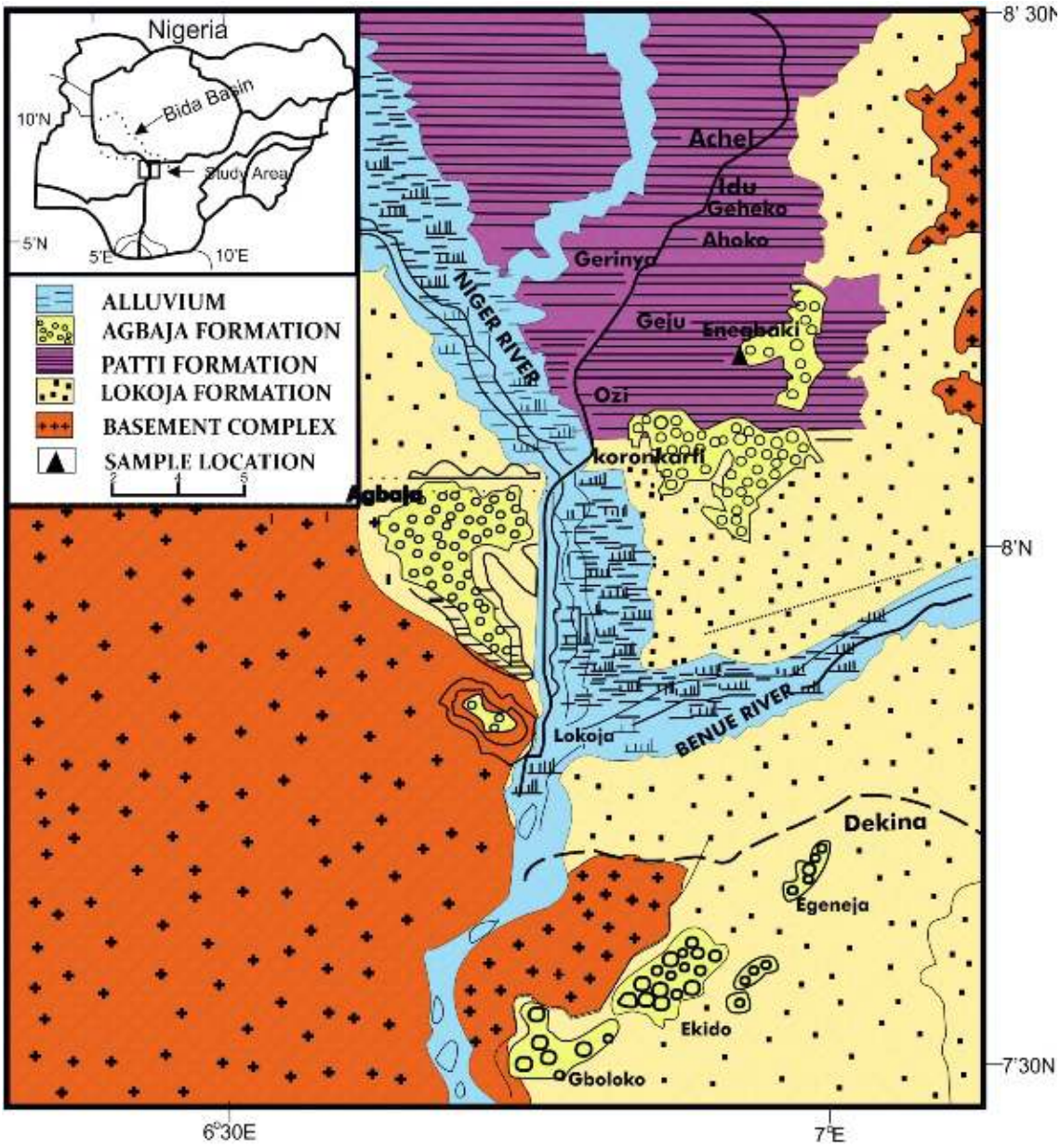


Fig. 1: Geological map of the southern Bida Basin showing the Mt Patti area to the west of Lokoja and Koton-karfi area to the north of the confluence of river Niger. (Modified after Ojo and Akande, 2009).

Basin Evolution and Sedimentation History

The Bida Basin in the northcentral Nigeria is a northwest southeastern trending inlandsedimentary basin. The basin is a linear depression with shallow sedimentary fill of about 3,000 m thick (Udensi and Osazuwa, 2004). The basin which is perpendicular to the main axis of Benue Trough has been described as a rift bounded tensional structure produced by faults associated with the breakup of the Gondwana (King, 1950; Kennedy, 1965).

The pioneering work on the depositional sequence in the Bida Basin is by Adeleye (1973,1974). Other research efforts that have contributed significantly to the stratigraphy of the basin include that of Jan du Chene et al. (1978), Mebradu et al. (1986) and Agyingi (1993).

Stratigraphic successions in the basin comprise of the Northern Sub-Basin in the Bida area and the Southern Sub-Basin in the Lokoja area (Jones, 1958). The Bida Basin was regarded as the northwestern extension of the Anambra Basin (Akande et al., 2005). The basin is characterized bynorthwest trending Campanian–

Maastrichtian sediments deposited as a result of block faulting, basement fragmentation, subsidence, rifting and drifting connected to the opening of the South Atlantic Ocean in the early Cretaceous. The southern Bida Basin was interpreted to be controlled by NW-SE trending faults as revealed by Landsat imageries (Kogbe et al., 1981). There is a convergence of opinion in support of rift origin and indeed the authors have linked the origin of Bida Basin to the well published mid Cretaceous Benue mega structure (Kennedy, 1965 and Ojo and Akande, 2012).

Sedimentation started in the basin with the Campanian Lokoja Formation, which overlies non-conformably, the Precambrian to Lower Paleozoic crystalline basement rocks (Fig. 2). The formation comprises of conglomerates, sandstones and claystones lithologic units which are thought to have been deposited in alluvial fan to shallow marine environments (Ojo and Akande, 2003). The Lokoja Formation is overlain by the Maastrichtian Patti Formation, and is made-up of intercalations of sandstone, shale, siltstone, claystone and ironstones (Ojo *et al.,* 2020). Campanian to Maastrichtian age have been assigned to the shale-claystone and sandstone member by Jan du Chene*et al*. (1978) and Agyingi (1993) respectively. A meandering river system have been suggested by Agyingi (1991) as depositional model for the Patti Formation sediments. Although Braide (1992) interpreted the shale-claystone member as nonmarine swamp sediments, Ojo and Akande (2006) however interpreted through paleoecologic studies that the basal part of the shale-claystone member represents a period of shallow marine flooding during the Maastrichtian.

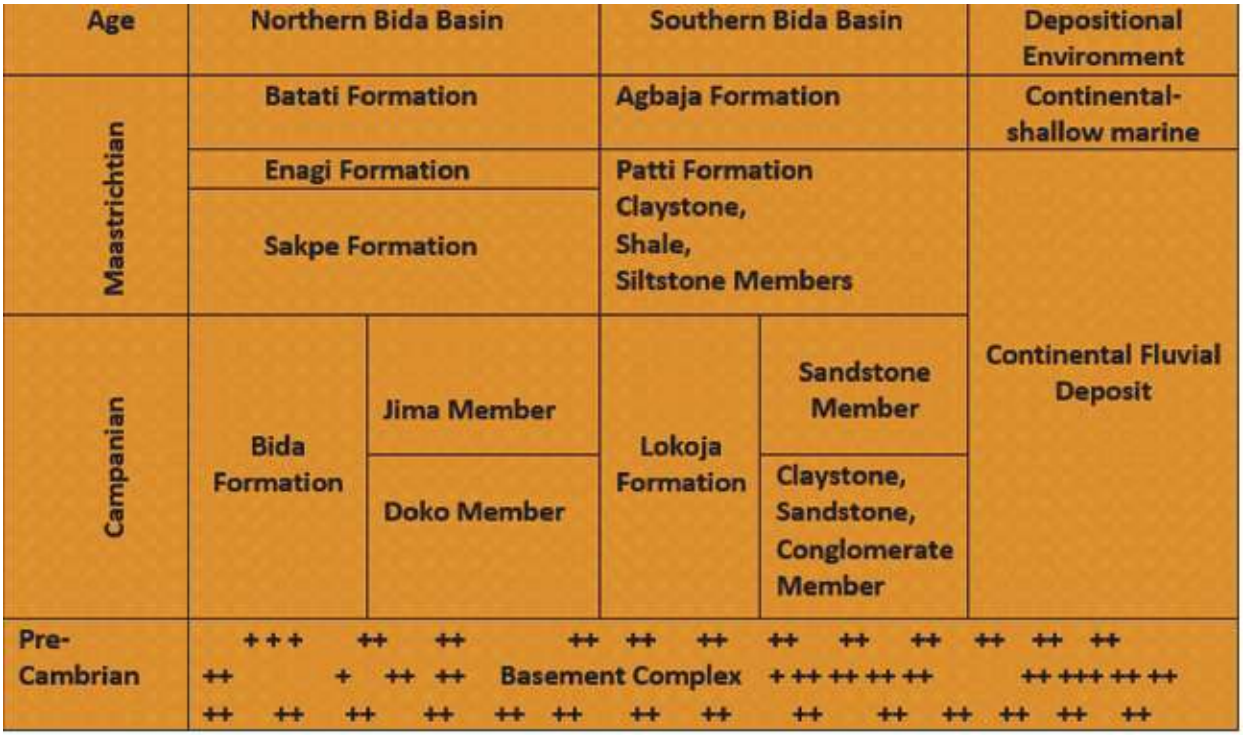


Fig. 2: Stratigraphic framework of the Bida Basin (Modified after Adeleye, 1973).

The uppermost lithostratigraphic unit is the Agbaja Formation which directly overlies the Patti Formation on the Agbaja Plateau and in many other locations. The Formation is characterized byoolitic – pisolitic, laminated – massive and concretional ironstone facies and forms the lateral equivalent of Batati Formation in the northern Bida sub basin. As reported by Ladipo *et al.* (1994) and Muck*et al.* (1999) the ironstones were formed from minor marine reworking and replacement of some primary kaolinitic clay precursors.

Materials and Methods

The logging, description and sampling of Mount Patti and Koton – Karfi sections were carried out and produced vertical profiles of the sedimentary successions. The stratigraphic and textural relationship of the ironstone with associated lithologies such as shales, siltstones and sandstones were documented (Figs. 3 and 4).

Thin and polish sections of some selected ironstone

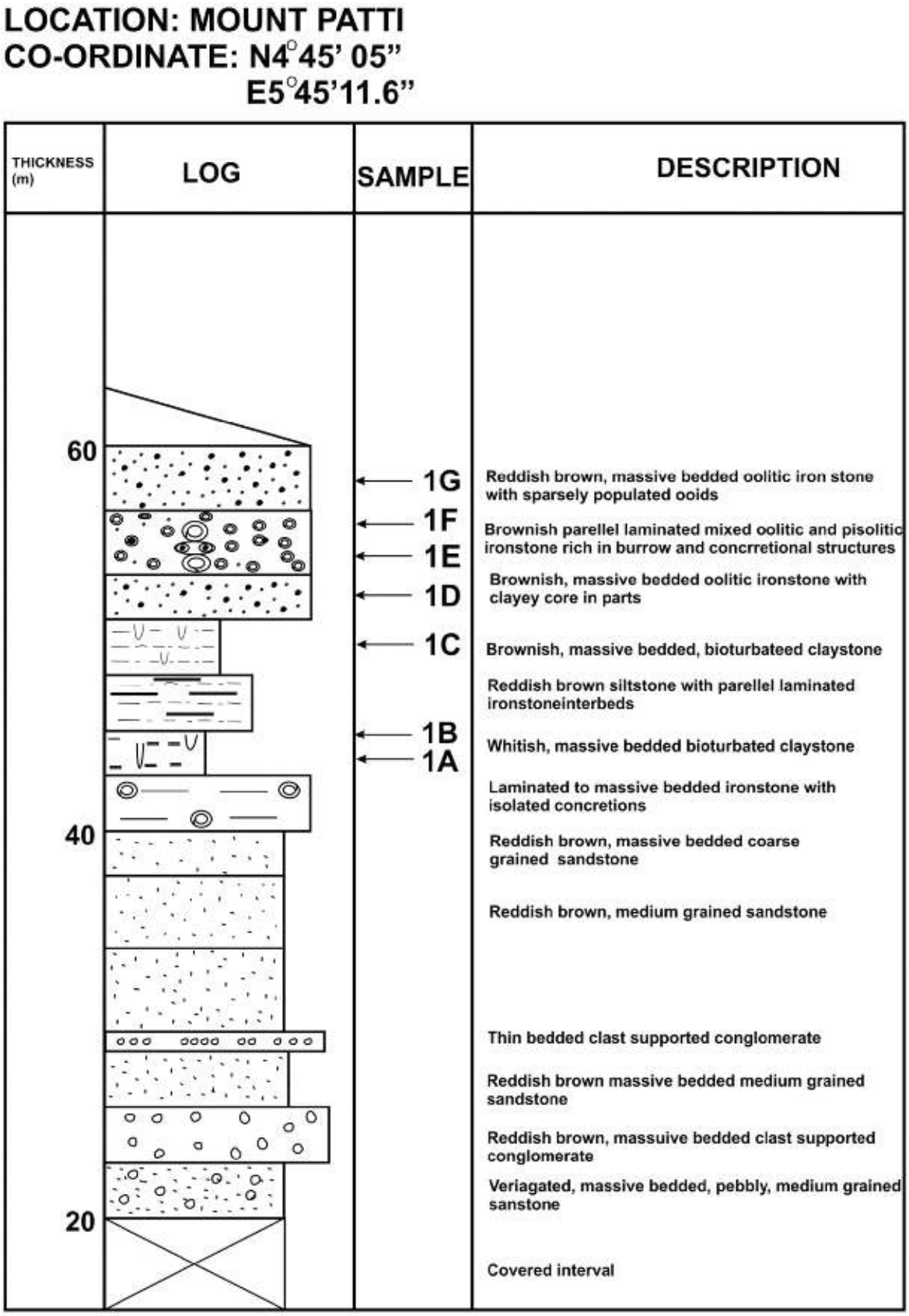


Fig. 3: Lithostratigraphic section of the section at Mount Patti to the west of the confluence of river Niger. The underlying lithologies of the capping ironstone represent the Lokoja and Patti formations. At this location, the exposed section attains a total thickness of 60 m.

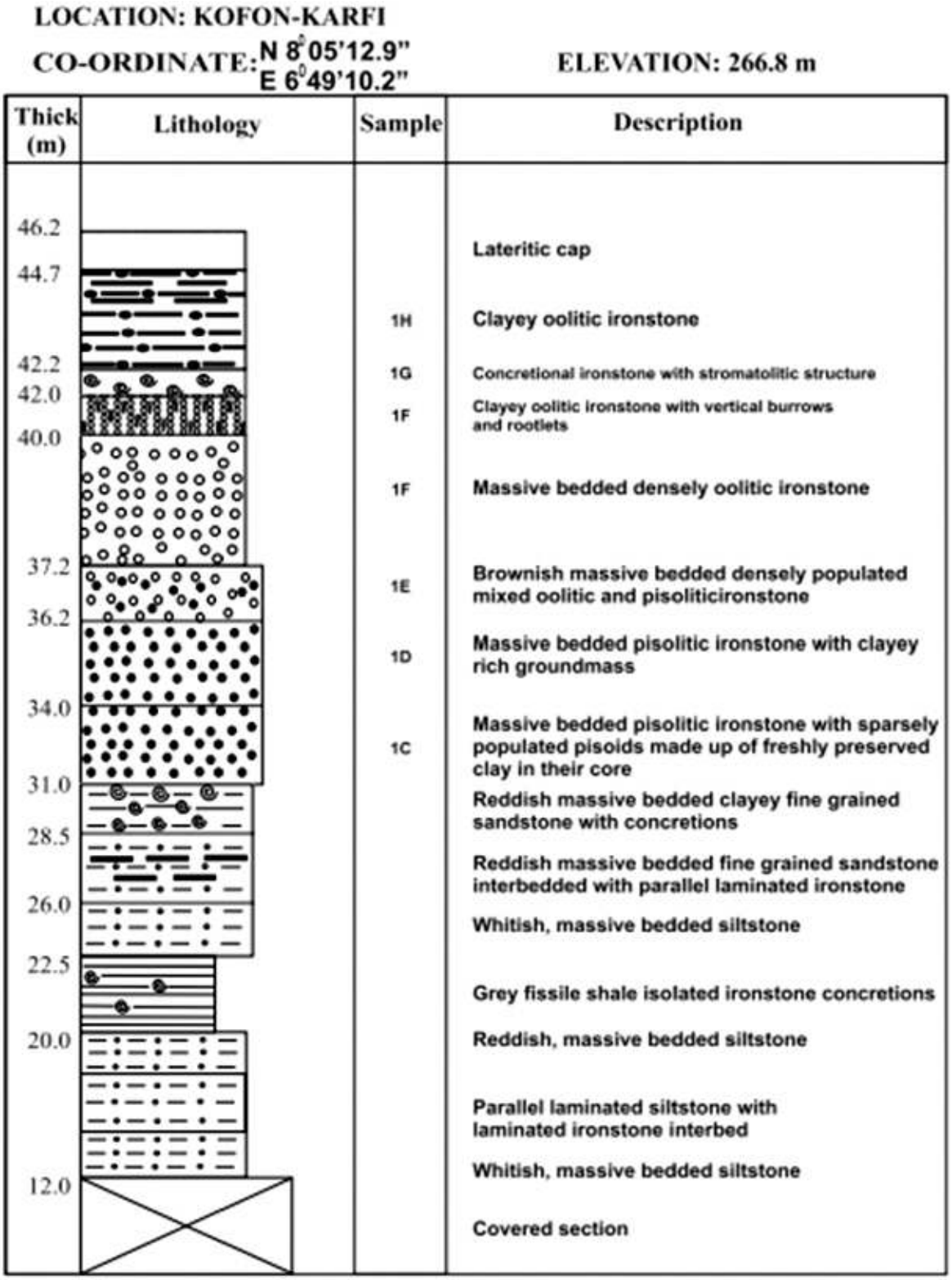


Fig. 4: Lithostratigraphic section at Koton-Karfi area, south of the confluence of river Niger. The underlying lithologies of the capping ironstone represent the Lokoja and Patti formations. At this location, the exposed section attains a total thickness of 46 m.

samples were prepared at the workshop of Geology and Mineral Sciences Department, Kwara State University, Malete and studied under transmitted and reflected light microscope to access the texture and composition of the ironstones. Scanning Electron Microscopy (SEM) analysis was carried out at the Department of Material

Science and Engineering laboratory, Kwara State University, Malete for six samples of the different lithofacies of the ironstone in order to diagnose and understand the micro and macro-structures as well as diagenetic relationships among the Fe – coated grains and matrix of the studied ironstone.

For the mineralogical investigation, powdered X-Ray Diffraction analysis was carried out at the Chemistry Department, University of the Free State, South Africa on representative sample using a riffle splitter, the samples were milled in a tungsten carbide vessel and prepared according to the standardized Panalytical backloading system, which provides nearly random distribution of the particles. The samples were analyzed using a PanalyticalX'Pert Pro powder diffractometer in θ–θ configuration with an X'Celerator detector and variable divergence- and fixed receiving slits with Fe filtered Co-Kα radiation (λ=1. 789Å). The phases were identified using X'PertHighscore plus software. The relative phase amounts (weight%) were estimated using the Rietveld method (Autoquan Program). Errors are on the 3 sigma level in the column to the right of the amount.

Results and Discussions

Facies

Field evidences reveal that the ironstones are dark to reddish brown, well indurated and occurs in association with sandstones, siltstones and claystones (Figs. 3 and 4). The ironstones as well as the associated lithologies are characterized by cross and parallel laminations, ripple marks, bioturbations and burrows of *Thalassinoides*and *Skolithos ichnogenus* (Figs. 5a, b, d, 6 a and c) which is an indication of close relationship in their origin before iron enrichment. The ironstones in the study are classified into oolitic – pisolitic, laminated – massive and concretional lithotypes (Figs. 5a-f and 6a-d). The ironstone occurs as interbed and dykes (Figs. 5a and 6a) within the transition interval with the underlying Patti Formation (Fig. 5d) and mostly as consistent cap over the investigated sections (Figs. 5c, e and 6b).

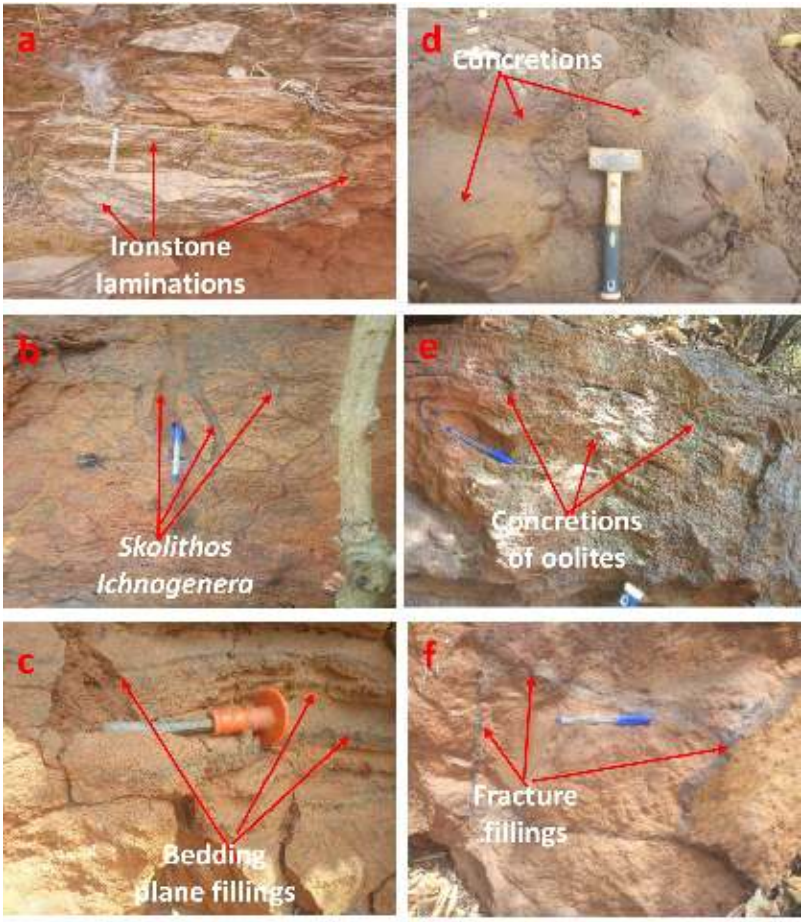


Fig. 5 (a – f): (a) Brownish, laminated to massive bedded ironstone (b) Brownish, massive bedded ironstone with common dwelling and feeding burrows,(c) Laminated pisolitic ironstone with iron-oxide filled bedding planes at Mount Patti (d) concretional ironstone at Mount Patti (e) Pisolitic ironstone at Mt Patti, and(f) Brownish, massive bedded ironstone with inter connected fracture fillings.

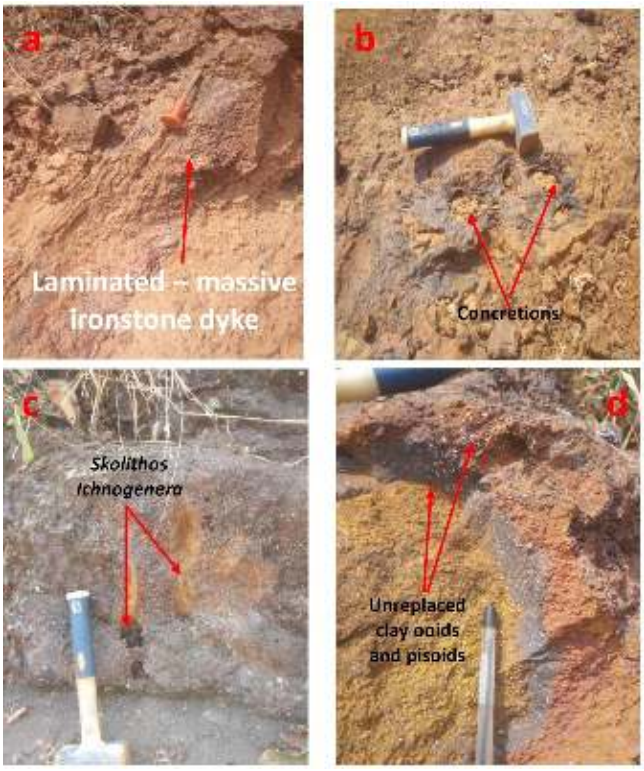


Fig. 6 (a – d): (a) Laminated – massive ironstone occurring as fracture filling at Koton Karfi (b) Concretional ironstone at the top of Koton - Karfi section (c) Dark brown massive bedded oolitic ironstone with vertical burrows at Koton - Karfi, and (d) Pisolitic ironstone with unreplaced kaolinitic coated grains at Koton - Karfi.

Oolitic – pisolitic Ironstone Lithotype

This lithotype is characterized by admixture of oolitic and pisolitic Fe – coated grains (Figs. 5c, e, 6c and d). Pisoids in this lithotype range in size from 0. 3 to 0. 6 mm whereas the size of the ooids range from 0. 1 to 0. 2 mm in diameter. The smallerooids are mostly spherical while the larger ooids and some pisoids are elongated. The Fe - coated grains are embedded in a groundmass of kaolinitic claystone with varying level of iron enrichment. At Koton – Karfi section, the basal part is characterized by preserved unreplaced coated grains and matrix as lithorelicts (Figs. 4 and 6d). Other parts, however exhibit varying level of iron replacement from partial to total replacement. Towards the upper part of the section, the groundmass contains more unreplaced precursors than the coated grains. At Mount Patti, the coated grains and ground mass are more replaced with little or no preserved precursor materials.

Laminated - Massive Ironstone Lithotype

This lithotype with thickness ranging from 0. 2 – 0. 5m occurs at the basalpart of the oolitic – pisolitic ironstone lithotype (Figs. 5a and 6a) and in some cases in association with the concretional facies consistently in all the investigated sections (Fig. 5e). They are usually made up of parallel laminated bands of iron replaced claystone and siltstone with some sand fractions. angular to rounded monocrystalline quartz grains embedded in a silty or clayey groundmass with varying level of iron enrichment.

Concretional Ironstone Lithotype

The concretional lithotype occur towards the upper part of the Koton – Karfi. It is characterized by irregular layers of thin bands which occur around cores usually of trapped sediment and voids in some cases (5d and 6b). They usually contain deformational structures such as desiccation cracks and voids which often exposes the internal structure of the concretions (5d, e and 6b). The irregular layers are essentially composed of partially to totally replaced clay and silt precursors.

Petrographic study and Scanning Electron Microscopy

Four main primary textural components recognizable in the investigated ironstone from microscopic analysis are:

1. framework of ferruginous coated grains and detrital clasts,
2. groundmass (finer grained interstitial clay and silt materials),
3. cement (mainly authigenic goethite and hematite filling interstitial voids and replacing the precursors), and
4. pore spaces.

The framework clasts typically consist of a mixture of ferruginous coated grains, detrital quartz grains and heavy minerals, some of which are iron bearing (Figs. 7a,d, 8a and c). Matrix consists of clay sized particles whichare essentially kaolinite and with varying level of iron replacement. Minor silt-sized quartz grains were also identified as matrix component (Figs. 8b and d). The irregular distribution of matrix and grain relationship allow the identification of two types of packing in the ironstone which are openly or sparsely packed (Fig. 7a, 8e, 9e and f) and closely or densely packedgrains (Fig. 7b, d, 9a and b). In the densely packed, the ferruginous coated grains and detrital clasts which act as framework are grain supported. They exhibit short, long and concavo – convex contacts (Figs. 7a and 8c) due to dense grain population within limited proportion of groundmass. In the sparsely populated

grain type however, the matrix/groundmass is greater than the grains making the framework component to float as embedded grains within the groundmass (Figs. 8a - d).

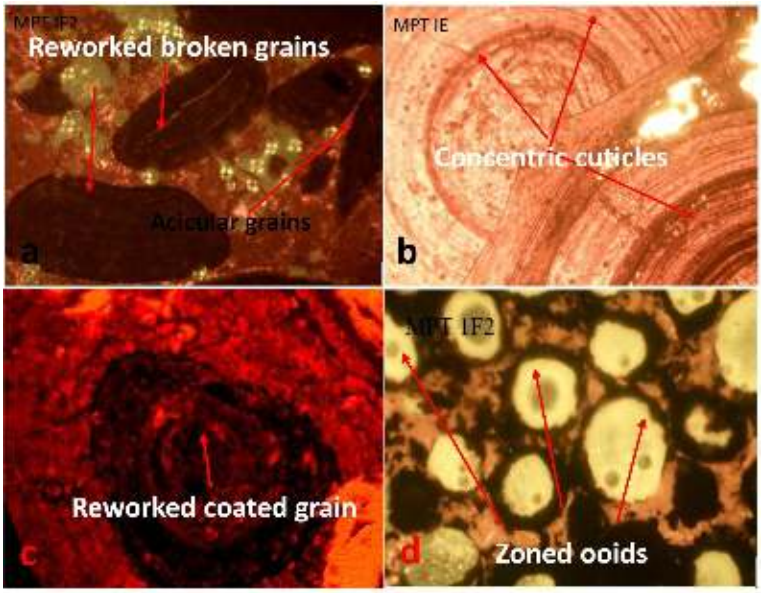


Fig. 7 (a – d): (a) Reworked fragmental and acicular grains embedded in a groundmass of partially to totally replaced matrix (b) Well rounded fragmented pisoidswith unreplaced kaolinitic precursors in the groundmass,(c) Reworked pisoids with older ooids as nucleus and (d) Well sorted oolitic coated grains with totally zoned cuticles.

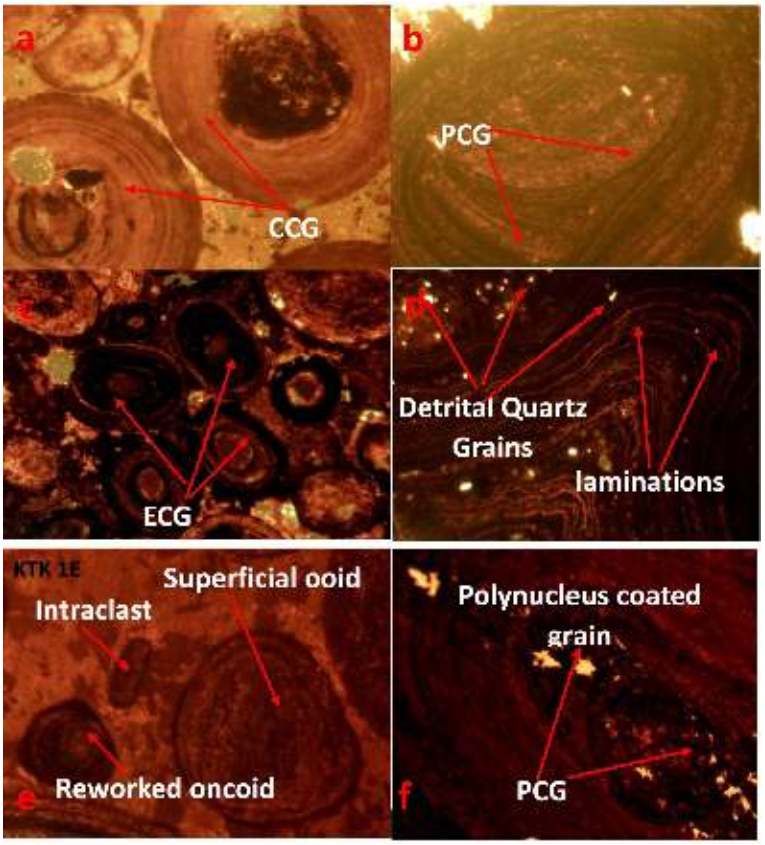


Fig. 8 (a – f): (a) Well sorted and well rounded, finely laminated Fe-coated grains with detrital magnetite grains and superficial ooids (b) Polynucleus coated grain with detrital quartz grain and eccentric cuticles around a reworked broken fragment as the core (c) Well sorted oolitic coated grains with zoned cuticles. d) Irregular and alternating cuticles with detrital quartz grains in a concretional ironstone (e) Reworked fragmental grains and pisoids with older ooids as nucleus, and(f) Reworked older grain and trapped matrix forming apolynucleuscoated grains.

SEM images show the textural and morphological characteristics of the Fe – coated grains, detrital clasts, their enclosing groundmass and the different minerals that make up the ironstones (Fig. 10a – d). Microscopic images (Figs. 8b, 9b and 10c) reveal scars on the surface of some Fe – coated grains resulting from attrition and impart during transportation (Figs. 8b and 9b). Other morphological attributes reveal the presence of true ooids, superficial ooids, peloid, matrix, pores and bioturbations (Figs. 8a – f, Table 5). Pores in the ironstone are in form of desiccation cracks and voids which resulted from diagenetic compaction and dewatering (Figs. 10b and d). Voids are also common in the core of concretions. The summary of the textural characteristics observed in the investigated ironstones is presented in Tables1 and 5.

Microscopic morphological investigation of the ironstone allows the recognition of concentric, eccentric, distorted (spastoliths), superficial, complex, and broken coated grain types similar to the findings of Guerrak (1987) and they are explained as follow:

a. Concentric Fe –Coated Grain (CCG) – This coated grain type occurs as both ooids and pisoids (Figs. 7a, b, 8a, 9c, 10c and d) and is the most common Fe – coated grain in the ironstones. They consist of well-rounded grains thin and finely laminated cortices, concentrically arranged around a nucleus. These cortices are composed of alternating goethite, hematite magnetite and kaolinite, whereas the cores are either trapped matrix particle, or reworked older smaller coated grains which are usually darker than the outer younger cortices. The thickness of the cuticles is variable.
b. Eccentric Fe –Coated Grains (ECG)– They are similar to those described by Knox (1970) and are recognized to constitute about 20% of the whole Fe-coated grains identified in the studied ironstone. In this type, the cuticles were accreted eccentrically around a nucleus of various shapes and compositions (Figs. 7b and 10d). In most cases, they are made up of a single core (Fig. 8a). The eccentric Fe-coated grains are usually more or less flattened and range in size from 1 to0. 4 mm in length. They can be considered as the intermediate between concentric and distorted Fe-coated grains.
c. Distorted Fe –Coated Grains (DCG) – This type of Fe-coated grain can also be referred to as spastoliths (Guerrak, 1987). They have varied shapes usually more deformed than the eccentric grains which range from slightly flattened (Figs. 7b and 8f) to nearly acicular (Fig. 8a). While the size of the ooids varies from 0. 1 mm to 0. 6 mm. The core is mainly made up of trapped matrix particles and older whole or fragmental coated grains. Intragrain fractures and cracks are common with this type of Fe – coated grain.
d. Broken or Fragmental Fe – Coated Grains (BCG) – This type of Fe-coated grains is well documented in the investigated ironstone as evidence of reworking and allochthonous origin for the coated grains (Figs. 8a, b and 9a). They occur as isolated fragments or core material in some coated grains with varying sizes and degree of reworking.
e. Superficial Fe –Coated Grains (SCG) – They represent the first step in the development of the coated grains. The cortex consists of only one regular layer surrounding a nucleus of trapped sediment or fragments older grain (Fig. 8d). Sometimes the layer is discontinuous which is due to incomplete process of ooid formation or abrasion during transportation. This grain type is more common in oolitic and pisolitic grains.
f. Polynucleus or Complex Fe –Coated Grains (PCG) – This type of Fe-coated grainsis usually made up of multiple nucleus of two or more older ooids or fragments of older ooids fused together within the core or as two or more separate cores within a coated grain(Figs. 8b and f). They commonly occur in the pisolitic ironstone as evidence of reworking.
g. Zoned Fe –Coated Grains – The zoned Fe – coated grains are most common among the oolitic grains. They are mainly characterized by few thick and usually continuous cortices which are usually completely replaced in most cases (Figs. 7d and 8c).

Mineralogy

The result of themineralogical investigation through X-Ray Diffraction reveal the presence of quartz, kaolinite, goethite, hematite and magnetite in the ironstones (Figs. 10a - d and Table1). SEM images of the studied ironstone samples (Fig. 9a – d) also reveal the characteristics of the identified minerals and their intimate relationship with the Fe – coated grains and matrix of the ironstone. Kaolinite is the main mineral phase in the ironstone precursor. As expected, kaolinite is more enriched in the samples with unreplaced and partially replaced lithorelicts. Goethite is volumetrically the most important diagenetic mineral in

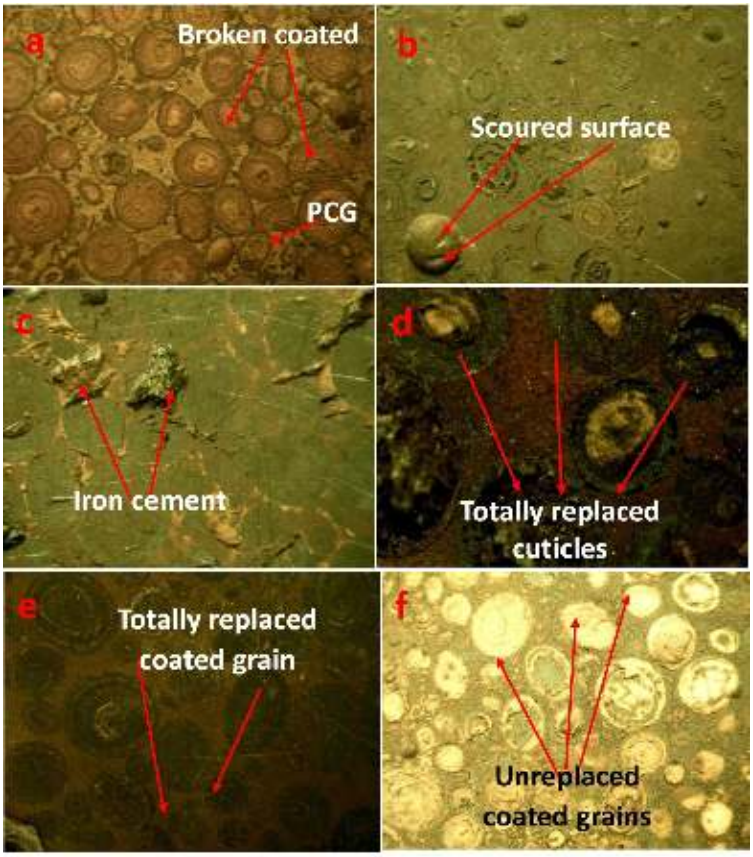


Fig. 9 (a – f): Polish section slides of the investigated ironstone samples,(a) concentric and broken coated grains (b) coated grains with scoured surface (c) iron cement as pore fillings (d) totally replaced cuticles with unreplaced core materials (e) totally replaced Fe-coated grains, and f: partially and totally replaced Fe-coated grains.

the ironstone. It can be as high as 100 wt. % (Figs. 10c and d) when the precursor is totally replaced and varies proportionately in samples with partially replaced lithorelicts. Quartz represents detrital mineralogy and it is most enriched in the ironstone with greater amount of unreplaced precursor. Hematite occurs in close association with goethite in the ironstone. It exists mainly as laminations in coated grains and as pore fillings.

Discussions

Depositional Environment and Formation of Fe – Coated Grains

The clays which serve as the ironstone precursor were believed to have been reworked from older successions and transported as suspension load and redeposited under quiet water condition within restricted bay or below wave in a shallow marine environment. Similar process was interpreted for the ooidal ironstones at Agbaja Plateau by Ladipo *et al*. (1994). Broken or fragmental coated grains and absence of fine laminations in the claystone beds are indication of agitated water condition.

Subsequent reworking of these kaolinitic clays formed coated grains through wave action either by shallowing of the basin or during storms when the wave base is lowered in a high energy shelf environment. Lowering of the wave base during storm is more plausible because shallowing of the basin would have aided incursion of clastic materials into the basin which was not the case as revealed in the petrography and SEM photographs. This claim is supported by the little or no detrital grains in the ironstone as evidenced by microscopic results.

The presence of asymmetrical and unbroken Fe-coated grains affected by neighboring coated grains is an indication of deformation before complete consolidation but after the coated grains were formed. These features in the investigated ironstone does not suggest that the ooids formed in situ as concluded by Adeleye (1973). This plastic deformation of ooids indicates that they were not completely rigid when mechanical compaction started and suggests that a progressive hardening took place during burial (Baturin, 1982). This is also supported by varying level

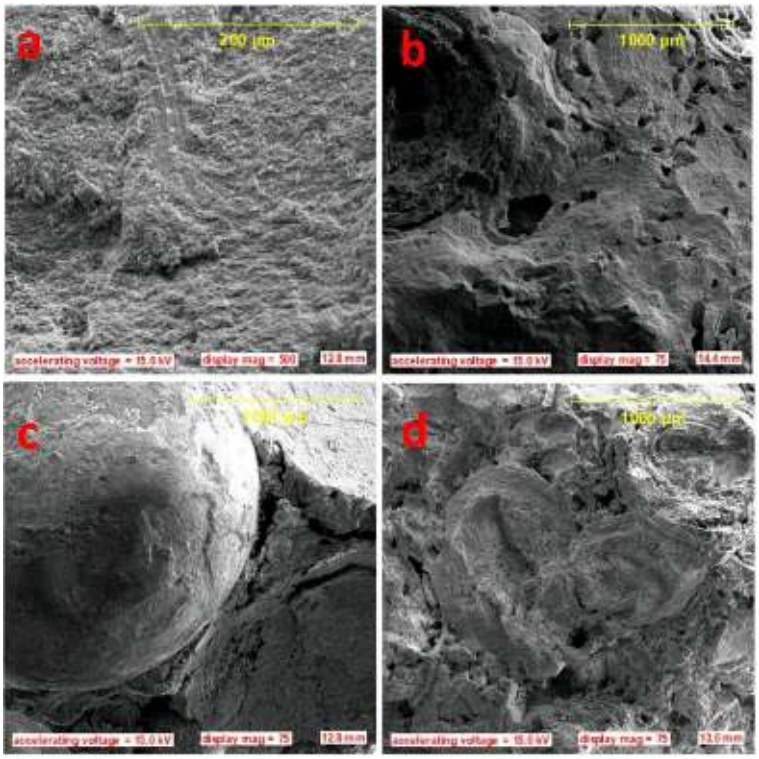


Fig. 10 (a – d): SEM images of the ironstones showing varying textural attributes (a) Partially to totally replaced kaolinitic matrix with iron replaced *Skolithos* burrow in the upper center part (b) Desiccation holes in the within the Fe-coated grains and the matrix resulting from diagenetic dewatering (c) Scour surfaces on a Fe-Coated grain resulting from attrition during transportation. and (d) Fe-coated grains with trapped sediment as the nucleus.

Table 1: Summary of Textural and mineralogical composition of the Agbaja Formation oolitic and pisolitic ironstones at Mount Patti and Koton – Karfi.

Locations	Sample No	Clastic/Matrix/Cement Ratio (%)			Grains (mm)		Mineralogy (%)						
		Clast	Matrix	Cement	Coated grains/clasts	Matrix	Am	Ch	Sd	Mg	Mh	Gt	He
Koton Karfi	KTK 1D	40 (pisoids) 15 (ooids)	10	35	1. 5 2. 6	<0. 01	20.0	15.6	29.3	31.6	-	-	3.6
	KTK 2G	40 (pisoids)	25	35	1. 5 – 2. 6	<0. 01	20.0	15.6	29.3	31.6	-	-	3.6
Mount Patti	MPT 1F	40 (pisoids) 15 (ooids)	10	35	1. 5 – 2. 6	<0. 01	20.0	15.6	29.3	31.6	-	-	3.6
	MPT 2F	40 (pisoids) 15 (ooids)	10	35	1. 5 2. 6	<0. 01	20.0	15.6	29.3	31.6	-	-	3.6

Note: K – Kaolinite, **Qt** – Quartz, **Gt** – Goethite, **He** – Hematite, **Mg** -Magnetite.

of iron enrichment.

Petrographic evidences from polish and polish sections suggest that the ooids and pisoids are transported and reworked. This also reveal that, iron oxide is initially precipitated as gelatinous material into pore spaces and as cement before diagenetic compaction, before the sediment is completely hardened. The presence of older coated grains as reworked fragments and as nuclei of younger coated grains (Figs. 7a, b and d) indicates that the formation of ooids and pisoids occurred repeatedly in a dynamic environment (Yoshida et al., 1998).

Other textural features from petrographic study such as variation in size and shape of coated grains suggest a transported origin for the ironstone unlike in the Bhainskati ironstone where petrographic features show that the symmetrical shape, high sorting and absence of broken ooids ruled out transported origin (Devkota and Paudel, 2012). In addition, Devkota and Paudel (2012) also argued that preservation of delicate textural features of the ooids would not be likely if the

Bhainskati ironstone was transported from a distant source. No preservation of such structureswas observed in the investigated ironstone at Mount Patti and Koton – Karfi.

Devkotaand Paudel (2012) The presence of well-preserved ooid corticesand absence of relict carbonate phase in the Bhainskati ironstone are interpreted as an indication of a non-replacement, primary origin for the ironstone. On the contrary, petrographic studies of the ironstone from the study area reveal freshly preserved and partially to totally replacedkaolinite relicts as coated grains and matrix which are evidences of diagenetic replacement origin for the ironstone. Therefore, the textures observed in the Agbaja ooidal ironstone are not indicative of authigenic formation of coated grains. This supports the findings of earlier researchers who believe that the concentric fabric of ooids is a primary structure produced by mechanical accretion of clay particles (Ladipo *et al.,* 1994; Mucke*et al.,* 1999).

Table 2: XRD Semi quantitative results of the investigated samples (wt. %).

XRD Semi quantitative results (wt. %)	Quartz	Kaolinite	Goethite	Magnetite	Hematite
KTK 1D	-	-	48	21	31
KTK 2G	27	29	44	-	-
MPT1F	-	-	100	-	-
MPT2E	-	-	100	-	-

Diagenesis and Fabric Evolution

Most troublesome to recognize and interpret are the post – depositional changes through which iron bearing sediments are formed (Pettijohn, 1975). These changes played important roles in the evolution of the oolitic ironstone (Galmed*et al.,* 2021) and usually include diagenetic reorganization, compaction, precipitation, cementation, replacement and recrystallization which all produce marked changes in mineralogy and texture of ironstones.

Microscopic and mineralogical results reveal that precursor materials including kaolinitic clay matrix, coated grains and other detrital materials such as quartz and Fe – bearing heavy minerals formed primarily from intensely weathered adjourning basement complex rocks and then deposited as the main precursor materials for the ironstone. The post – depositional changes in the ironstone evolved through the following diagenetic stages (Table 4).

Early diagenetic Stage: The main diagenetic modifications in the investigated ironstones at this stage include: formation of kaolinitic claystone with coated grains. This is evidenced by preservation of lithorelicts of kaolinite as unreplaced and partially replaced coated grain and matrix within the ironstone.

Middle Diagenetic Stage: At this stage, Hydrous Ferric Oxide (HFO) is precipitated as iron cement into pore and as fracture fillings which was later recrystallized to form goethite. As revealed by thin and polish section.

Table 3: Textural classification of Agbaja Formation oolitic and pisolitic ironstones at Mount Patti and Koton – Karfi. After Hallsworth and Knox (1999).

<table>
<tr><td colspan="5">Depositional texture recognisable</td><td>Depositional texture not recognisable</td></tr>
<tr><td colspan="3">Contains matrix
(silt and clay < 32 μm in diameter)</td><td>Lacks matrix</td><td rowspan="2">Components bound together by action of plants and animals in the position of growth</td><td rowspan="2"></td></tr>
<tr><td colspan="2">Matrix-supported</td><td colspan="2" rowspan="2">Grain-supported</td></tr>
<tr><td>> 75% matrix</td><td>< 75% matrix</td><td></td><td></td><td></td></tr>
<tr><td>Iron-mudstone</td><td>Iron-wackestone</td><td>Iron-packstone</td><td>Iron-grainstone</td><td>Iron-boundstone</td><td>Ironstone (use qualifiers to describe crystal size)</td></tr>
</table>

Precipitation of iron – oxide cement is controlled by the porosity and permeability of the precursor material.

***Late Diagenetic Stage**:* This stage is characterized by dehydration of goethite to form hematite and magnetite as well as diagenetic compaction which led to cracking and grain deformations. Microcracks (Fig. 7a and b) observed in the ironstones could be said to be late diagenetic and resulted from progressive water loss from the kaolinitic claystone precursor. This is owing to the fact that none of these fissures is filled by iron cement.

Table 4: Diagenetic sequence in the formation of Agbaja Formation oolitic and pisolitic ironstones at Mount Patti and Koton – Karfi.

Processes	Depositional	------ Increasing burial ------		
		Early	middle	Late
Reworking of siliciclastic detritus including kaolinitic coated grains and iron bearing heavy minerals.				
Formation of Kaolinitic claystone with coated grains.				
Precipitation of HFO.				
Replacement of the precursors by goethite.				
Dehydration of goethite to form hematite and magnetite.				
Diagenetic dewatering and compaction.				

The paragenetic sequence in the formation of the ironstonesis in the order ofdiagenetic recrystallization and dehydration of the amorphous clay precursor which precede the progressive formation of hydrousferric oxide, goethite, and hematite in successive stages of dehydration (Fig. 11). These processes began with the formation of iron pigmentation in form of stain on the precursor and followed by varying level of iron enrichment and replacement. The resulting color of the matrix and coated grains is due to goethite and hematite pigmentation. Hematite and magnetite have variable concentrations in the ironstone. Some magnetite grains occur as detrital heavy minerals, while others occur as a result of extreme dehydration of goethite and hematite.

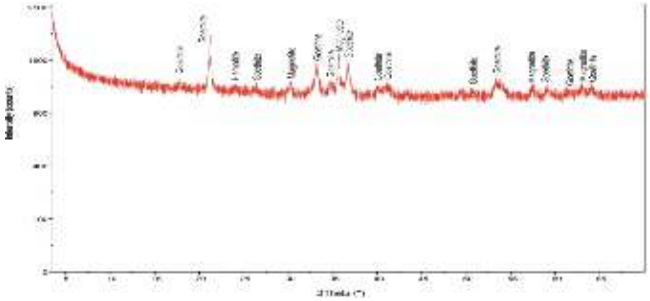


Fig. 11(a): X-ray diffraction pattern of sample KTK1D from Koton - Karfi.

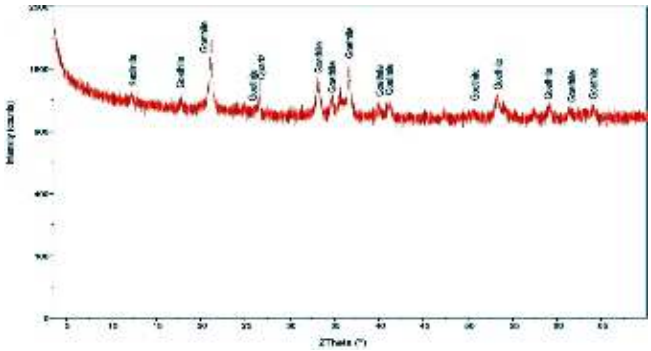


Fig. 11 (b): X-ray diffraction pattern of sample KTK1G from Koton - Karfi.

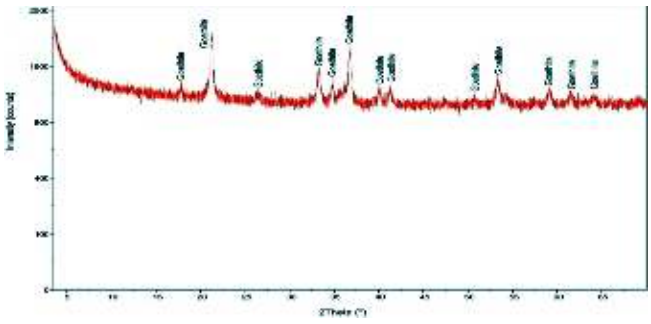


Fig. 11(c): X-ray diffraction pattern of sample MPT1F from Mt. Patti.

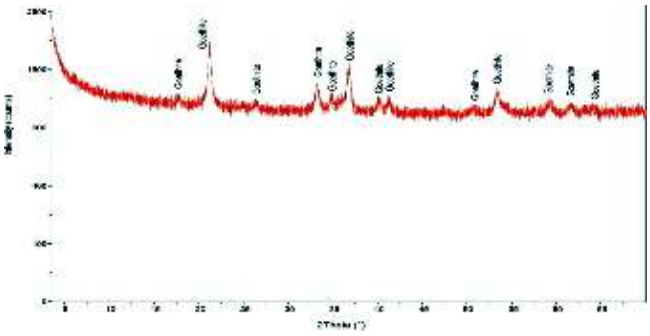


Fig. 11(d): X-ray diffraction pattern of sample MPT1E from Mt. Patti.

Diagenetic alterations in the ironstonesresult in textural and mineralogical changes (Pettijohn, 1975; Nahon, 1991) which culminateinto fabric evolution as revealed by microscopic evidences indicates that precipitation of Fe - cement occur mainly as:

i. Concretional growth around metastable minerals or impermeable trapped sediment leading to the formation of Fe – coated grains (Figs. 3e and 4d),
ii. Diffused replacement of argillaceous matrix/groundmass which is controlled by ambient porosity and permeability of the precursor material (8d and 9d) and
iii. Infilling of joints, fractures and voids (Figs. 3c, f, 4d, and 8c and 9d).

The irregular distribution of matrix and Fe – coated grains relationship allow the identification of two types of packing in the ironstone which are closely or densely packed and openly or sparsely packed grains. This is the basis for classifying the ironstone as iron – wackstone and iron – packstone (Table 3) according to Hallsworth and Knox (1999).

The resultant texture and microfabric in the ironstone reveal that the chief process which is chemical precipitation of hydrous ferric oxide displaced, replaced and/or cemented the original sedimentary material as noted by Jonathan and Chenoweth (1996). Replacement evidences in the ironstone is indicative of iron enrichment due to the action of meteoric water which introduced mineralizing fluid into the pore spaces in the precursors.

Comparison with other Ironstones

The morphological and microfabric characteristics of the ironstones at Mount Patti and Koton – Karfi were compared in Table 5 with Ordovician oolitic ironstone, Farmennian Oolitic Ironstone Proximal facies, Farmennian oolitic Ironstone distal facies and Late – Middle Devonian Oolitic Ironstone at Eifel from France, Belgium and Germany (Dreesen et al., 2016).

The Agbaja ironstone shows high similarity in type and size of coated grains, matrix, fabric, sorting and bioturbations with the other Phanerozoic ooidal ironstone (Table 5). However, the Agbaja Formation ironstone at Mount Patti and Koton – Karfi lack reworked bioclasts. The iron cement are mainly goethite and hematite formed from iron-oxide while core materials are made up of trapped sediment and older coated grains (Fig. 8). Replacement origin of the ironstone is supported by varying level of iron enrichment and intimate relationship between kaolinite, goethite and hematite as revealed by microscopic results. No carbonate is associated with the ironstone or its precursors.

Conclusions

The Agbaja ironstones exposed at Mount Patti and Koton – Karfi are investigated and the study concludes as follows; Kaolinitic clay with coated grains and other detrital materials such as quartz and Fe – bearing heavy minerals formed primarily from intensely weathered adjourning Basement Complex rocks formed the main precursor materials for the ironstone.

1. Scarred surfaces and broken Fe – coated grain type revealed by microscopic evidences are pointers to allochthonous origin. This is supported by the co-existence of other coated grain types such as superficial, concentric, eccentric, distorted and polynucleus as well as variable sorting of the framework components which are evidences of reworking in a high energy shelf environment.
2. The mineralogy of the ironstone as revealed by XRD analysis, SEM and petrographic images is characterized by detrital kaolinite and quartz while goethite, hematite and magnetite are iron minerals of replacement origin with goethite which may be as high as 100 wt. % in totally replaced ironstones as volumetrically the most important diagenetic mineral.
3. Textural and mineralogical changes as revealed by microscopic evidences reveal that precipitation of Fe - cement which occur mainly as concretionary growth, diffused replacement of argillaceous matrix/groundmass and infilling of joints, fractures and voids.
4. The ironstone fabric evolved through formation

Table 5: Comparative textural characteristics of Agbaja ironstone with other Phanerozoic ooidal ironstones (Modified after Dressen et al., 2016).

	Ordovician OIS	Famennian OIS (Proxima facies)	Famennian OIS (Distal facies)	L-M Devonian OIS-Eifel	Agbaja Ironstone at Mt Patti and Koton – Karfi
Real ooids	XXX	XXX	X	X	XXX
Pseudo-ooids	O	XX	XX	XX	XX
Rounded bioclasts	O	XX	XX	XXX	O
Pisoids	O	XX	O	O	XXX
Oncoids	O	X	O	X	X
Intraclasts	O	X	X	XX	X
Lithoclasts	O	X	O	O	X
Microstromatolithes	X	H>C (S)	O	H (S)	X
Cortex mineralogy	Alternating HCS	H>C (S)	C>H	H (S)	Alternating GHK
Nucleus	Q, C	Q, Fossil	Fossil	Fossil	Trapped sediment and ooids
Grain size	Small (<500)	Variable	Variable	Variable	Variable
Grain sorting	Excellent	Bad – Good	Medium -Good	Medium-Good	Medium-Good
Matrix	Siliciclastic	Siliciclastic/carbonate	Carbonate	Carbonate	Siliciclastic
Cement	HCD	HCSD, Fe-C	Fe-C, S	Fe-C, S	GH
Grain supported	O	X	X	X	XX
Matrix supported	X	X	O	O	XX
Bioturbations	X	X	X	O	X

Note: Relative frequency of the microfabric components is indicated by the symbols as below: **O** (totally absent), **X** (Present) **XX** (common), **XXX** (Very frequent or abundant). Mineralogical composition includes: **K** – Kaolinite, **G** – Goethite, **H** – Hematite, **C** – Chlorite, **D** – Dolomite, **S** – Siderite, **C** – Calcite, **Fe-Cal** – Ferruginous calcite, **Q** – Detrital quartz grain.

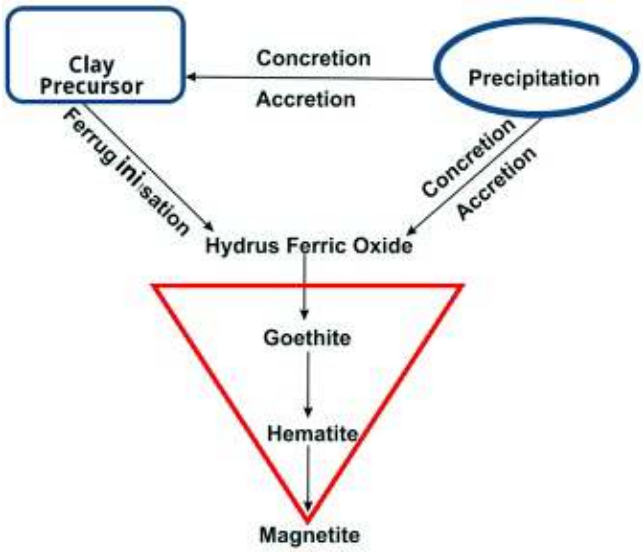


Fig. 12: Paragenetic sequence in the textural and mineralogical evolution of the Agbaja ironstones exposed at Mount Patti and Koton Karfi.

of kaolinitic claystone with coated grains at early diagenetic stage through precipitation and replacement of hydrous ferric oxide cement which was later recrystallized to goethite at middle diagenetic stage, and dehydration of goethite to form hematite and magnetite as well as compaction and deformation which occur during the late stage of diagenesis.

5. The ironstones are mainly post-depositional in origin with evidences of selective replacement of the kaolinitic protolith by iron oxide which is evidenced by preserved coated grains and matrix in the original fabrics of the precursor.

Acknowledgement

The authors sincerelyappreciate the two anonymous reviewers for their critical review and useful contributions and criticisms to improve this work.

References

Abimbola, A.F. (1997). Petrography and parageneticstudies of the Agbaja Ironstone Formation, Nupe Basin, Nigeria: Journal of African Earth Sciences, 25, 169 – 181.

Abimbola, A.F., Badejoko, T.A. and Elueze, A.A. (1999). The Agbaja Ironstone Formation, Nupe Basin. Global Journal of Pure and Applied Sciences, 5 (3), 375-384.

Adeleye, D.R. (1973). Origin of ironstones, an example from middle Niger valley. Journal of Sedimentary Petrology, 43, 709-727.

Adeleye, D.R. (1973). Origin of ironstones, an example from the Middle Niger valley, Nigeria. Journal of Sedimentary Petrology, 43, 709–727.

Adeleye, D.R. (1974). Sedimentology of the fluvial Bida Sandstones (Cretaceous) Nigeria. Journal of Sedimentary Geology, 12, 1–24.

Agyingi, C.M. (1993). Palynological evidence for a late Cretaceous age for Patti Formation, Eastern Bida Basin, Nigeria. Journal of African Earth Sciences, 17, 513–523.

Akande, S.O., Ojo, O.J. and Ladipo, K. (2005a). Upper Cretaceous Sequences in the Southern Bida Basin, Nigeria. A Field Guidebook, Mosuro Publishers, Ibadan, 60pp.

Baturin, G.N. (1982). Phosphorites on the Seafloor: Origin, Composition, and Distribution, Amsterdam, Elsevier, 343pp.

Braide, S.P. (1992). Geological development, origin and energy mineral resources potential of theLokoja Formation in the southern Bida Basin. Journal of Mining and Geology, 28, 33–44.

Devkota, S. and Paudel L.P. (2012). Petrology and genesis of the Bhainskati iron ore deposit of Palpa District, western Nepal:Bulletin of the Department of Geology, Tribhuvan University, Kathmandu, Nepal, 15, 63–68.

Dreesen, R., Savary, X. and Goemaere, E. (2016). Definition,classification and microfacies characteristics of oolitic ironstones used in the manufacturing of red ochre A comparative Petrographical analysis of Paleozoic samples from France, Belgium and Germany. Anthropologica et Praehistorica, 125 (2014), 203 – 223.

Galmed, M.A., Abuamarah, B.A., Ghrefat, H.A. and Al-Zahrani, A.A. (2021). Petrology of oolitic ironstones of Ashumaysi Formation of Wadi Fatima, western Arabian Shield, Saudi Arabia. Journal of King Saud University – Science, 33 (2021), 101266.

Guerrak, S. (1987). Paleozoic marine sedimentation and associated Oolitic iron-rich deposits, TassilisN'Ajjer and Illizi Basin, Saharan platform, Algeria: Journal of African Earth Sciences, 6(1), 1-8.

Jan du Chene, R.E., Adegoke, O.S., Adediran, S.A. and Petters, S.W. (1978). Palynology and foraminifera of the Lokoja Sandstone (Maastrichtian), Bida Basin, Nigeria. Revista Espanola de Micropaleontologia, 10, 379–393.

James, H.L. (1966). Chemistry of the iron-rich sedimentary rocks. In Data of Geochemistry, U. S. Geological Survey Professional Paper, 440-W. 60pp.

Kogbe, C.A., Ajakaiye, D.E. and Matheis, G. (1981). Confirmation of rift structure along the middle Niger Valley, Nigeria. Journal of African Earth Sciences, 1, 127–131.

Knox, R.W. (1970). Chamosite ooliths from the Winter Gill Ironstone (Jurassic) of Yorkshire, England: Jour. Sed. Petrology, 40, 1216 – 1225.

Ladipo, K.O., Akande, S.O. and Mucke, A. (1994). Genesis of ironstone from middle Niger sedimentary basin evidence from sedimentological, ore microscopic and geochemical studies: Journal of Mining and Geology, v. 30.

Mebradu, S., Imhanobe, J. and Kpandei, L.Z. (1986). Palynostratigraphy of the Ahoko sediments from the Nupe Basin, N. W. Nigeria. Review of Paleobotany and Palynology, 48, 303–310.

Mucke, A., Badejoko, T. A. and Akande, S. O. (1999). Petrographic – mechanical studies and origin of Agbaja Phanerozoic ironstone formation, Nupe Basin, Nigeria: a product of a ferruginised ooidal kaolin precursor not identical to the Minette type. Mineralium Deposita, 34, 284–296.

Mucke, A. and Farshad, F. (2005). Whole rock and mineralogical composition of phanerozoic ooidal ironstones, comparison and differentiation of types and subtypes: Ore geology reviews. Elsevier Science. 26, 227-262.

Ojo, O.J., Bamidele, T.E., Kelani, I., Adedoyin, A.D. and Akande, S.O. (2016). Facies Relationships, Mineralogy and Geochemical Characteristics of the Maastrichtian Ironstones of Patti Formation, Bida Basin, 26th Colloquium of African Geology, Abstracts with Programs, p77.

Ojo, O.J., Bamidele, T.E. , Adepoju, S.A. and Akande, S.O. (2020). Genesis and paleoenvironmental analysis of the ironstone facies of the Maastrichtian Patti Formation, Bida Basin, Nigeria: Journal of African Earth Sciences,147 (2020).

Ojo, O.J. and Akande, S.O. (2003). Facies relationships and depositional environments of the Upper Cretaceous Lokoja Formation in the Bida Basin, Nigeria. Journal of Mining and Geology 39, 39–48.

Ojo, O.J. and Akande, S.O. (2006). Sedimentological and palynological studies of the Patti Formation, southeastern Bida Basin, Nigeria: implication for Paleoenvironments and paleogeography. Nigerian Association of Petroleum Explorationists Bulletin, 19, 61–77.

Petra´nek, J. and Van Houten, F.B. (1997). Phanerozoic ooidal ironstones. Czech Geological Survey Special Papers, 7, 71p.

Pettijohn, F.J. (1975). Sedimentary rocks: Harper & Row, N. Y., 628p.

Udensi, E.E. and Osazuwa, I.B. (2004). Spectra determination of depths to magnetic rocks under the Nupe Basin, Nigeria. Nigeria Association of Petroleum Explorationists Bulletin, 17,22–37.

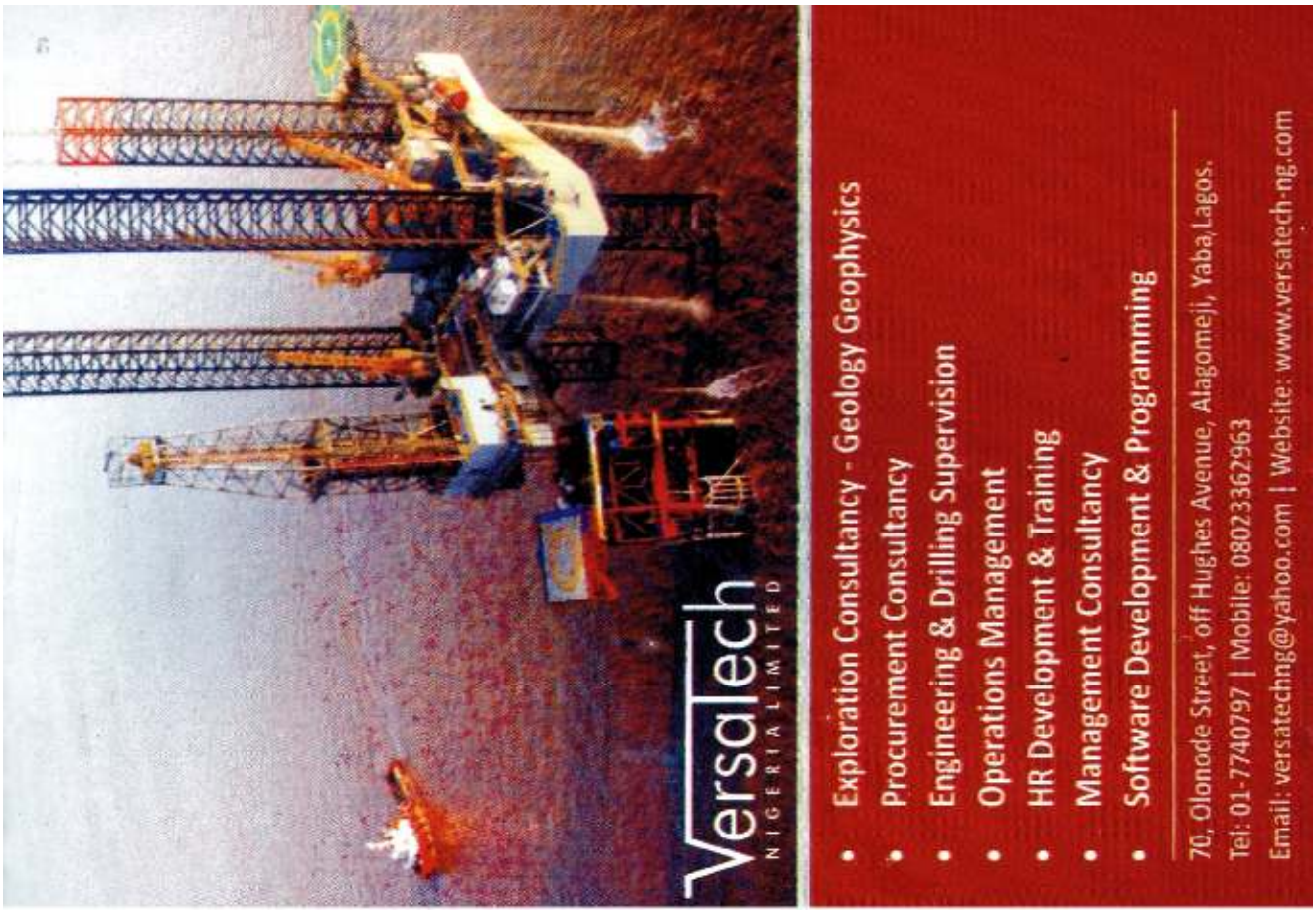
Kennedy, W.Q. (1965). The influence of basement structure on the evolution of the coastal (Mesozoic and Tertiary) basins. In: Recent Basins around Africa. Proceedings of the Institute of Petroleum Geologists Society, London, 35–47.

King, L.C. (1950). Outline and distribution of Gondwanaland. Geological Magazine 87, 353–359.

Kimberley, M.M. (1994). Debate about ironstone: has solute supply been surficial weathering, hydrothermal convection, or exhalation of deep fluids? TerraNova, 6, 116 - 132.

Yoshida, M., Khan, I.H. and Ahmad M.N. (1998). Remnant magnetization of oolitic ironstone beds, Hazara area, Lesser Himalayan thrust zone, Northern Pakistan: Its acquisition, timing, and paleoenvironmental implications. Earth Planets Space, 50, 733–744.

Young, T.P. (1989). Phanerozoic ironstone: an introduction and review. In: Young, T. P., Taylor, W. G. E. (Eds.), Phanerozoic ironstones. Geological Society, Special Publication, 46, 9–25.



Pictorial view of the new NMGS House under construction at Abuja.

