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Petrography and Geochemistry of the Banded Iron Formation of the Gangfelum Area, Northeastern Nigeria

Anthony Temidayo Bolarinwa[1]

[1] Department of Geology, University of Ibadan, Ibadan, Nigeria

Correspondence: Anthony Temidayo Bolarinwa, Department of Geology, University of Ibadan, Ibadan, Nigeria. E-mail: atbola@yahoo.com

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Abstract

The Gangfelum Banded Iron Formation (BIF) is located within the basement complex of northeastern Nigeria. It is characterized by alternate bands of iron oxide and quartz. Petrographic studies show that the BIF consist mainly of hematite, goethite subordinate magnetite and accessory minerals including rutile, apatite, tourmaline and zircon. Chemical data from inductively coupled plasma optical emission spectrometer (ICP-OES) and inductively coupled plasma mass spectrometer (ICP-MS) show that average $Fe_2O_{3(t)}$ is 53.91 wt.%. The average values of Al_2O_3 and CaO are 1.41 and 0.05 wt.% respectively, TiO_2 and MnO are less than 0.5 wt. % each. The data suggested that the BIF is the oxide facies type. Trace element concentrations of Ba (67-332 ppm), Ni (28-35 ppm), Sr (13-55 ppm) and Zr (16-25 ppm) in the Gangfelum BIF are low and similar to the Maru and Muro BIF in northern Nigeria and also the Algoma iron formation from North America, the Orissa iron oxide facies of India and the Itabirite from Minas Gerais in Brazil. The evolution of the Gangfelum BIF involved metamorphism of chemically precipitated or rhythmically deposited iron-rich sediments into hematite-quartz rocks. The banding of the BIF suggested a break in iron precipitation probably due to iron oxide deficiency.

Keywords: Banded Iron Formation, geochemistry, hematite, goethite, Gangfelum

1. Introduction

The Banded Iron Formations (BIFs) occur within the Precambrian basement complex of Nigeria around the Lokoja-Okene-Kabba, Maru, Muro and Birnin Gwari schist belts (Figure 1). These rocks are commonly associated with the metasedimentary and metavolcanic rocks of Late Proterozoic age. Three main facies of the BIFs in Nigeria are recognised, which include the oxide, silicate and sulphide facies. The oxide facies, represented by the banded silica-iron oxide assemblage, is the most widespread in occurrence. The silicate facies consists of the quartz-garnet-grunerite assemblage, while the sulphide facies includes the pyrite-bearing carbonaceous schist or phyllite intercalated with iron-rich layers.

Olade (1978) classified the Itakpe ore deposit around Okene (Figure 1) into a massive magnetite, a banded to granular hematite-magnetite, and a homogenous hematite-magnetite ores. This ore deposit is regarded as a product of high grade amphibolite facies metamorphism of iron-rich sediments (Olade, 1978). Mucke & Neumann (1986) reported dark iron-rich bands alternating with lighter quartz bands in the rocks of the Ajabonoko area (Figure 1). A total thickness of 200 m and a conservative reserve of 60 million tonnes were estimated for this ore deposit. Adekoya (1998) and Adekoya *et al*. (2012) reported the occurrence of BIF within the pelitic to semi-pelitic phyllites of the Maru and Muro areas. The $Fe_2O_{3(t)}$ of the deposit is said to range from 44.07 to 58.41 wt.%. Okonkwo (1980) noted the occurrence of a BIF in the phyllite and quartz mica-schist of the Kushaka schist belt (Figure 1). Others include the magnetite-rich Kakun ore deposit, reported to be of igneous progenitor (Mucke & Neumann, 1986), and the Agbado-Okudu and Ochokochoko hematitic ore deposits in southwestern Nigeria. However, very little is known about the Gangfelum iron deposit due to poor accessibility. This work was carried out to investigate the petrography, geochemistry and origin of the iron ore mineralization in the Gangfelum District, Adamawa area, northeastern Nigeria.

2. Geological Setting

The Gangfelum area lies between the longitude 11º55′ E and 12º00′ E and the latitude 8º49′ N and 8º55′ N (Figure 1). The area is generally undulating with a high relief of about 1400 m and lowland area of 408 m to 447 m. It is part of the Mambila Plateau which stretches to the northwestern parts of Cameroun (Figure 1). The Adamawa, Hawal and Oban Massifs form the eastern sector of the Nigerian Basement Complex. Within this sector, only the Oban Massif has been studied in detail (Haruna *et al.,* 2011, 2013). The Adamawa and Hawal Massifs form the continental sector of major volcanic centers, which extends over 1000 km from the South Atlantic to Central Cameroun (Fitton, 1980). Adamawa massif is within the Pan-African Province of West Africa whose diverse basement rocks are affected by episodes of orogenies that resulted in the intense deformation, igneous activity, folding, metamorphism, melting, uplift and widespread fracturing of the rocks.

Migmatite covers more than one-third of the study area extending in the northeast-southwest direction. Prominent migmatite ridges occur around Wuro, Gboki and Zabi (Figure 2). Biotite-hornblende gneiss occurs in the southwestern part of the study area (Figure 2). Porphyritic granite occurs at the north and northeastern parts of the area (Figure 2). They are medium to coarse grained. Foliation in the rock is defined by the parallel alignment of feldspar megacryst and biotite specks. The iron oxide-rich veins trend SW-NE in the Gangfelum, Sakla and Dadoru villages (Figure 2). The veins are about 2.4 m long, 0.5 m wide and 1 m thick.

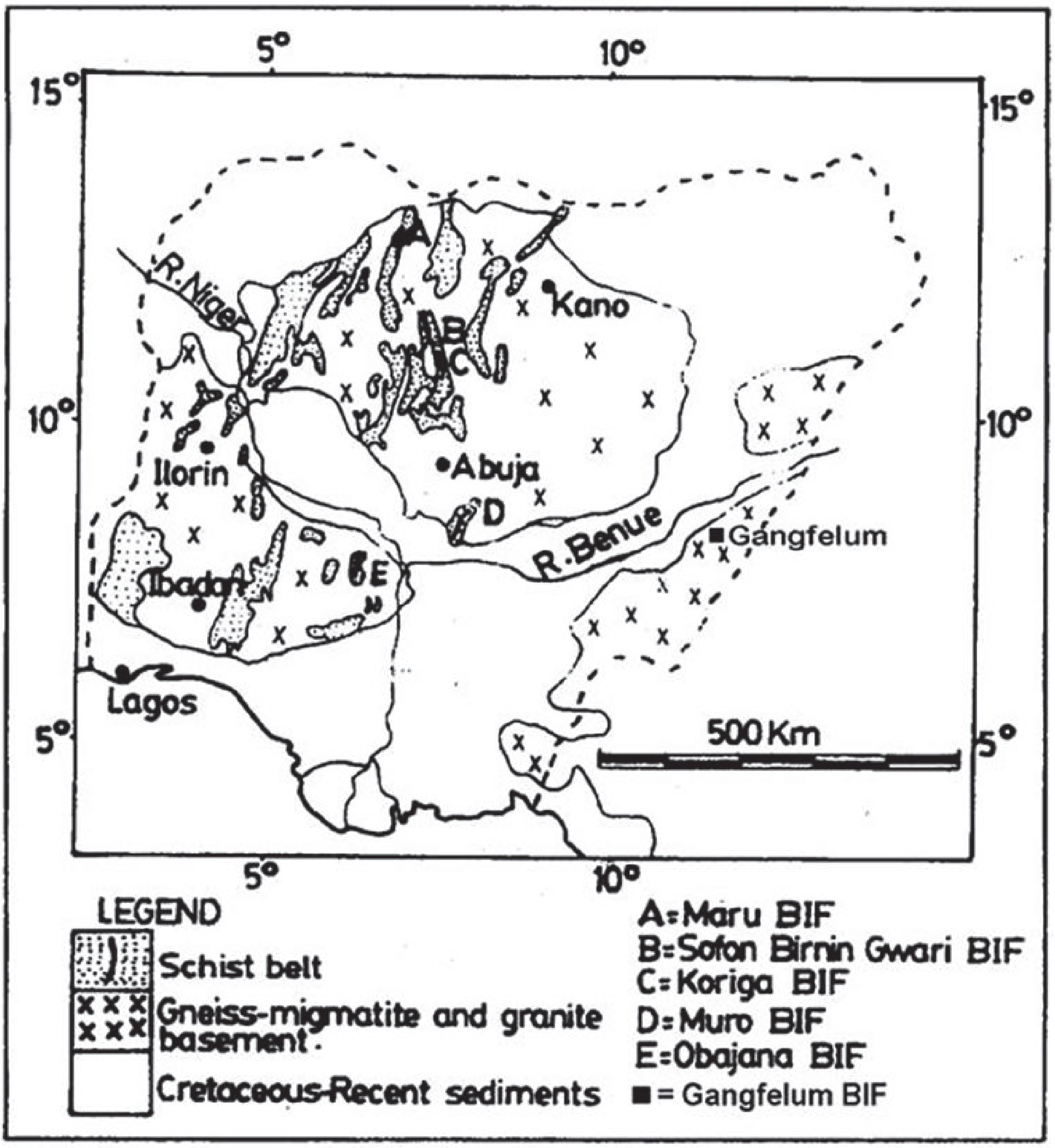

Figure 1. Geological map of Nigeria (Oyawoye, 1970) showing the location of Gangfelum BIF and other BIFs in Nigeria

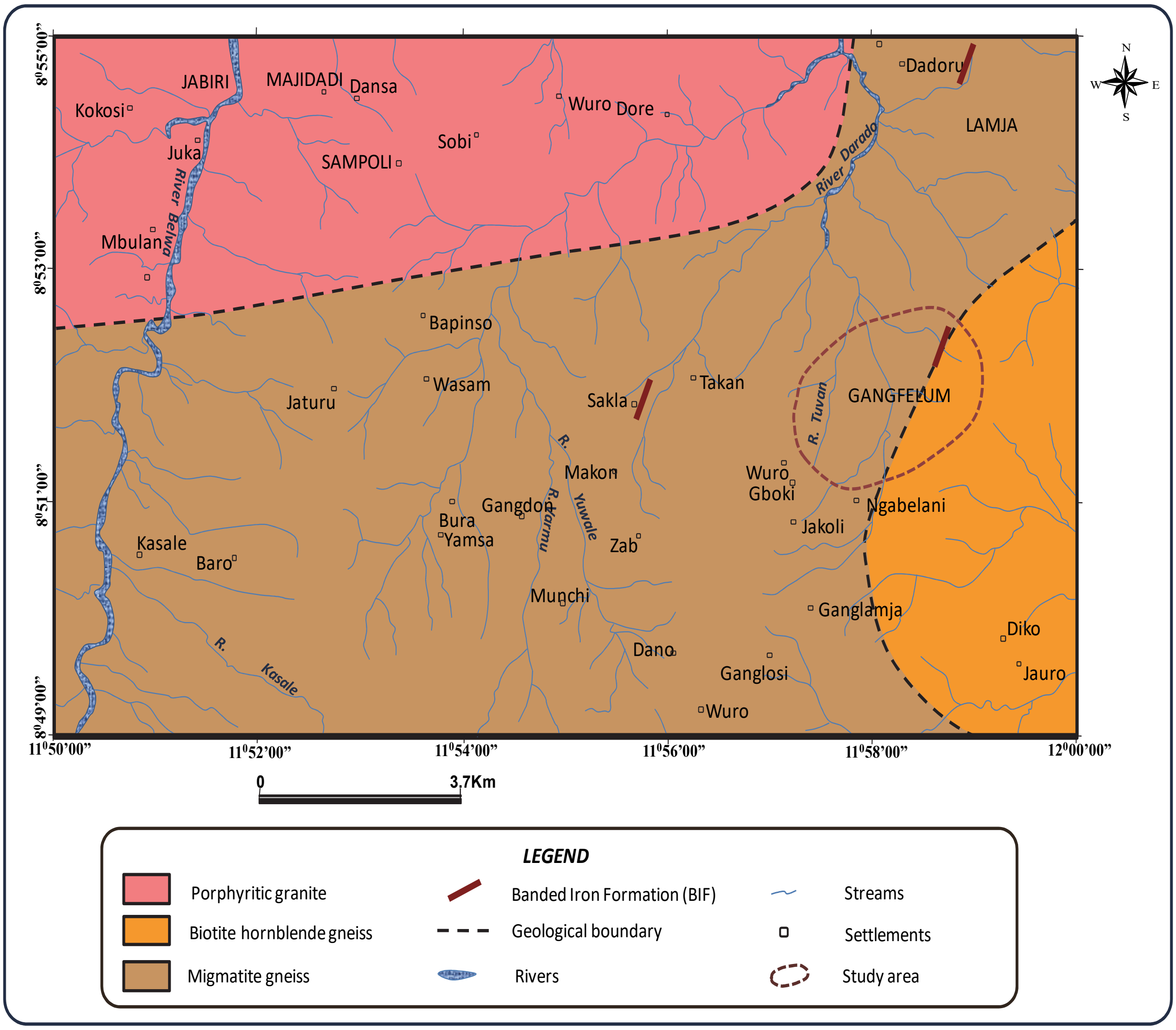

Figure 2. Geological map of the Gangfelum area

3. Method

The polished thick sections of the BIF ore samples prepared in the Department of Geology, University of Ibadan, Ibadan, Nigeria were examined under a reflected light ore microscope. Five representative iron ore samples were pulverized and analysed at the ACME Analytical Laboratories, Canada for X-ray diffraction analysis. The X-ray powder-diffraction data were recorded at 3-80° 2θ with Co-Kα radiation on a Bruker D8 Advance Bragg-Brentano diffractometer equipped with a Lynx Eye-XE detector. The X-ray tube was operated at 35 kV and 40 mA. The X-ray diffractogram was analyzed using the International Centre for Diffraction Database PDF-4 and Search-Match software by Bruker. The diffraction data was refined with Rietveld program Topas 4.2 (Bruker AXS), and interpreted using diagnostic patterns of standard minerals in the JCPDS (1974) diffraction file.

Twenty one representative samples of the iron ore were pulverized and analyzed using the inductively coupled plasma optical emission spectrometer (ICP-OES) and inductively coupled plasma mass spectrometer (ICP-MS) methods following a lithium metaborate/tetraborate fusion and nitric acid digestion of a 0.2 g sample at the ACME Laboratory in Vancouver, Canada. Major and trace elements contents of the iron ore samples were determined. The detection limit is > 0.01 % for the major elements, and > 0.5 ppm for the trace elements. Many international standards were used for the measurement of accuracy and precision of analyses. These standards were analysed alongside the BIF samples as unknowns. Duplicate samples were also analysed. The resulting precision was better than 5% for most of the elements.

4. Results and Discussion

4.1 Petrography and Mineralogy

The Gangfelum BIF is hard and compact, fine-grained, reddish-brown to black in colour. It is banded consisting of thin alternating iron-rich and silica-rich layers. The thin (mm) iron-rich layers containing hematite, goethite and magnetite alternating with thicker (cm) quartz-rich layers were observed in the hand specimen. Photomicrographs of the BIF samples are shown in Figure 3. Quartz, hematite, goethite, magnetite and some accessory minerals, notably rutile, apatite, tourmaline and zircon were identified in the polished section of the ore. The light coloured minerals are magnetite and hematite while the darker grains are quartz replaced with goethite. Quartz crystals occur as interlocking mosaic in transmitted light. Fractures in the quartz crystals indicate the effect of post-deformational stress Also, crystals of quartz, albite, amphibole and other silicate grains occur as inclusions within hematite and magnetite. Ilmenite and maghemite occur as gold-coloured minute inclusions.

The X-ray diffraction analysis on five representative samples showed that hematite constitutes about 42 vol. % of the ore (Figure 4). Hematite (α-Fe_2O_3) peaks occur at 2θ degrees of 24.25, 33.30, 35.27, 41.02 and 54.20. Goethite [α-$Fe^{3+}O(OH)$] peaks occur at 2θ degrees of 22.25-21.41 and 41.22. Quartz content is about 41 vol. % of the ore. The presence of α-Fe_2O_3, α-$Fe^{3+}O(OH)$ and α-quartz portends metasedimentary origin. Magnetite peaks are reflected at 30.1, 35.50, and 43.10 2θ degrees, while ilmenite and maghemite peaks are very weak (Figure 4).

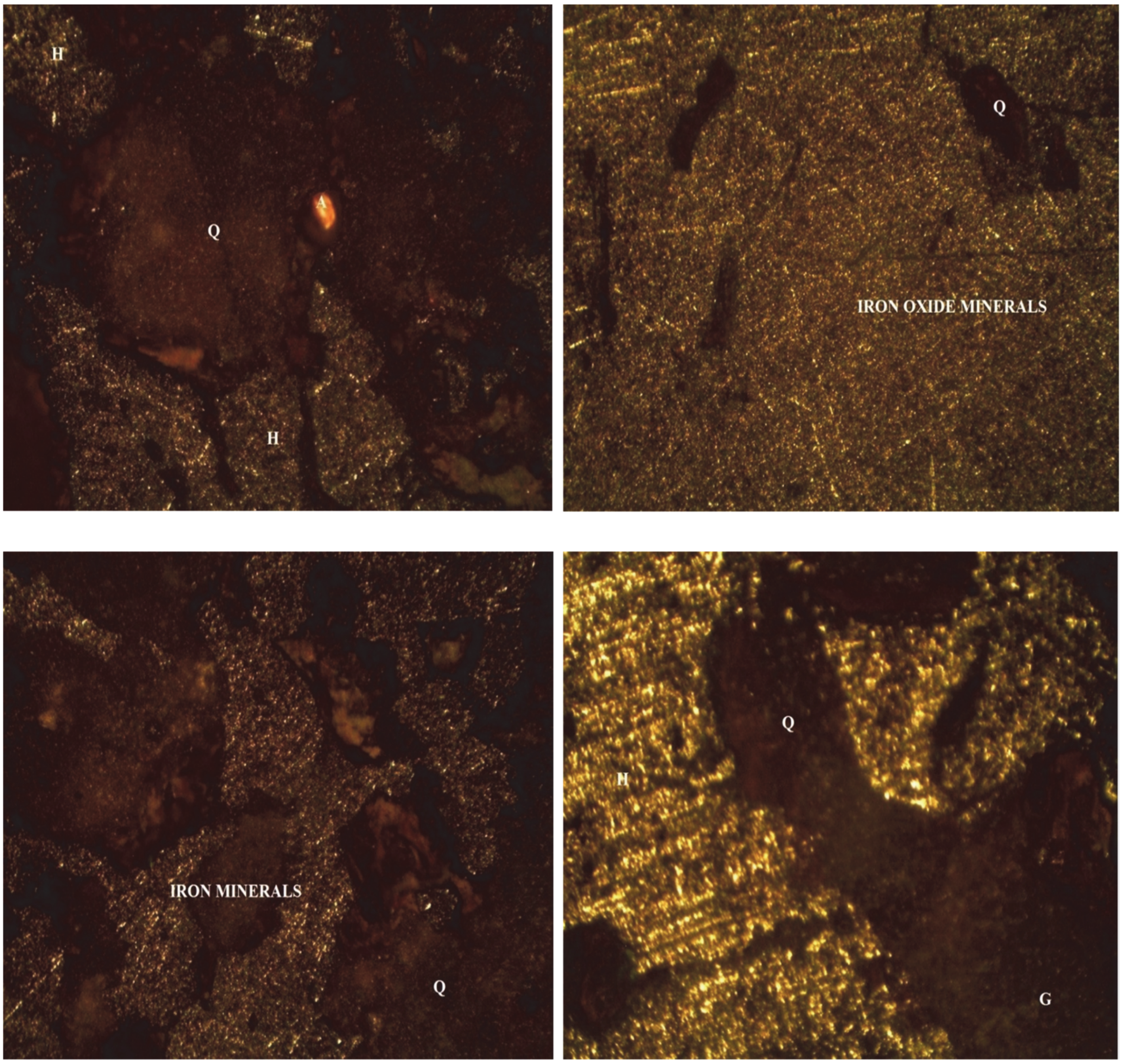

Figure 3. Photomicrograph of the Gangfelum iron ore. Reflected light microscope (x 10)

Top - Quartz (Q) impregnated with goethite (reddish-brown) and hematite (H). Bottom – Quartz (Q) impregnated with goethite (reddish-brown) and goethite (G) with subhedral hematite and magnetite grains (H).

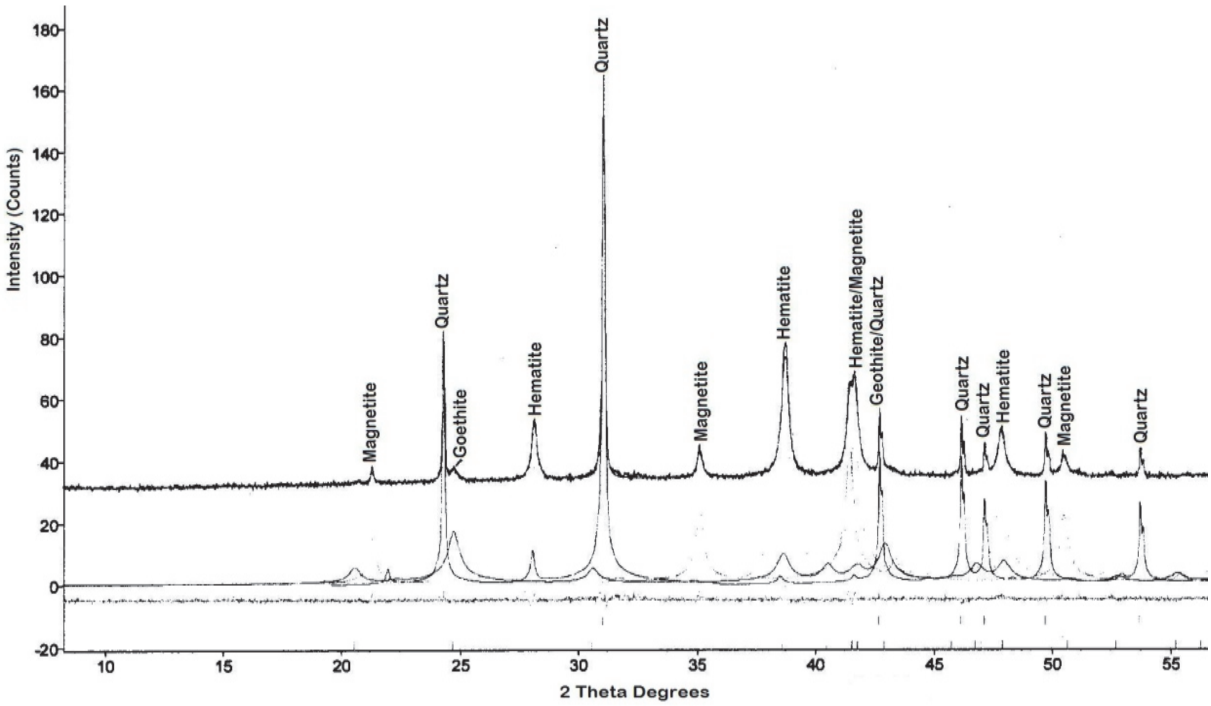

Figure 4. X-ray diffraction chart of the BIF sample from Gangfelum area

4.2 Geochemistry

Results of the chemical compositions of the twenty-one samples of the Gangfelum BIF were grouped into seven, based on petrography and chemical similarities and presented in Table 1. As shown in Table 1, the $Fe_2O_{3(t)}$ content ranged from 47.8-61.77 wt.% with an average value of 53.91 wt.%. The high $Fe_2O_{3(t)}$ value may be attributed to supergene enrichment due to impregnations and replacements associated with post-metamorphic activities. The pre-metamorphic kaolinite precursor are impregnated with and partially replaced by hematite and goethite in the form of fine colloidal aggregates, which penetrates the cavities of the kaolinite. The SiO_2 values ranged from 34.36 - 48.26 wt. % with an average value of 41.98 wt. %. The silica content is inversely proportional to the iron content. Alumina has an average value of 1.41 wt. % and ranged between 0.98 - 2.30 wt. %. The CaO content of the iron ore is very low with an average value of 0.05 wt. %. Other oxides such as TiO_2 and MnO are less than 0.5 wt. % each, while P_2O_5 is less than 0.01. The chemical data suggested that the BIF is the oxide facies type. Trace element concentrations; Ba (67-332 ppm), Ni (28-35 ppm), Sr (13-55 ppm) and Zr (16-25 ppm); in the Gangfelum BIF are low but similar to other Precambrian iron ores all over the world.

The variation diagrams of the chemical data showed that $Fe_2O_{3(t)}$ increases with a decrease in silica and Al_2O_3, which possibly indicates replacement of precursor silica and kaolinite with goethite, which subsequently dehydrated to hematite. This is similar to the observation of Mucke & Neumann (1986) on the BIF of Itakpe area, Nigeria. Al_2O_3 decreases with increase in TiO_2 indicating a similar genetic source for the TiO_2 and $Fe_2O_{3(t)}$ in the BIF samples. The plot of CaO+MgO against Na_2O+K_2O showed a weak positive correlation (Figure 5) suggesting low contamination during precipitation of the BIF. The Gangfelum BIF also plots within the field of the Precambrian BIF as shown on the Govett (1966) Al_2O_3-SiO_2-Fe_2O_3 ternary diagram (Figure 6).

The Gangfelum BIF is similar to the Maru and Muro BIFs in Nigeria (Table 2). The Kakun iron ore, within the same Precambrian basement complex of Nigeria, has lower silica and higher magnetite contents and has been postulated to be associated with igneous and meta-igneous precursor due to the presence of exolution blebs of ilmenite in bornite, high magnetite contents and some peculiar trace and rare-earths compositions (Okolo, 1987). The average $Fe_2O_{3(t)}$, Al_2O_3, TiO_2, MgO, CaO, Na_2O, Cr, Ni and Zn content of the Kakun ore is higher compared to the Maru and Muro BIF. Abhulimen (1986) stated that the occurrence of the Kakun iron ore in form of plugs or dykes suggested magmatic origin. Hematite is the major iron oxide present in the Gangfelum iron ore with subordinate magnetite and goethite, unlike the Maru, Muro and Kakun ones which have magnetite as their major iron oxide with specular hematite in the Muro, Maru and Birnin Gwari ores. The Kakun ores, on the other hand, have no hematite as reported by Okolo (1987).

Table 1. Major (wt.%) and Trace elements (ppm) composition of the iron ore samples in the Gangfelum area

Oxides	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Average**	**Range**
	n = 3	**n = 3**	**n = 3**	**n = 3**	**n = 3**	**n = 3**	**n = 3**	**n = 21**	**n = 21**
SiO_2	46.29	48.26	47.28	34.36	38.52	39.91	39.23	41.98	34.36-48.26
TiO_2	0.35	0.29	0.32	0.44	0.40	0.38	0.39	0.37	0.29-0.44
Al_2O_3	2.30	1.42	1.86	0.98	1.66	0.56	1.11	1.41	0.98-2.30
$Fe_2O_{3(t)}$	47.86	48.22	48.04	61.77	56.72	57.59	57.16	53.91	47.86-61.77
MnO	0.09	0.08	0.09	0.10	0.10	0.09	0.10	0.09	0.08-0.10
MgO	0.03	0.01	0.02	0.02	0.02	<0.01	0.01	0.02	<0.01-0.03
CaO	0.06	0.04	0.05	0.06	0.05	0.05	0.05	0.05	0.04-0.06
Na_2O	0.32	0.19	0.26	0.1	0.21	0.05	0.13	0.18	0.05-0.32
K_2O	0.80	0.47	0.64	0.22	0.51	0.10	0.31	0.44	0.10-0.80
LOI	1.80	0.90	1.35	1.90	1.70	1.20	1.45	1.47	0.90-1.90
Total	**99.9**	**99.88**	**99.91**	**99.95**	**99.89**	**99.93**	**99.94**	**99.92**	**99.88-99.95**
Trace elements (ppm)									
Ba	332	209	271	125	231	67	149	198	67-332
Co	22	28	25	30	28	45	38	31	22-45
Cr	41	45	42	48	41	60	46	46	41-60
Cu	10	13	14	16	12	25	15	15	10-25
Ni	28	30	29	29	29	35	32	30	28-35
Sr	55	37	46	38	38	13	26	36	13-55
Zn	11	15	12	10	14	10	12	12	10-15
Zr	25	17	21	20	20	16	18	20	16-25
Y	8	5	7	8	8	6	7	7	5-8
Nb	15	11	13	19	19	16	18	16	11-19
Sc	4	3	4	4	4	3	4	4	3-4

n = 21 – Number of samples

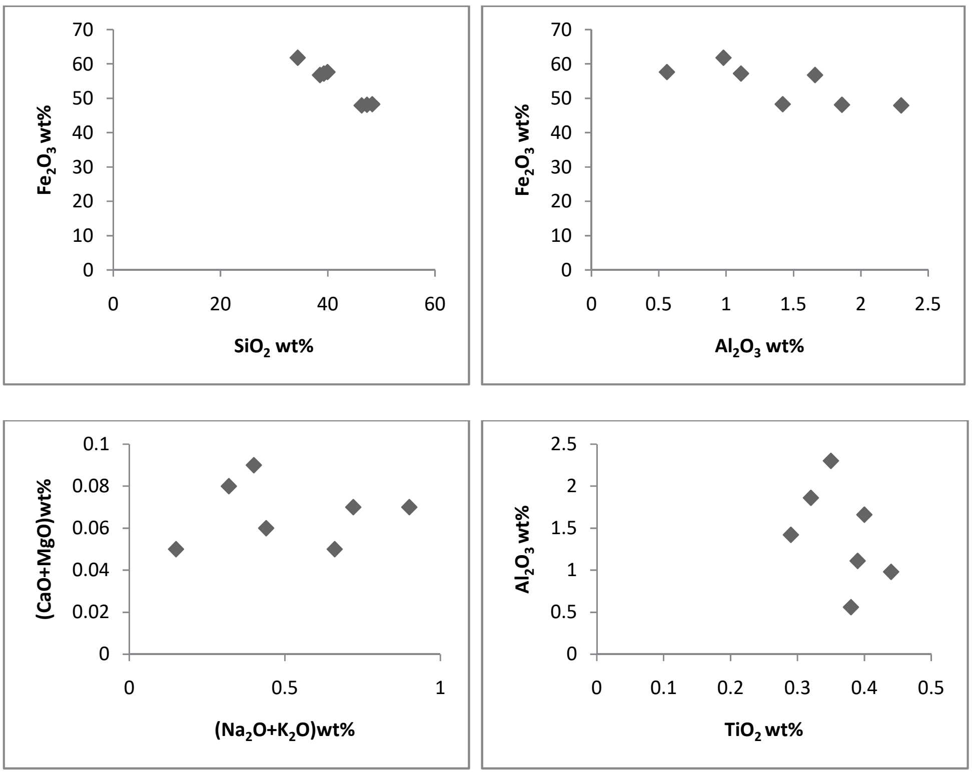

Figure 5. Binary plots of major oxides of the Gangfelum iron ore

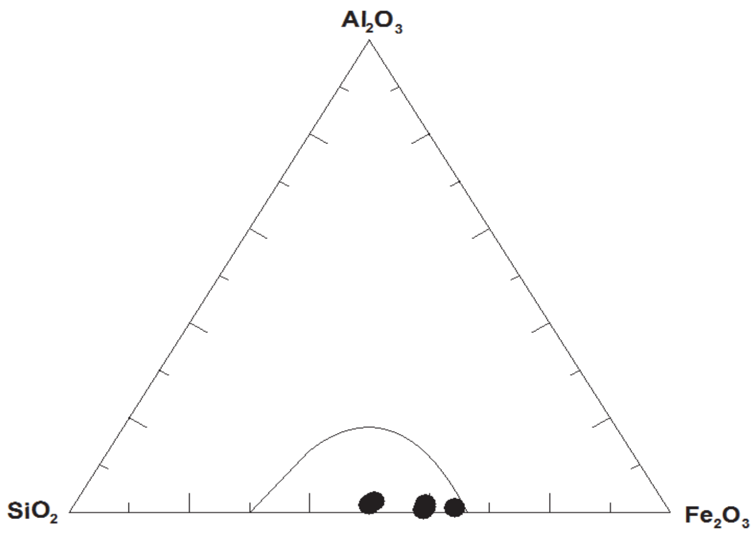

Figure 6. Plot of the Gangfelum iron formation in the Precambrian field of SiO_2-Al_2O_3-Fe_2O_3 ternary diagram (after Govett, 1966)

Table 2. Averages and ranges of major oxide (wt.%) and trace elements (ppm) of iron-formations from Gangfelum, Maru, Muro and Kakun areas in Nigeria

	This Study		Maru		Muro		Kakun	
Oxides	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
SiO_2	41.98	34.36-48.26	34.35	26.33-43.95	57.66	51-64.96	20.17	13.50-30.46
TiO_2	0.37	0.29-0.44	0.16	0.01-0.29	0.02	0.01-0.05	1.74	1.45-1.98
Al_2O_3	1.41	0.98-2.30	4.25	2.25-9.19	0.28	0.09-0.55	8.12	8.00-8.40
$Fe_2O_{3(t)}$	53.91	47.86-61.77	54.30	45.16-60.55	42.02	38.71-48.62	56.80	50.55-61.75
MnO	0.09	0.08-0.10	4.83	2.31-9.94	0.06	0.03-0.12	0.07	0.05-0.09
MgO	0.02	<0.01-0.03	0.13	<0.01-0.44	0.01	0.01-0.06	3.58	2.01-4.42
CaO	0.05	0.04-0.06	0.11	0.03-0.20	0.02	0.01-0.10	6.68	4.20-8.40
Na_2O	0.18	0.05-0.32	0.01	0.01-0.06	0.01	0.01-0.01	1.10	0.98-1.22
K_2O	0.44	0.10-0.80	0.65	0.01-3.01	0.02	0.01-.0.07	0.77	0.50-0.93
P_2O_5	<0.01	<0.01	0.09	0.04-0.20	0.05	0.01-0.15	0.27	0.16-0.60
LOI	1.47	0.90-1.90	3.47	1.79-5.98	0.81	0.01-2.14	ND	ND
Total	**99.92**							
Trace elements (ppm)								
Ba	198	67-332	293	164-802	41	<9-99	ND	ND
Co	31	22-45	100	80-173	166	142-194	47	36-59
Cr	46	41-60	23	<10-36	10	<10-19	100	86-114
Cu	15	10-25	<10	<10	40	<10-264	37	30-45
Nb	16	11-19	5	<5-9	5	<5-7	ND	ND
Ni	30	28-35	<10	<10	<10	<10	116	75-181
Sc	4	3-4	ND	ND	ND	ND	ND	ND
Sr	36	13-55	51	32-179	18	16-20	ND	ND
Y	7	5-8	22	9-45	<5	<5	ND	ND
Zn	12	10-15	26	<10-90	<10	<10	143	120-186
Zr	20	16-25	60	50-85	39	36-41	ND	ND

ND: Not determined or reported.

The Gangfelum BIF consists predominantly of oxide facies, which is represented by the silica-iron oxide assemblage similar to the Muro BIF, though the latter include minor carbonate facies of siderite and metachert (Adekoya *et al.* 2012). The Maru BIF, on the other hand, consists of magnetite-oxide facies with minor silicate-bearing facies (Adekoya, 1998). The trace element concentration of the Gangfelum BIF is similarly low, which is characteristic of Precambrian iron formations (James, 1954, 1983). The nickel contents of Kakun ore (75-181 ppm) is considerably higher than those of the Gangfelum (28-35 ppm), the Maru (<10 ppm) and the Muro BIFs (<10 ppm). The Ganfelum BIF is similar to other Precambrian BIFs in other parts of the world (Table 3). The MnO

(0.09 wt.%) and most of the trace elements of the Gangfelum BIF is comparable to the Algoma oxide facies iron formation from North America, the Orissa iron oxide facies of India and the Itabirite from Minas Gerais, Brazil (Majumder *et al.,* 1982).

4.3 Origin of the Gangfelum BIF

The Gangfelum BIF is located within the Precambrian basement complex of northeastern Nigeria which has not been studied in detail compared to other parts of Nigeria. Minor BIF-related metasediments, similar in parts to those obtained in adjacent Cameroon (Chombong *et al.,* 2013) occur within the basement rocks, thus refuting the previous assumption that the Nigerian schist belts are restricted to the western half of the country.

The formation of the BIF began with the transition of clastic sedimentation to chemical sedimentation in a restricted or proto basin. Weathering, erosion and sedimentation was lithologically and stratigraphically controlled with paleogeographic and climatic implications. Several basalts, granitoids and gneisses provided the primary source of iron through weathering. The environment and climatic conditions were favourable for the liberation and concentration of iron in the soils during the weathering of the continental areas. It is therefore postulated that iron and silica were carried in solution from the nearby continental mass and were rhythmically deposited as sediments in water through direct precipitation. The chemically precipitated iron and silica were metamorphosed and recrystallized to hematite-quartz rocks. The banding of the BIF suggested a break in iron precipitation probably due to iron oxide deficiency.

Table 3. Averages and ranges of major oxide (wt.%) and trace elements (ppm) of iron-formations from Gangfelum, Maru compared with the Lake Superior (USA), Algoma (Canada), Orissa (India) and Itabirite (Brazil) silicate and oxide facies iron formations

	This Study					
Oxides	**Average**	**Range**	**[1]Lake Superior**	**[2]Algoma (Canada)**	**[3]Orissa (India)**	**[4]Itabirite (Brazil)**
SiO_2	41.98	34.36-48.26	47.20	50.50	49.13	51.58
TiO_2	0.37	0.29-0.44	0.21	0.02	0.02	0.09
Al_2O_3	1.41	0.98-2.30	1.39	3.00	1.45	3.06
$Fe_2O_{3(t)}$	53.91	47.86-61.77	35.4	26.90	46.33	42.62
MnO	0.09	0.08-0.10	0.73	0.06	0.76	0.14
MgO	0.02	<0.01-0.03	1.24	0.01	1.29	1.56
CaO	0.05	0.04-0.06	1.58	1.51	1.64	1.54
Na_2O	0.18	0.05-0.32	0.12	0.31	0.12	0.32
K_2O	0.44	0.10-0.80	0.14	0.58	0.15	0.59
P_2O_5	<0.01	<0.01	0.06	0.21	0.06	0.21
LOI	1.47	0.90-1.90	ND	ND	ND	ND
Trace elements (ppm)						
Ba	198	67-332	180	170	70	179
Co	31	22-45	27	38	35	69
Cr	46	41-60	122	78	30	28.5
Cu	15	10-25	10	96	10	22
Nb	16	11-19	ND	ND	ND	ND
Ni	30	28-35	32	83	83	20.3
Sc	4	3-4	ND	ND	ND	ND
Sr	36	13-55	42	83	15	20.5
Y	7	5-8	41	54	ND	ND
Zn	12	10-15	2	33	ND	ND
Zr	20	16-25	56	84	10	17.3

ND: Not determined or reported.

1 – Lake Superior silicate facies BIF, North America (Gross & Mcleod, 1980; Suresh & Basavanna, 2014; Selmi*et al.,* 2009).

2 – Algoma oxide facies iron formation, North America (Gross and Mcleod, 1980).

3 – Orissa oxide faciesiron formation, India (Majumder *et al.,* 1982).

4 – Itabirite from Mines Gerais, Brazil (Majumder *et al.,* 1982).

5. Conclusions

The Gangfelum iron formation is located within the basement complex of northeastern Nigeria, which consists mainly of migmatite-gneiss, biotite-hornblende gneiss and porphyritic granites. The average $Fe_2O_{3(t)}$ content is high (53.91 wt.%) while TiO_2, Al_2O_3, MgO, CaO, Na_2O, K_2O, MnO and P_2O_5 are low. The trace element concentrations are low and similar to other Precambrian BIFs in the world. The iron ore consists predominantly of the oxide facies. Geological evidences support a metasedimentary origin. The iron and silica were chemically precipitated, metamorphosed and recrystallized to hematite-quartz rocks. The banding of the BIF suggested a break in precipitation of iron probably due to iron oxide deficiency.

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