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Geochemical and Mineralogical Characterization of the Gold-Bearing Deposit for Efficient Beneficiation Process

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ABSTRACT

The optimization of gold beneficiation processes requires a comprehensive understanding of the geochemical and mineralogical characteristics of the ore. This study investigates gold-bearing deposits from selected artisanal mining sites (Bakolori dam, Danfako and Gimawa) in Zamfara State, Northwestern Nigeria, using integrated geochemical (X-ray fluorescence), mineralogical (X-ray diffraction) and atomic absorption spectrophotometry (AAS) techniques. Fifteen representative ore samples were collected from the mine site with quartz-vein hosted mineralization zones and weathered lateritic profiles. The representative samples were analyzed using X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS), X-ray diffraction (XRD) and atomic absorption spectrophotometry (AAS). XRF results revealed high concentrations of SiO2 (68.69–79.55%) and Al2O3 (13.02–15.45%), with Fe2O3 levels ranging from 1.14% to 7.50%. Trace indicator elements such as Sb2O3 and SrO were present in low concentrations. AAS confirmed the presence of gold (Au) with concentrations between 0.4845% and 0.5719%, highest in Bakolori Dam samples, indicating a predominance in alluvial deposits. XRD analysis identified quartz (13–60%) as the dominant mineral, with significant kaolinite, chlorite, sillimanite, and hydromolysite. The mineralogical composition suggests the potential for by-product recovery of industrial minerals alongside gold extraction. These findings provide essential mineralogical and chemical insights to optimize beneficiation and enhance the economic value of Zamfara gold deposits.

Keywords— **Gold mineralization, geochemical characterization, XRF, XRD, beneficiation, Zamfara State, Nigeria**

I. INTRODUCTION

Nigeria is situated in a mobile zone separating older cratons of West Africa and Gabon and underlain by nearly equal proportions of sedimentary and crystalline rocks [1], [2]. The Basement Complex includes igneous and metamorphic rocks of Precambrian age that cover about half of Nigeria, dividing Nigeria into

North and South "geologically". Basement complex rocks are important elements for consideration not just for their mineralization potentials but also because they act as container for sedimentary basin fills, parents of particles that constitute sediments found in the basins, and their associated structural processes also influence the architecture of depositional basins during the Phanerozoic time in Nigeria.

Gold occurs in hydrothermal veins, disseminated sulfide deposits, and placer deposits, commonly associated with pyrite, arsenopyrite, chalcopyrite, and quartz [2], [3], [4], [5]. Its high density, low hardness, conductivity, and resistance to corrosion make it valuable. Gold is a strategic and economically significant mineral, valued for its industrial, ornamental, and monetary applications. Its remains one of the most valuable and sought-after metals in the global economy, with uses ranging from monetary reserves and jewelry to electronics and medicine [6]. Its unique physical properties—including high malleability, resistance to corrosion, and excellent electrical conductivity—make it indispensable across sectors such as electronics, dentistry, and jewelry manufacturing [6]. In Nigeria, gold occurrences have been documented in multiple geological terrains, particularly within Zamfara, Kaduna, and Osun States [5], [7]. Despite substantial reserves, the Nigerian gold sector remains underdeveloped, with artisanal mining dominating production and limited scientific data guiding beneficiation processes. Also, the mineral sector is gaining renewed attention due to diversification efforts aimed at reducing dependence on crude oil. Among the gold-producing regions, Zamfara State in Northwestern Nigeria has emerged as a key artisanal and small-scale mining (ASM) hub [5]. However, extraction methods are typically rudimentary, leading to low recovery rates, high ore losses, and environmental degradation, especially heavy metal contamination [8], [9].

The global competitiveness of gold extraction depends significantly on comprehensive geochemical and mineralogical characterization. Such characterization identifies ore grade, mineral associations, and gangue composition—parameters crucial for selecting optimal beneficiation techniques [5], [10]. In the context of Zamfara State, where gold-bearing formations are often associated with schist belts and quartz veins, understanding the ore's mineralogical matrix is a prerequisite for designing efficient extraction workflows [5].

Previous studies have investigated the environmental and health impacts of gold mining in Zamfara [4], [8] [11], [5] and provided preliminary geological descriptions of the mineralized belts [8]. However, there is limited research linking detailed geochemical and mineralogical characterization to beneficiation process optimization. This gap has led to inefficient processing techniques, such as uncontrolled amalgamation with mercury, which contributes to environmental contamination without maximizing gold recovery [5].

Studies worldwide highlight structural controls and geochemical anomalies in gold distribution [12], [13] while in Nigeria, significant deposits in Zamfara, Kaduna, and Osun States remain underexploited due to limited mineralogical characterization [5]. Effective beneficiation requires precise determination of ore mineralogy, grade, and impurity profile. Techniques such as XRD, XRF, AAS, and electron microscopy enable identification of gangue minerals, guiding processing methods to minimize costs and maximize recovery, aligning with Nigeria's economic diversification into solid minerals.

Modern beneficiation strategies rely heavily on understanding ore mineralogy and chemistry [5]. The behavior of gold during processing is influenced by its host mineral phases, grain size distribution, and association with sulfides or oxides [10]. Hence, systematic geochemical and mineralogical characterization is critical for designing an optimal flow sheet that maximizes gold recovery while minimizing environmental risks.

This study aims to bridge the knowledge gap by applying integrated XRF, XRD, and AAS techniques to characterize gold-bearing deposits in Zamfara. The outcomes are expected to guide process mineralogy decisions, promote value addition, and support Nigeria's economic diversification agenda.

II. MATERIALS AND METHODS

A. Samples Location and Collection

The study area lies within the northwestern Nigerian basement complex, specifically between latitudes 12°10′ N and longitude 6°15′ E. This region is part of the Pan-African mobile belt, dominated by schists, gneisses, migmatites, and quartzite intrusions. Mineralization is structurally controlled, with gold occurring in quartz veins hosted by metasedimentary and metavolcanic sequences. The area experiences a tropical wet-and-dry (Aw) climate, with annual maximum temperatures averaging 36°C [9].

Regionally, the geology is characterized by low- to medium-grade metamorphic rocks such as quartz-mica schists, phyllites, and banded iron formations, intruded by syn- to post-tectonic granitoids. These units have undergone intense deformation, producing foliation, folding, and fracturing that serve as conduits for hydrothermal fluids. The Local geology of the study area reveals gold hosted in auriferous quartz veins associated with sulfide minerals such as arsenopyrite, pyrite, and chalcopyrite. Alteration zones typically display sericitization, silicification, and ferruginization. These features suggest an orogenic gold deposit model, where mineralization is structurally controlled and deposited from metamorphic fluids [9], [5].

Fifteen representative samples were collected from artisanal mine pits in Bakolori dam, Danfako and Gimawa (Plate 1), the samples were collected using jigger and shovel and kept in a waterproof polythene bag so as to restrict water. The coordinates of sampling sites are presented in Table 1. Also, Figure 1 presents the location map the study area.

B. Sample Preparation and Analysis

Representative sub-samples of the three locations were pulverized using a vibration grinding mill with a steel chamber, achieving 80% passing 75 µm after sieving through a 200-mesh screen. Samples were oven-dried at 110 °C to constant weight. Homogenized powders were allocated for X-ray fluorescence (XRF), X-ray diffraction (XRD) and Atomic Absorption Spectrometry (AAS).

Major element oxides were quantified using a Shimadzu EDXRF-702HS energy-dispersive spectrometer operated at 40 kV and 18 mA with a 10 mm collimator. Samples were prepared as fused glass discs (sample/melt ratio 0.5:5). Data acquisition was managed through Shimadzu EDX software, reporting Kα intensities in cps/µA [5].

Mineralogical composition was determined using a Bruker D8 Advance X-ray diffractometer with Cu-Kα radiation. Data were collected over a 2θ range of 5°–70° and phases identified using the ICDD PDF-4 database. XRD (Theta–Theta Configuration): Phase identification employed Cu Kα radiation, scanned from 0° to 70° 2θ. Peak matching utilized the ICDD PDF database [7].

Elemental concentrations (Au, Pb, Ni, Co) were determined using an AA1100N atomic absorption spectrophotometer with an air–acetylene flame and Ag/AgCl reference electrode. Samples were digested via aqua regia ($HCl:HNO_3$, 3:1) following 16 h pre-reaction at ambient temperature, heated for 2 h at ~80 °C, and filtered. Gold was pre-concentrated using 5% di-n-octyl sulfide in toluene. Calibration curves were prepared from Sigma-certified standards [10], [5].

(a) Danfako Site

(b) Gimawa Site

Plate 1: Sampling Sites.

Table 1 – Sampling coordinates and site descriptions

SN	Sample Site	Sample Acronyms	Sample Coordinate
1	Bakolori dam	BK	12° 30′N, 6° 11′ E.
2	Danfako	DN	12° 21′N, 6° 04′ E
3	Gimawa	GM	12° 20′N, 6° 08′ E

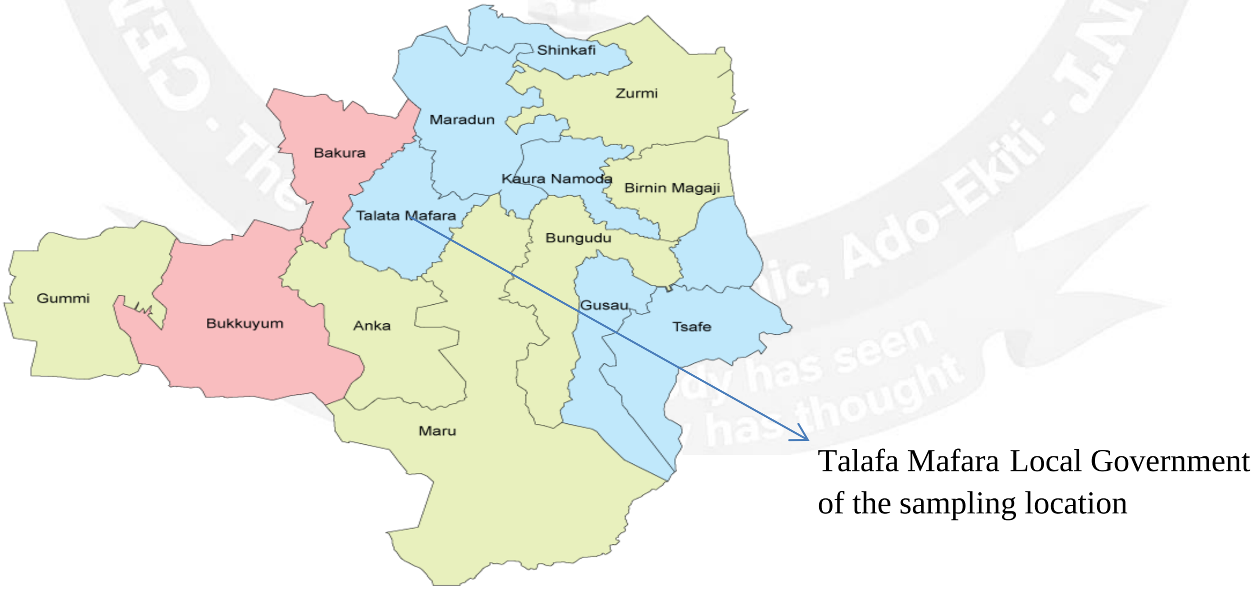

Figure 1: Location map of Zamfara State showing the local government area of the sampling locations

III. RESULTS

A. Geochemical Composition of the Samples

Table 2 presents the results of the geochemical composition of the samples from BK, DN and GM. All the three samples were dominated by SiO2 ranging between 68.69% and 79.55%. BK has the highest SiO2 (79.55%) while GM has the lowest (68.69%). Also, the samples have moderate Al2O3 which range between 13.02 and 15.45% suggests the presence of aluminosilicate minerals. The presence of Al2O3 and SiO2 could represent rocks (felsic) reflecting abundant quartz and iron-bearing minerals [5]. BK has the highest Al2O3 while BK has the lowest. More so, metallic oxide (Fe2O3, K2O and CaO) are present in the samples in small quantity ranging between 0.05 and 7.50. GM has the highest Fe2O3 contents while BK has the highest K2O and CaO contents. High Fe2O3 indicates oxidation of primary sulfides, potentially impacting gold liberation during processing. Other metallic oxide (TiO2, MnO, MoO3, PbO, Nb2O3, Sb2O3, SrO, and Ag2O) are present in trace quantity ranging between 0.00 and 0.14. GM has the highest TiO2, and MnO contents, BK has the highest MoO3, PbO and Ag2O contents, GM has the highest Sb2O3, and DN has the highest SrO content. DN and GM have no trace of MoO3 and PbO contents, DN has no trace of Sb2O3 and GM has on trace of SrO and Ag2O. All the samples have the same proportion of Nb2O3 (0.01%). Although all the samples did not reflect Gold (AU) trace, but elements indicative of hydrothermal gold mineralization, including Sb2O3 and SrO, were detected in BK samples and DN [5].

IV. DISCUSSION

A. Atomic Absorption Spectrophotometer (AAS)

This analysis was directed to assess the concentration of (AU) gold present in the samples. Table 3 presents the concentration of gold contents in the sample from the three locations. The presence of AU elements was detected in all the samples. Gold content ranged from 0.4845% in DN and GM to 0.5719% in BK, suggesting a higher concentration in alluvial deposits. The highest concentration was observed in BK which buttress the idea that this deposit is more concentrated in alluvial deposits contrary to the other two samples (DN and GM). This indicates the alluvial deposits of the BK is promising and more reliable. Although, more detailed and comprehensive studies is needed in all the three sites for adequate characterization of the concentration of gold (Au) in the deposit and unravel economical technique to separate the gold from its ore.

In addition, it was observed that gold concentrate are within the weathered to fresh rock in the other two samples [10] [5]. Also, it was observed that the concentrations of the other two samples are the same, indicating they are from same source and since their distance is relatively close this supports that the outcrop might be from same source with the same mode of occurrence.

B. Mineralogical Composition

The results of the mineralogical composition of the samples are present in Table 4. Quartz dominated the mineralogy (13–60%), followed by kaolinite (0.7–33%), chlorite (2–17%), hydromolysite, sillimanite, illite, and accessory minerals including albite and garnet. Bk has the highest quartz content (60%) which is ideal for alluvial deposit, while GM has the lowest quartz contents (13%). The association of gold with quartz supports a hydrothermal origin. Quartz-hosted free gold can be recovered by gravity concentration, while sulfide-associated gold may require flotation or oxidative pre-treatment before cyanidation [10], [7] [5].

GM has the highest kaolinite (33%) while BK has the lowest (0.7%) which is expected of alluvial deposit. Hydromolysite is higher in DN, while BK has no trace of the mineral. Also, sillimanite, ilmenite and illite are present in GM but absent in BK and DN. In addition, albite, anorthite and garnet are present in BK, but these mineral are absent in GM and DN. Leucite and lepidocrocite are present in DN but absent in BK and GM. However, chlorite was observed to be present in all the three samples, highest in GM (17%) and lowest in DN (2%).

The elevated silica and alumina levels are consistent with quartz-rich, kaolinite-bearing lithologies which is typical of hydrothermal alteration zones. The co-occurrence of Fe-bearing minerals such as chlorite and hydromolysite suggests a metamorphosed host rock environment with secondary mineralization processes [5]. The higher gold concentration in BK supports the economic viability of alluvial mining in the area. The significant kaolinite content in GM further presents opportunities for by-product recovery in the ceramics industry.

Table 2: Results of the Geochemical Composition of the Samples

S/No	Elemental Oxides	Bakolori Dam (BK)	Danfako (DN)	Gimawa (GM)	Range	Mean values
1	SiO_2	79.55	77.45	68.69	68.69 - 79.55	75.23
2	Al_2O_3	15.45	13.02	13.35	13.02 - 15.45	13.94
4	TiO_2	0.02	0.10	0.14	0.02 - 0.14	0.08
5	MnO	0.02	0.02	0.13	0.02 - 0.13	0.06
6	Fe_2O_3	1.14	4.29	7.50	1.14 - 7.50	4.31
7	K_2O	1.60	0.05	0.42	0.05 - 1.60	0.69
8	CaO	1.28	0.94	0.29	0.29 - 1.28	3.29
9	MoO_3	0.01	0.00	0.00	0.00 - 0.01	0.01
11	PbO	0.04	0.00	0.00	0.00 - 0.04	0.04
13	Nb_2O_3	0.01	0.01	0.01	0.00 - 0.01	0.01
14	Sb_2O_3	0.003	0.00	0.004	0.00 - 0.004	0.004
15	SrO	0.01	0.03	0.00	0.00 - 0.03	0.02
20	Ag_2O	0.004	0.003	0.00	0.00 - 0.04	0.004

Table 3: Atomic Absorption Spectrophotometre revealing Gold concentration in the Sampes

S/No	Sample Location	Concentration (%)
1	Bakolori Dam (BK)	0.5719
2	Danfako (DN)	0.4845
3	Gimawa (GM)	0.4845

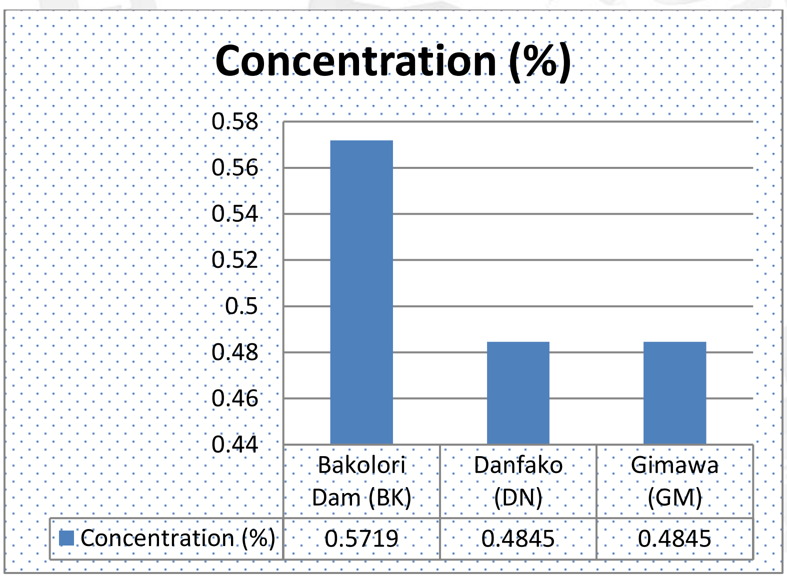

Figure 2: Showing the graphical representation of AAS Gold Concentration in the samples collected.

Table 4: Mineralogical Concentration of the Samples

S/No	(%) Mineral	Chemical Formula	BK	GM	DN
1	Quartz	SiO_2	60	13.0	48.0
2	Hydromolysite	$FeCl_3.6H_2O$	Nil	4.0	22.0
3	Kaolinite	$Al_2Si_2O_5\ (OH)_4$	0.7	33.0	19.0
4	Sillimanite	$Al_2O_3\ .SiO_2$	Nil	11.0	Nil
5	Chlorite	$Mg_2Al_3(Si_3Al)O_{10}(O)_8$	9.0	17.0	2.0
6	Illite	$KAl_2Si_3AlO_{10}(OH)_2$	Nil	20.0	Nil
7	Ilmenite	$Fe.TiO_3$	Nil	1.0	Nil
8	Albite	$Na(AlSi_3O_8)$	6.5	Nil	Nil
	Anorthite	$Ca.Al_2(SiO_4)_2$	18.0	Nil	Nil
10	Garnet	$3(Ca,Fe,Mg)O.(Al,Fe)_2O_3.3SiO_2$	6.5	Nil	Nil
11	Leucite	$Al_2O_3.K_2O.4SiO_2$	Nil	Nil	7.0
12	Lepidocrocite	$Fe_2O_3.H_2O$	Nil	Nil	1.9

V. CONCLUSION

This study demonstrates that the Zamfara gold-bearing deposits are quartz-dominated with economically relevant gold concentrations, particularly in alluvial environments. Mineralogical data provided gives a foundation for targeted beneficiation strategies, while geochemical profiles highlight the potential for multi-mineral exploitation. Optimal beneficiation should integrate gravity concentration, flotation, and cyanidation, with pre-treatment for refractory ores. These findings provide a pathway to improve recovery rates, reduce environmental hazards, and enhance the economic viability of mining in Zamfara. Future work should focus on ore petrography which involves the detailed description and analysis of rocks, especially their composition, texture, and structure more also metallurgical testing which is the scientific examination and analysis of metals and ores to determine their physical, chemical and mechanical properties, as well as how they behave during processing and use., and large-scale resource estimation.

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