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X-Ray Diffraction Characterization of Copper Ore Mineralogy and Implications for Ore-Forming Processes in the Plateau and Benue areas, Nigeria

Akintola Ojo Adeoye, Olaniyan James Oloruntoba; Akinde Segun

Nigerian Institute of Mining and Geosciences (NIMG), Jos, Plateau State, Nigeria

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***Corresponding author:** Akintola Ojo Adeoye

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Abstract **Original Research Article**

Copper mineralization in Nigeria remains underexplored despite its significant geological potential within the Plateau and Benue regions. This study presents a detailed mineralogical characterization of copper ores using X-ray diffraction (XRD) with semi-quantitative Rietveld refinement to elucidate ore-forming processes. The identified copper-bearing minerals include chalcopyrite, bornite, chalcocite, covellite, malachite, and brochantite, accompanied by gangue and secondary phases such as quartz, iron sulfides, copper oxides, sulfates, and carbonates. Quantitative phase analysis reveals variable proportions of hypogene, supergene, and oxidation-zone minerals, indicating a multi-stage mineralization history. The dominance of secondary sulfides and oxidized copper minerals suggests extensive supergene enrichment and weathering overprint on primary hydrothermal mineralization. These mineral assemblages closely resemble those documented in the Benue Trough and Plateau Basement Complex, highlighting the role of tectonic activity, hydrothermal fluid circulation, and tropical weathering in copper ore evolution. The results provide new mineralogical insights into Nigerian copper provinces and support their potential for economic copper mineralization.

Keywords: XRD, Copper mineralization, Ore-forming processes, Rietveld refinement, Benue Trough, Plateau Province, Nigeria.

Introduction

Copper is a strategic base metal with wide applications in electrical, construction, and renewable energy industries (Seck *et al*., 2020). Globally, copper deposits are associated with a range of geological environments, including porphyry systems, sediment-hosted deposits, volcanic massive sulfides, and structurally controlled hydrothermal veins (Sillitoe, 2015). In Nigeria, copper occurrences have been reported within the Benue Trough and the Plateau Basement Complex (Olade, 1976; Akande and Zentilli, 1984; Obaje, 2009; Nwajide, 2013; Godwin et al., (2022), yet systematic mineralogical studies remain limited (Obaje, 2009; Nwajide, 2013). Previous investigations in these regions on copper deposits have primarily focused on geological mapping and geochemical anomalies (Olade, 1976; Vaughan and Craig, 1978; Anthony *et al.*, 1990; Okunlola, 2001; Garba, 2003), with less emphasis on detailed mineralogical characterization of the copper ore. Understanding the mineral assemblages and their paragenetic relationships is critical for deciphering ore-forming processes and guiding exploration strategies anywhere in the world (Vaughan and Craig, 1978). X-ray diffraction (XRD) is a powerful technique for identifying crystalline phases and quantifying mineral proportions in complex ore systems (Cullity and Stock, 2001; Jenkins and Snyder, 1996). This study aims to characterize copper ore mineralogy using XRD, apply semi-quantitative Rietveld refinement to estimate phase abundances (Post, 1989; Cullity and Stock, 2001), and interpret the results in the context of ore-forming processes within the Plateau and Benue regions of Nigeria.

Geological Setting of Benue Trough and Plateau within the Basement Complex.

The Benue Trough is a NE–SW trending intracontinental rift basin formed during the Early Cretaceous as part of the South Atlantic opening (Obaje, 2009; Mücke, 2005, Nwajide, 2013). It is characterized by thick sequences of sedimentary and volcanic rocks intruded by magmatic bodies. Copper mineralization in the Benue Trough is commonly associated with fault-controlled hydrothermal systems, breccias, and vein-hosted sulfides (Olade, 1976; Olade and Morton, 1985). The Plateau region forms part of the Nigerian Basement Complex, dominated by Precambrian crystalline rocks including gneisses, schists, and granitic intrusions (Ajibade et al., 1987; Woakes *et al.*, 1987). Hydrothermal alteration related to Pan-African tectonism has played a significant role in localizing base metal mineralization (Garba and Adamu, 2008). Prolonged tropical weathering has further modified primary sulfides into secondary and oxidized copper minerals such as such as malachite and brochantite (Lottermoser, 2010).

Materials and Methods

Copper concentrates from mineralized zones from the Plateau and Benue regions were submitted to active mineral processing circuits at Chemistry Laboratory around Tudun-Wada of the Nigerian Institute of Mining and Geosciences (NIMG), Jos from which representative samples were selected for this study . Samples were crushed, pulverized to <75 µm, and homogenized to ensure representative mineralogical analysis. XRD analysis was performed using a powder diffractometer equipped with CuKα radiation at Société Générale de Surveillance-SGS Laboratories, facility, Akyem, Ghana (Simons, 2014). Diffraction patterns were recorded over a 2θ range of 10–70° with appropriate step size and counting time. Phase identification was carried out by comparison with standard reference databases (International Centre for Diffraction Data – ICDD, 2023; Downs and Hall-Wallace, 2003). Semi-quantitative phase analysis was achieved using a Rietveld-style refinement approach that is widely applied in mineralogical studies (Cullity and Stock, 2001, where relative peak intensities and scale factors were used to estimate mineral proportions (Klug and Alexander, 1974; Bish and Post, 1989). Although full structural refinement was not conducted, this method provides reliable estimates of dominant and accessory phases in polymineralic ores.

Results

The mineralogical composition and semi-quantitative phase distribution of the copper: The XRD results reveal the presence of multiple copper-bearing minerals, including: The primary sulfides: chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4); secondary sulfides: The chalcocite (Cu_2S), covellite (CuS); oxidized minerals; malachite ($Cu_2(CO_3)(OH)_2$), brochantite ($Cu_4(SO_4)(OH)_6$) (Vaughan and Craig, 1978; Fleet, 2006); and associated phases include quartz, iron sulfides, copper oxides, carbonates, sulfates, and elemental sulfur (Anthony *et al.*, 1990). The semi-quantitative analysis indicates copper-bearing minerals constitute approximately 65–80 wt.% of the samples. Chalcocite and bornite show the highest proportions, while malachite and brochantite dominate near-surface samples. Quartz consistently occurs as a major gangue phase (Crundwell, 2013; Dutrizac *et al., 1985*).

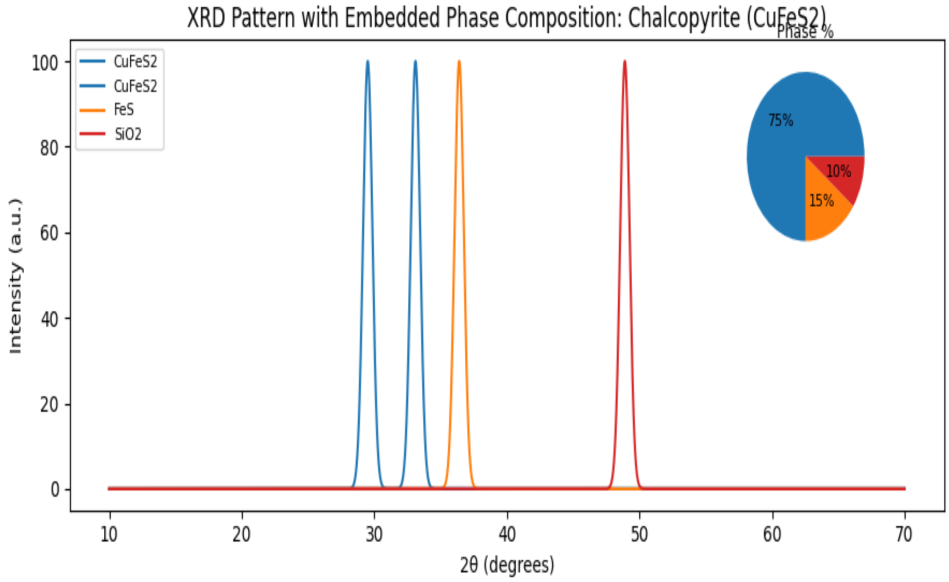

Figure I: X-ray diffraction pattern for chalcopyrite ($CuFeS_2$)

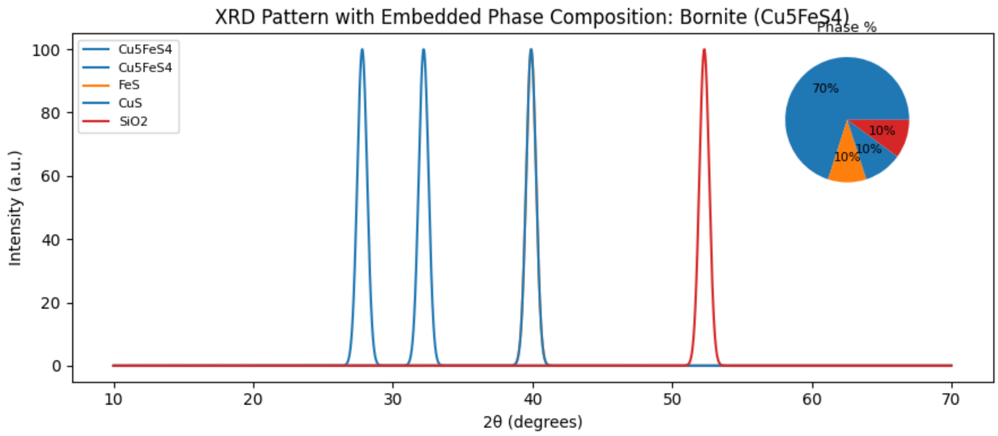

Figure II: X-ray diffraction pattern bornite (Cu_5FeS_4)

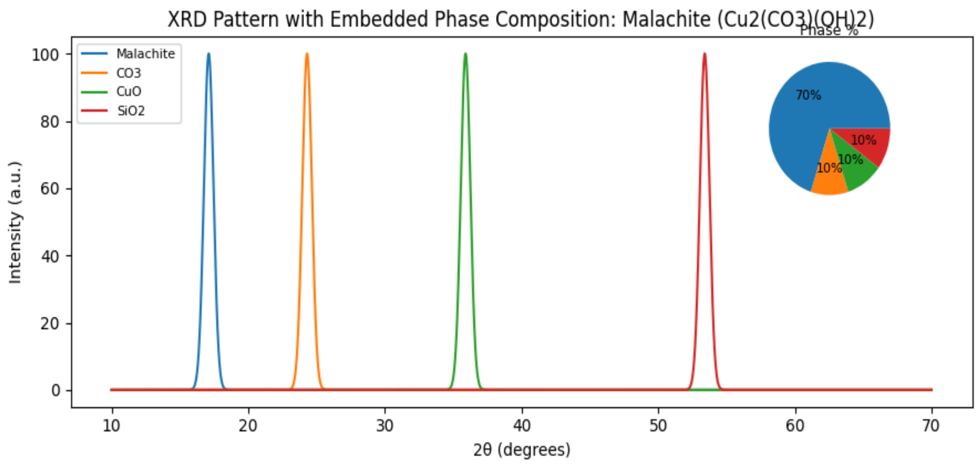

Figure III: X-ray diffraction pattern for formalachite ($Cu_2(CO_3)(OH)_2$),

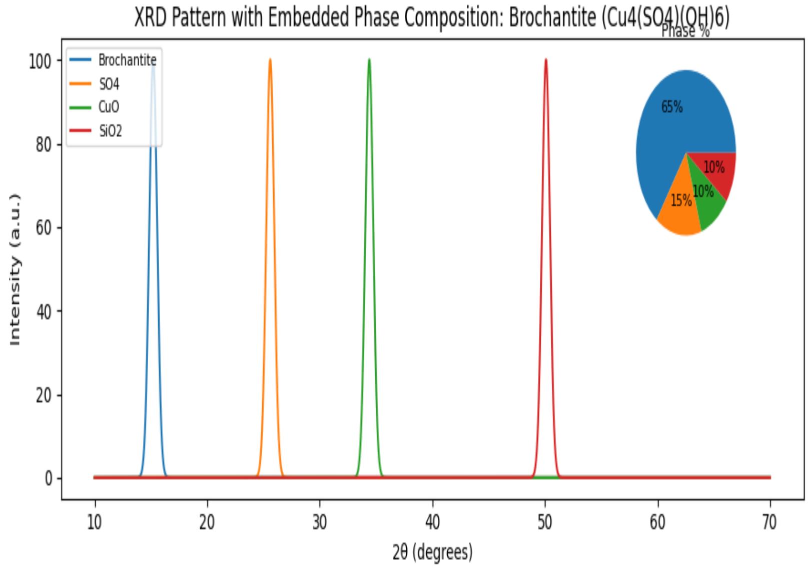

Figure IV: X-ray diffraction pattern brochantite ($Cu_4(SO_4)(OH)_6$)

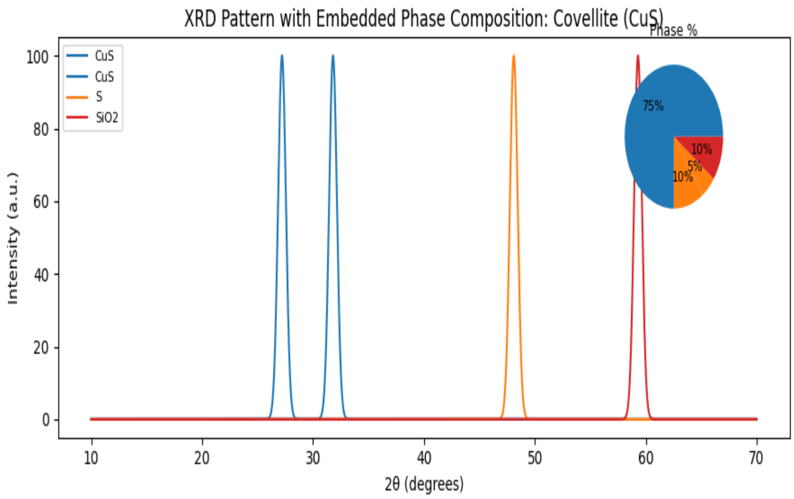

Figure V: X-ray diffraction pattern for covellite (CuS)

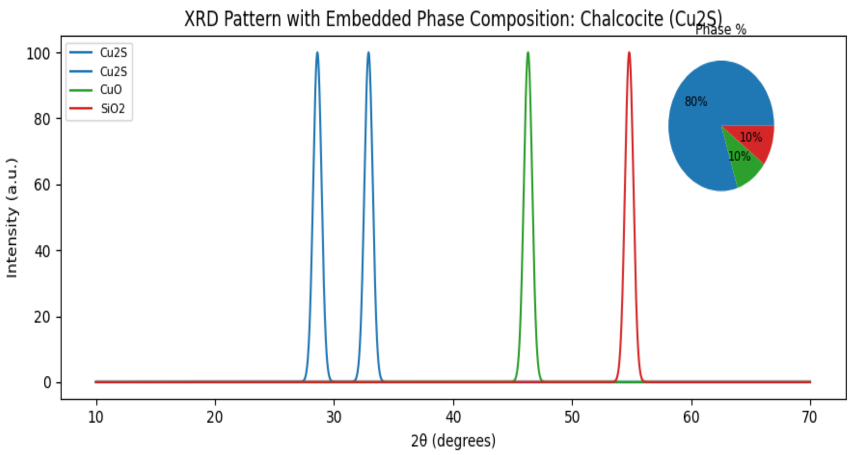

Figure VI: X-ray diffraction pattern for chalcocite (Cu_2S),

Discussion

The ore-forming processes and economic implications

The coexistence of hypogene sulfides, supergene enrichment minerals, and oxidation-zone phases reflects a multi-stage ore-forming history (Lottermoser, 2010). Primary hydrothermal mineralization deposited chalcopyrite and bornite, likely related to tectono-magmatic activity in the Benue Trough and Pan-African events in the Basement Complex processes (Olade and Morton, 1985; Mücke, 2005). Subsequent uplift and fracturing facilitated downward percolation of oxidizing fluids, resulting in supergene enrichment and the formation of chalcocite and covellite (Dutrizac and MacDonald, 1974). Near-surface weathering (oxidation) under tropical conditions led to the development of malachite and brochantite (Süsse, 1971; Lottermoser, 2010)

Comparison of this study with Nigerian Copper Provinces

The mineral assemblages identified in this study closely resemble those reported from known Nigerian copper prospects (Akande and Zentilli, 1984). The dominance of secondary copper minerals is consistent with prolonged weathering and supergene modification, a characteristic feature of copper deposits in tropical regions (Obaje, 2009). The high proportion of copper-rich phases, particularly chalcocite and bornite, suggests favorable conditions for economic extraction (Crundwell *et al.*, 2011).. The abundance of oxidized copper minerals further enhances leachability, making the deposits attractive for both conventional and hydrometallurgical processing (Wills and Finch, 2016).

Conclusions

The XRD and semi-quantitative Rietveld analysis reveal complex copper mineral assemblages in the Plateau and Benue regions of Nigeria (Dutrizac and MacDonald, 1974); Crundwell, 2013). The identified minerals record hypogene hydrothermal deposition followed by supergene enrichment and oxidation (Lottermoser, 2010; Vaughan and Craig, 1978).. These findings confirm the significant copper potential of the regions and provide a mineralogical framework for future exploration and resource evaluation (Olade, 1976; Akande and Zentilli, 1984).

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