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Investigations of Ore and Tailing Samples for Improving Extracting Methods and Enhancing Gold Recovery of Artisanal and Small-Scale Miners: A Case Study of Singida Region in Tanzania, East Africa

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Abstract

The Artisanal and Small-Scale Miners (ASSM) are engaged in gold mining activities across various regions in Tanzania, yet their production rates have been consistently subpar. This research aims to determine deficiencies in recovery techniques and the overall mineral extraction process, emphasizing the necessity of improving mineralized zone discovery and extraction methods through collaborative efforts among geologists, mining and mineral processing engineers, and ASSM. Leveraging geophysical and geological data, tailings, and ore studies using geostatistical software packages, this study evaluated mineralization in the Singida area to comprehend the mineralization controls and reasons for low gold metal recovery at different sites. Primary mineralization suites include As, Pb, and Sb, with Hg, Ag, and Te indicating potential pathfinders. The presence of Au-Cu-Zn polymetallic mineralization is evident. Structurally, the mineralization is predominantly governed by NE – SW first-generational structures and to some extent by NNW – SSE second-generational structures. The mineral extraction methodology targets Au recovery, yet it proves ineffective, as significant Au content remains in the tailings. This research highlights the necessity of conducting ore characterization and metallurgical tests before commencing mineral extraction processes, aiming to enhance processing and recovery methods, thus facilitating the efficient extraction of Au, Cu, and Zn in the Singida area to strengthen the economic prospects of ASSM and the country. This is a creditable practice worth emulating by other African countries to ASSM activities.

1. Introduction

This study stems from the work program composed by the lead author in the Singida Region from 2014 to 2016, to identify the deficiencies in Artisanal and Small-Scale Mining (ASSM) activities in Tanzania. Gold occurrences in Tanzania have been predominantly associated with mafic rocks, initially, and subsequently re-mobilized during diverse tectonic, metamorphic, and magmatic events, before being redeposited in geologically suitable and tectonically controlled reservoirs (Manya, 2012; Thomas et al., 2016). Fundamentally, primary gold resources in Tanzania are linked to Archaean and Proterozoic formations, with the distribution of deposits largely influenced by factors such as lithology (Banded Iron Formation, greenstones), faulting, folding, and shearing (Manya, 2012; Kabete et al., 2012; Ngole et al., 2016; Thomas et al., 2016). Thermal events associated with subduction consistently elevate geothermal gradients within hydrated accretion sequences, initiating and driving long-distance hydrothermal fluid migration and forming significant vertical hydrothermal gold deposits (Mruma et al., 2014; Thomas et al., 2016). The primary factors dictating the style of mineralization, which ultimately determine the locations and nature of mineral deposits, encompass geological attributes (structure, stratigraphy, intrusions, and rock type), as well as pressure, temperature, hydrology, and the chemical composition of the mineralizing fluid, all of which determine the capacity to carry metals, along with the associated vein and alteration assemblages.

The Tanzanian Craton (TC) in East Africa is renowned for its rich deposits of base metals, particularly gold. The Singida area, located at the heart of the TC, exhibits favorable geological features and is abundant in various precious minerals that could significantly contribute to the country's economic growth. This assertion is supported by studies conducted by Kabete et al. (2012), Koegelenberg et al. (2016), Kalimenze et al. (2023), and Gawusu et al. (2024). Numerous investigations on stream sediments and soil geochemistry have revealed substantial concentrations of gold (Au) in the area, indicating promising zones for potential gold deposits (Mvile et al., 2021; Kalimenze et al., 2023; Abu et al., 2024). The most prevalent pathfinder elements for Au deposits in the Singida region are Cu, Zn, As, Fe, Sb, and Pb (Mvile et al., 2021; Kalimenze et al., 2023). Like other mineral-rich areas in Africa, the Singida region is characterized by gold-bearing sheared meta-sedimentary and volcanic rocks with low to medium metamorphic grades, which are conducive to artisanal and small-scale mining (ASSM) operations (Kabete et al., 2012; Mshiu et al., 2015; Gawusu et al., 2024). Gold occurrences in Tanzania are well-documented and are mainly associated with mafic rocks (Manya 2012; Lawley et al., 2014; Henckel et al., 2016; Mvile et al., 2021; Kalimenze et al., 2023) and are mostly situated within the Neoproterozoic settings and the Paleoproterozoic Ubendian metamorphic belt (Cabri et al., 2017; Kalimenze et al., 2023). Several sites in the Singida Region, including Londoni – Sambaru, Muhintiri, Iramba – Sekenke, Mpambaa, and Misigiri-Kirondatal, are mineralized with gold. Additionally, the Ibaga site contains significant amounts of poly-metallic minerals such as Pb, Cu, and Zn, along with some gold.

The Tanzanian government endeavors to stimulate job creation and elevate the country's gross domestic product (GDP) by focusing on the mining sector. Specific regions within the Singida area have been earmarked for ASSM to align with these aspirations. However, ASSM operations in these areas have encountered challenges in exploration and achieving satisfactory metal extraction, consequently leading to a less optimistic outlook for the projected GDP from ASSM. The deficiencies in geological knowledge about mineralization controls in the region and the lack of expertise in ore mineralogy, chemistry, metallurgy, and mineral associations are significant contributing factors to the low discovery and recovery rates in the highly mineralized Singida area.

The Mining Vision 2025 outlines ambitious targets for the mining sector, particularly ASSM to contribute over 10 % to the country's GDP (Fisher, 2007). To enhance productivity in the ASSM industry, it is imperative to improve geological data collection and assess the presence of precious minerals other than gold at various sites. This study aims to: (i) identify the factors influencing mineralization in the ASSM working sites in the Singida region, (ii) characterize the mineralization and associated ore minerals, and (iii) evaluate the potential reasons for the low resource recovery in the area through the analysis of geochemical data, interpretation of geophysical data, and assessment of target metal recovery using correlation matrix and probability plots techniques. Gold mineralization has been analyzed using multivariate statistical, machine learning, and geostatistical methods, as demonstrated by Nude et al. (2012), Sunkari et al. (2019), Mvile et al. (2021), Kalimenze et al. (2023), and Gawusu et al. (2024) over several years. These methodologies have been influential in delineating potential zones for gold deposits in recent times. The authors believe that this paper will offer valuable insights for other African countries with similar precious mineral resources, particularly gold, grappling with recovery and environmental concerns stemming from unmonitored mining activities.

2. Materials and Methods

2.1 Sampling Protocols

During the initial phase, a comprehensive examination of the challenges encountered by small-scale mining operations in the Singida region was carried out through site visits to all seven (7) sites. Structured questionnaires were utilized to obtain relevant information, and a meticulous collection of 93 samples was conducted. This collection included 65 rock and ore samples, 23 tailing samples, two stream samples, one termite-mound sample, and two soil samples. The sampling process involved the acquisition of country rock, altered zone (altered sample), ore sample (vein), and tailings samples, to identify the mineralized zone, characterizing the ore, and evaluating processing methods. The samples were subsequently sent to the Geological Survey of Tanzania (GST) for further processing and analysis. Laboratory analysis of the samples was crucial in determining the grades of the ores of interest and their associated elements, a fundamental aspect of mineral beneficiation. Gold was analyzed using the Fire Assay technique with an AAS finish, while an XRF machine was employed for the analysis of all other major and trace elements. Additionally, high-resolution airborne magnetic data were obtained from Sander Geophysics Limited and were made available through the GST. The geophysical data used in this study were provided by the GST, with the magnetic data acquired at a line spacing of 0.25 km for traverse lines and 2.5 km for tie lines. Data acquisition was conducted at a flight height of approximately 60 m, with traverse and tie line direction-oriented N-S and E-W simultaneously.

2.2. Data processing and analysis

The laboratory results and geochemical assay data were precisely analyzed using specialized interpretation software compatible with Excel. This software facilitated the creation of bar graphs, charts, and probability plots, enabling a more profound comprehension of the characteristics and mineralization patterns of the deposits. Furthermore, we used ArcGIS software for interpolation and creating prediction maps to investigate the occurrence and distribution of mineralization within the area. These tools provided invaluable insights into the nature and extent of mineralization, thus enriching our understanding of the geological features present. The Oasis Montaj software was employed in the treatment of magnetic data, utilizing a 65 m grid cell to produce Total Magnetic Intensity (TMI). The TMI underwent processing through reduction-to-pole (RTP) transformation filters to attain a grid with symmetrical anomalies. To interpret the TMI and other geophysical data effectively, a series of linear and non-linear filtering routines were employed. The datasets were gridded to generate various images that enhanced the visualization of structures and lineaments. This data processing and analysis methodology aligns with previous work conducted by Briggs (1974), Swain (1976), Baravon (1957), Blakely (1995), Laizer et al 2024, and Laizer and Mulibo (2024).

3. Geological Setting

3.1. Regional geology

The study area (Figure 1) is situated within the Archaean Tanzania Craton, an expansive region that stretches from western Kenya and southeast Uganda (Clifford, 1970). This area is notable for containing the oldest continental crust in East Africa and is localized within Tanzania, spanning from the Mbeya range to Lake Victoria in the south-north direction (a distance of approximately 600 km) and from Dodoma to Lake Tanganyika in the east-west direction (an approximate distance of 500 km) (Schlueter, 1997). Geologically, the Archaean Tanzania Craton is classified into three principal Supergroups: Kavirondian, Nyanzian, and Dodoman (Quennel et al., 1956; Barth, 1990; Pinna et al., 2004; Kabete et al., 2012b) based on comprehensive geological and geophysical analyses. Additionally, sub-units within these primary Supergroups have been identified by previous researchers (Quennel et al., 1956), but can be summarized into two primary groups: the Central Tanzania Craton and the Northern Tanzania Craton.

3.2. Local Geology

The study area encompasses seven (7) quarter-degree sheets (QDSs) namely 82, 83, 101, 102, 121, 122, and 123, situated at the heart of the Tanzania Craton and covers approximately 20400 square kilometers (Figure 1). The geological composition is primarily characterized by Neoarchaean granitoids, metasedimentary, and metavolcanic rocks. The Neoarchaean magmatism endured for approximately 160 million years (circa 2775 - 2612 Ma), though with intermittent periods (GST, 2015a; Abu et al., 2024). This magmatic activity was interspersed by crustal uplift and erosion of the older intrusive formations between 2712 and 2683 Ma, giving rise to siliciclastic sediments and concurrent volcanism, potentially in an island arc environment (Kabete et al., 2012; Manya, 2012). After this, expansive granite plutons and associated vein networks penetrated the volcano-sedimentary sequences, followed by the emplacement of smaller syenite plutons toward the culmination of the Neoarchaean magmatic episode. Deformation and low-grade metamorphism, evident in the volcano-sedimentary rocks, also influenced the intruding granites, as indicated by folded granite veins (Kabete et al., 2012, Mruma et al., 2014, Kalimenze et al.,2023). However, the precise timing of the tectonic-metamorphic event remains unknown. Notably, the syenite plutons exhibit minimal signs of deformation or metamorphism, potentially implying that the tectonic-metamorphic activity transpired around 2612 Ma. The regional dolerite dyke swarm was emplaced after the intrusion of syenite plutons in the Singida area, approximately at 1775 Ma (Mruma et al., 2014, Abu et al., 2024).

The regional ductile shears, often associated with gold mineralization, are believed to have occurred before the emplacement of the NE-SW dyke swarm, which intersected the area (Mruma et al.,2014; Abu et al., 2024). There is scarce evidence of Proterozoic or Paleozoic geological activity within the study area after the emplacement of the Paleoproterozoic dolerite dykes. The only recorded event during the Mesozoic period in the study area was the emplacement of the N-S basaltic dykes (Mruma et al., 2014). The geological features in this area date back to the sub-continental Jurassic period, which was followed by significant volcanic activity during the end-Karoo magmatic event. The current landscape of the Singida region is shaped by fault lines associated with the Cenozoic East Africa Rift System. The volcanic activity linked to this rift is primarily seen in the form of kimberlite deposits, which are thin dykes and small pipes, as part of the Eocene Mwadui Kimberlite Province. Near Ndago, ferruginous sandstones and conglomerates rest on a peneplain granite surface believed to be the regional Miocene Surface (Eades & Reeve, 1938). Ongoing tectonic activity in the East African Rift System is reflected in the Quaternary sediments, which include clastic and chemical deposits resulting from erosion. Residual soils cover the upland areas, while the valleys and the Wembere Mbuga are filled with transported sediments, particularly alluvium. Chemical sediments manifest as minor calcrete and silcrete layers in alluvium, and ferricrete in the soils. This study area is renowned for the artisanal mining of gold, copper, zinc, and detrital zircons that are valued for their rare earth content.

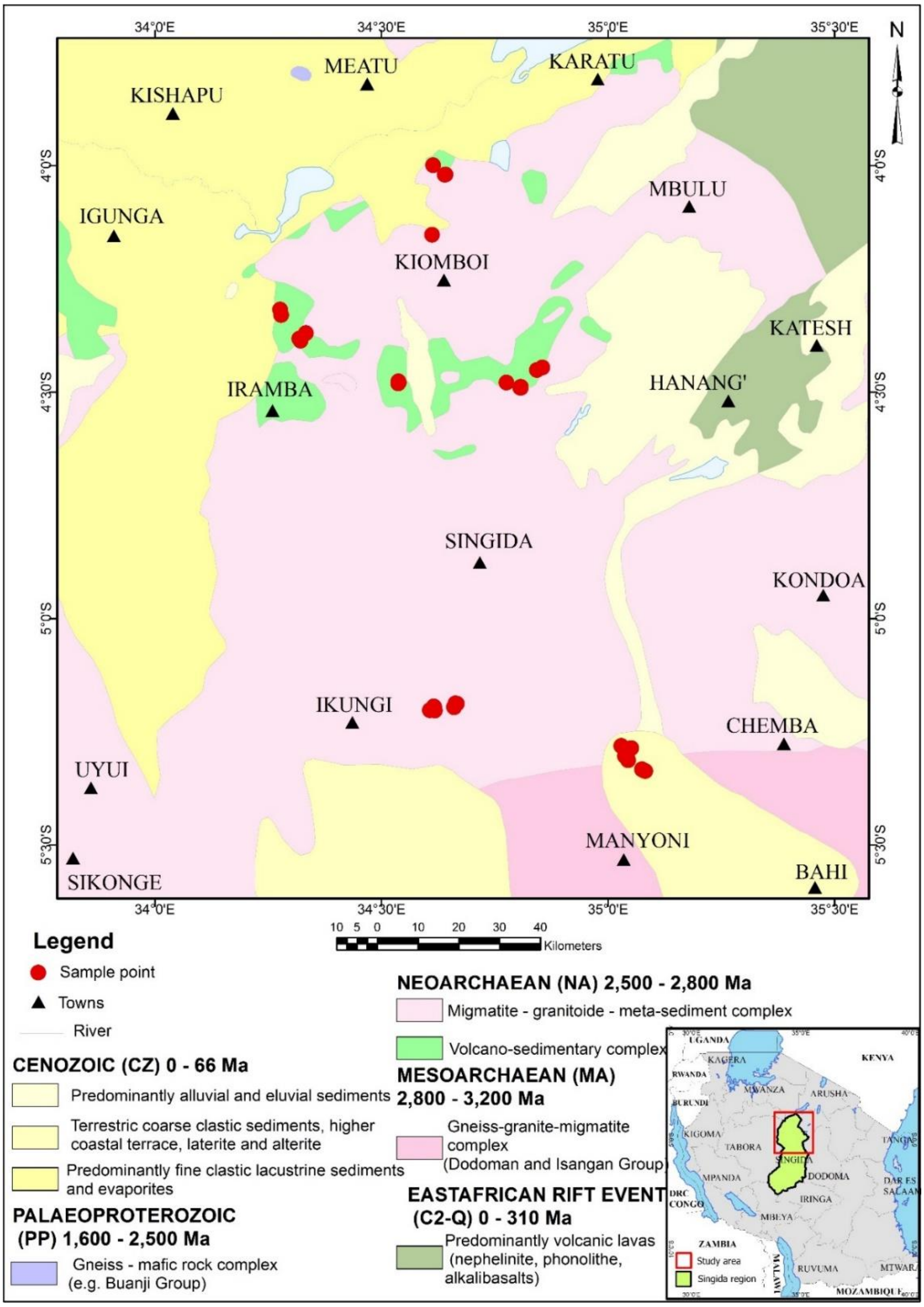

Figure 1: Location with sampling points and the geological map of the study area

4. Results and Discussion

4.1. Geophysical interpretations and the implication of mineralization

The study area contains various geological structures such as folds, faults, dykes, and shear zones. The rock units' physical properties were shown by variations in magnetic properties as seen in images of total magnetic intensity (TMI). The TMI has proven useful in confirming the extension of lithological units, characterizing mineralization zones, and identifying hidden subsurface structures (Zoheir and Emam, 2012, 2014; Laizer et al., 2024, Laizer and Mulibo 2024). Generally, the TMI image indicates that high anomalies of gold (Au) are associated with deformed mafic rocks, likely meta-volcanic rocks within specific structural trends.

4.1.1 Londoni - Sambaru site; The high-resolution airborne geophysical data in this geographical area provides valuable insights into both surface and subsurface structures. The TMI map of the region reveals multiple magnetic lineaments and shear/fault zones trending in the northeast-southwest direction (see Figure 2). Major dykes, which trend from southeast to northwest, intersect these geological structures (shear/fault) in the north-to-northwest direction. Laboratory analyses have demonstrated that the zone of gold and other base metal mineralization is concentrated along shear/fault zone areas (refer to Figure 2). These findings are verified by the research of Müller et al. (2020), d'Amour Uwiduhaye et al. (2020), and Laizer et al. 2024, Laizer and Mulibo 2024, who utilized geophysical methods to map geological structures with concentrations of metallic ores. The prevailing mineralized geological units primarily consist of meta basalts, basalts, and quartz veins located within the shear zone.

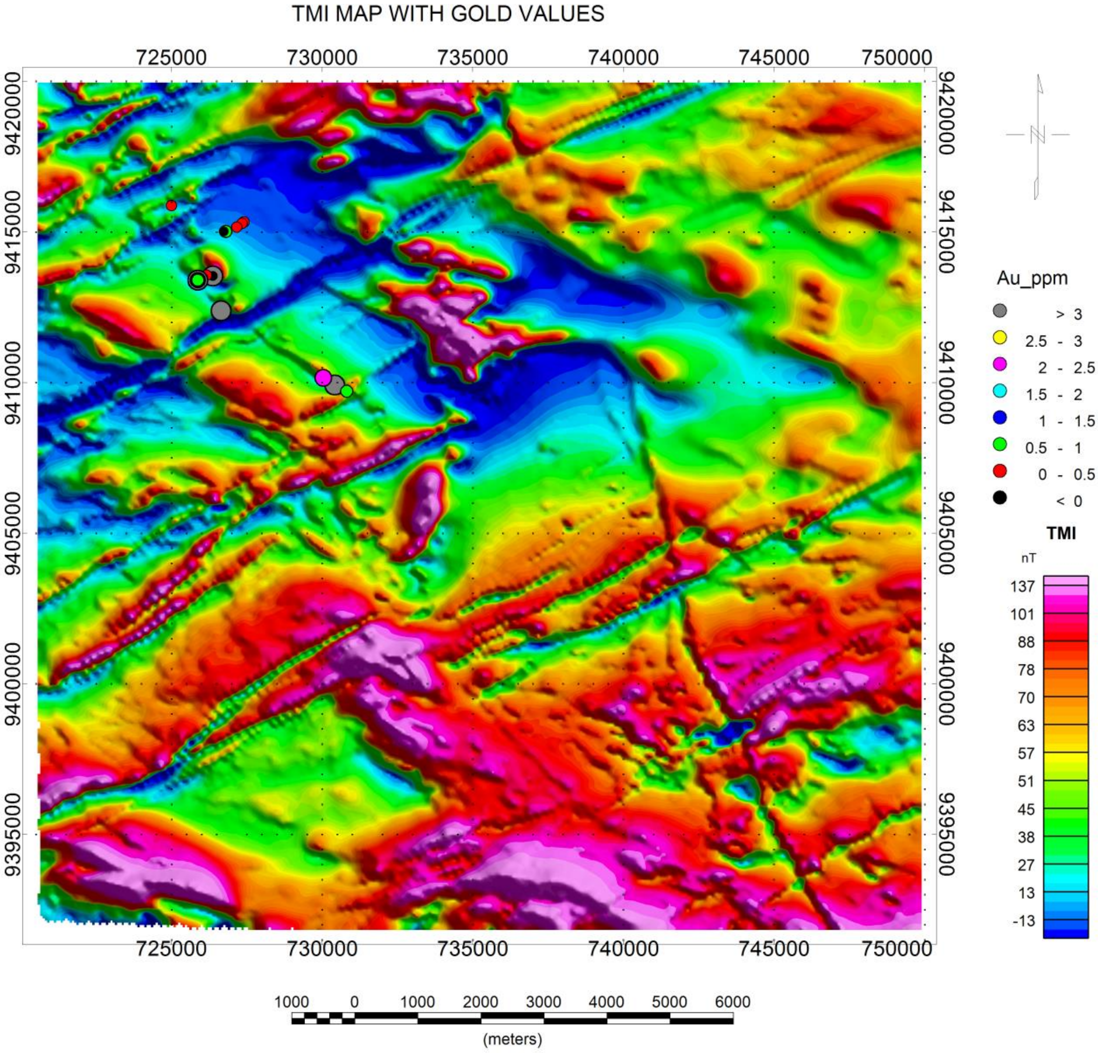

Figure 2: TMI map delineating geological structures and zone of mineralization occurrences

4.1.2 Muhintiri site; The area is characterized by nearly north-south dykes that are cross-cut by a set of faults trending northeast-southwest. The northeast-southwest faults are gold-mineralized geological structures (Figure 3).

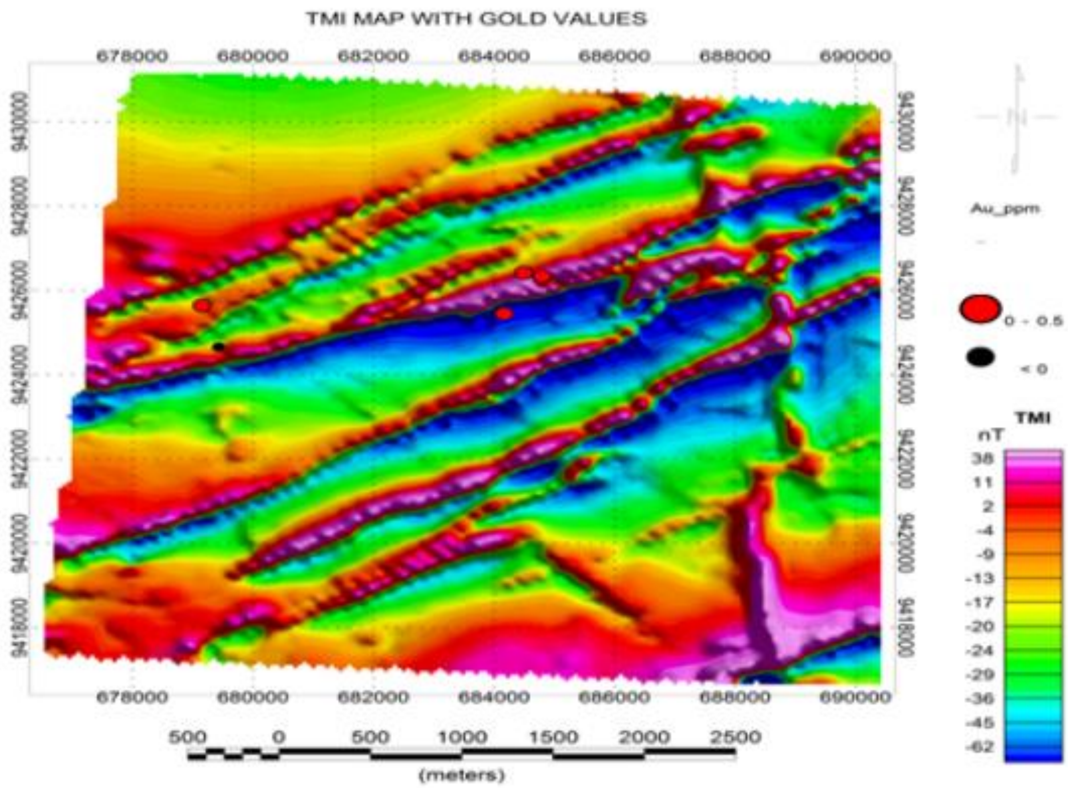

Figure 3: TMI image with various geological structures and zones where mineralization occurs

4.1.3 Mpambaa site; The computation of the Tilt Derivative (TDR) involves the utilization of the first vertical and total horizontal derivatives of the total magnetic intensity. This methodology plays a crucial role in delineating the continuity of geological structures and in supplementing magnetic fabric analysis. The TDR is derived from a ratio, resulting in a normalized intensity range and offering a uniform amplitude response to both shallow and deep-seated magnetic sources. This unique characteristic facilitates the visualization of linear structures extended to the mineralization zone, as demonstrated in Figure 4.

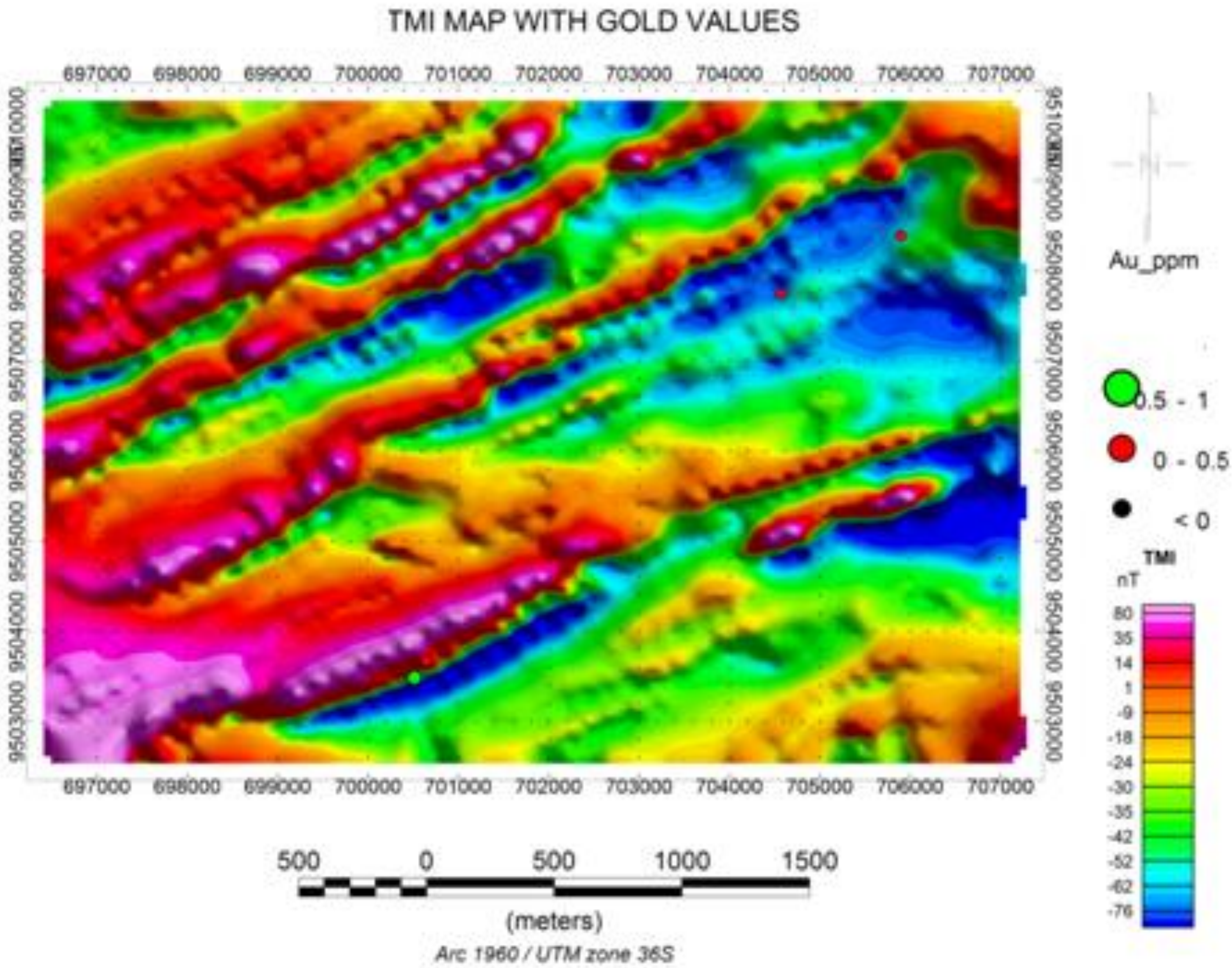

Figure 4: Geological structures trending NE-SW and the location of mineralization

4.1.4 Ibaga site; The observed magnetic intensity variations delineated in the map imply potential disparities in lithology or basement topography. These variations materialize as distinct zones on the Total Magnetic Intensity (TMI) map (refer to Figure 5). The regions are classified into three zones based on the magnetic intensity. The highest magnetic intensity values are predominantly situated in the northeast and southeast areas, with a prevalent trend towards the northeast. The intermediate magnetic intensity areas are associated with Cu mineralization (refer to Figure 5). However, the TMI map does not unequivocally elucidate the structures influencing mineralization. A conversion of the TMI into the Horizontal Derivative (HD) at 45 and 135 degrees and Tilt Derivative has brought to light linear structures that may indicate controls on mineralization (see Figure 6). The NE-SW structures are particularly emphasized at 135 degrees, with Cu mineralization aligning within the confines of high linear structures trending NE and slightly displaced. Filters such as the Tilt Derivative (TDR) have proven effective in reducing to pole (RTP) grid to enhance both strong and weak anomalies (Miller and Sigh, 1994; Verduzco et al., 2004, Laizer et al., 2024) and elucidate the boundaries of broad anomalies (Reid et al., 1990, Mushayandbedvu et al., 2001, Laizer et al., 2024). The hypothesis suggesting that mineralization is associated with NW-SE structures causing displacement also warrants consideration. According to Laizer et al. (2024) and Laizer and Mulibo (2024), dykes have been interpreted as potential mineralized structures for Au and contacts for Cu, with a variation in basement depth ranging from approximately 0.11 to 1,600 km. Both Au and Cu mineralization at Ibaga are hosted in a shear zone trending in the east-west and northeast-southwest directions.

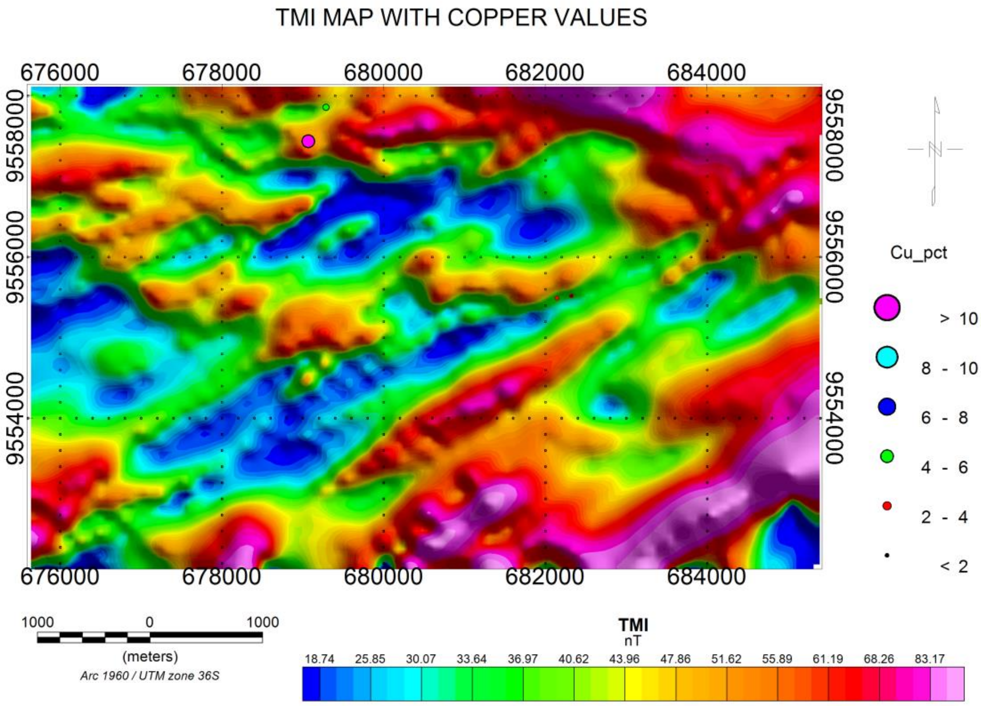

Figure 5: TMI indicates a potential mineralized zone at Ibaga

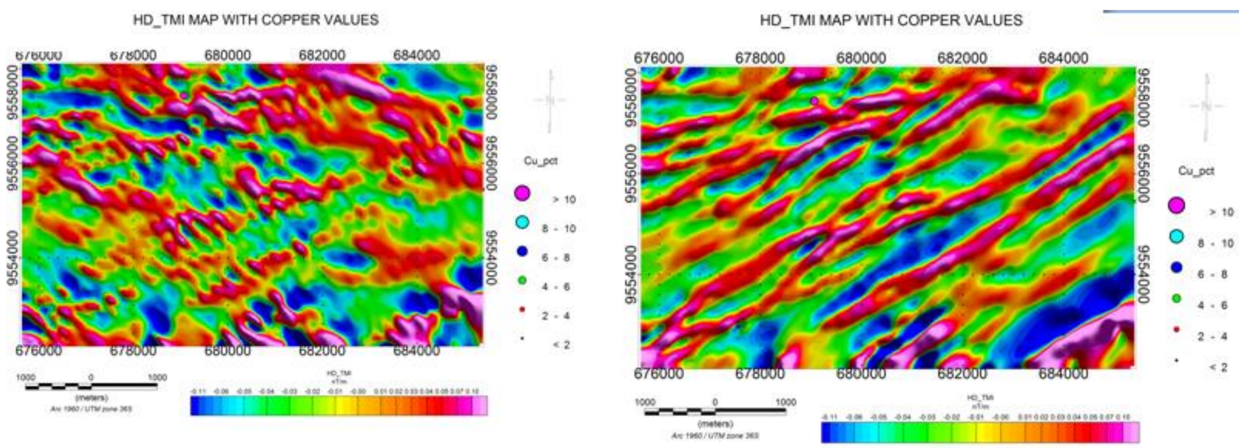

Figure 6: The horizontal derivatives at 45° and 135° respectively enhance the geological structures trending southeast (SE) and northwest (NW)

In the Londoni-Sambaru areas TMI image (Figure 2), the prevalent structural trend is oriented northeast to southwest, with additional cross-cutting structures trending northwest to southeast and exhibiting noteworthy concentrations of gold (Au). The TMI for the Muhintiri site lineament also illustrates a northeast-to-southwest trend, with high resolution delineating these structures. The red-yellowish color in Figure 3 TMI images, representing high-resolution data, reveals Au values of up to 0.76 g/t. The images in the Mpambaa (Figure 4) and Ibaga (Figure 5) areas indicate an association of Au and Cu with the northeast-to-southwest trend. The elevated Au values in the area are localized within the primary structures (northeast to southwest) and to some extent, the secondary structures (northwest/north-northwest to southeast/south-southeast). The mineralization trend indicated in the Singida ASSM areas is influenced by local geological structures and occurs in two distinct stages as also shown by Laizer et al. (2024) and Laizer and Mulibo (2024). This hypothesis could be substantiated through a comprehensive examination of ore petrography and mineralogy studies.

4.2. Geochemical interpretation and the implication for pathfinder elements

The interpretation is based on available data and primarily focuses on identifying major ores and their associated minerals. It also aims to pinpoint the key indicator or pathfinder elements for locating a major ore.

4.2.1 Ibaga site; The Ibaga area is known for its abundant presence of copper ore closely associated with zinc, exhibiting copper grades of up to 11.2% and zinc grades of up to 19.4% within the rock mass. Furthermore, trace amounts of elements such as arsenic (As), lead (Pb), selenium (Se), mercury (Hg), silver (Ag), tellurium (Te), and antimony (Sb) have been identified within the area. Although present in minimal quantities, these elements suggest that Ibaga may host a potential polymetallic Cu-Zn deposit with minor gold-silver occurrences. Research by Laizer et al. (2024) and Laizer and Mulibo (2024) indicates that the area showcases a polymetallic Cu-Zn mineralization style associated with syngenetic volcanogenic massive sulfides (VMS). The noteworthy elements in this context are copper, zinc, gold, arsenic, lead, mercury, silver, tellurium, antimony, and selenium, due to their economic significance or their role as pathfinder elements indicative of ore mineral occurrences. Notably, the strong correlation between Cu and Au implies the presence of gold in the Ibaga area, with As, Hg, and Pb acting as pathfinder elements for the presence of Cu-Zn polymetallic mineralization, validating Levinson's findings in 1974. The correlation matrix in Table 1 reveals significant associations between Cu and Au (r = 0.62), Zn and As, and Ag and Te (r = 0.99, 0.97, and 0.94, respectively), further supporting the existence of gold in the Ibaga area and suggesting the need for further exploration and investigation of the polymetallic mineralization in this region.

Table 1: The correlation matrix of metals and their corresponding pathfinder element in Ibaga areas

Metal	Au	Cu	Zn	As	Pb	Se	Hg	Ag	Te	Sb
Au /ton	1									
Cu ppm	**0.62**	1								
Zn ppm	0.04	0.04	1							
As ppm	0.14	0.14	**0.99**	1						

Metal	Au	Cu	Zn	As	Pb	Se	Hg	Ag	Te	Sb
Pb ppm	0.03	0.02	1	**0.98**	1					
Se ppm	0.07	0.15	0.21	0.19	0.23	1				
Hg ppm	-0.29	-0.43	0.35	0.38	0.34	-0.16	1			
Ag ppm	-0.01	0.06	**0.97**	**0.94**	**0.96**	0.19	0.28	1		
Te ppm	0.19	0.16	**0.94**	**0.97**	**0.92**	0.07	**0.51**	**0.88**	1	
Sb ppm	-0.53	-0.46	-0.31	-0.4	-0.31	-0.29	-0.01	-0.15	-0.38	1

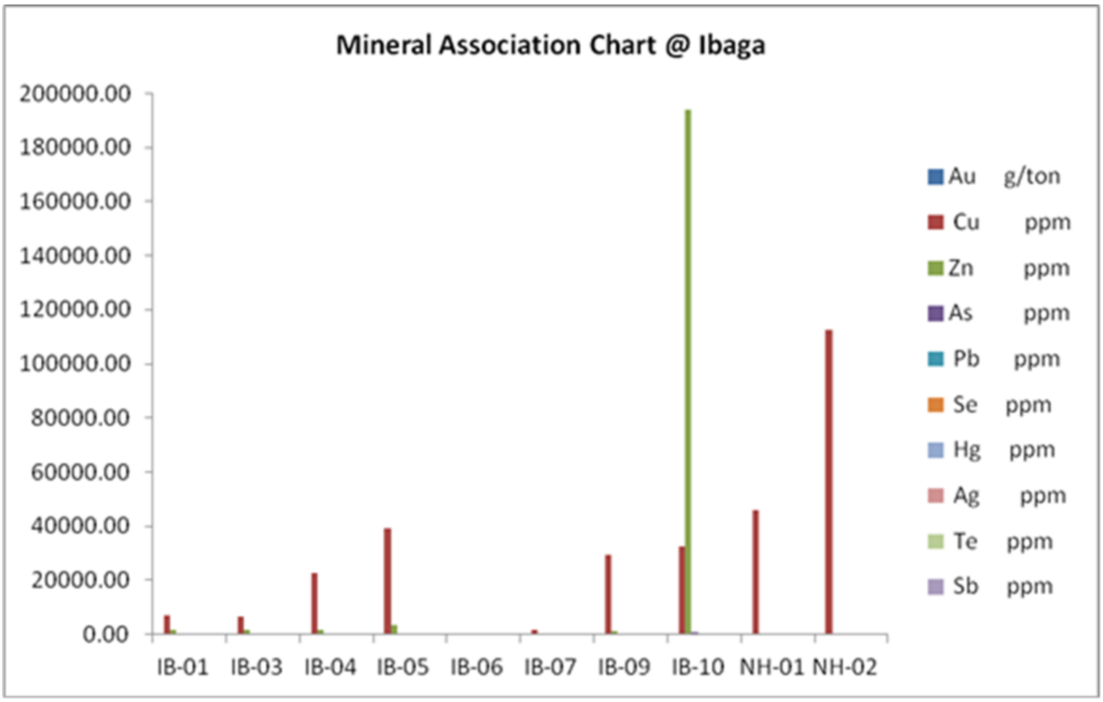

Figure 7: Mineral association graph at Ibaga site

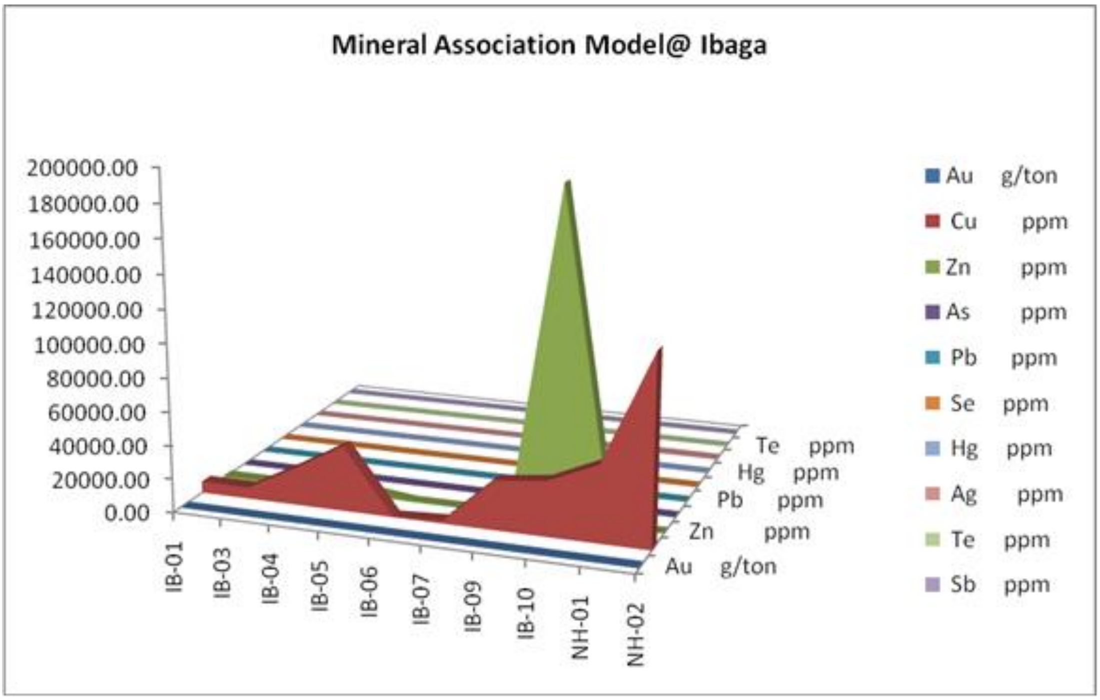

Figure 8: Displaying a Cu-Zn deposit model at Ibaga along with other trace elements

4.2.2 Londoni site; The presence of gold as a significant ore is closely associated with several other elements, including Copper (Cu), Zinc (Zn), Tellurium (Te), Arsenic (As), and Antimony (Sb) (refer to Figure 9). Assay results have revealed a grade of up to 17.19 g/t. The deposit is likely a polymetallic Au-Cu-Zn deposit, with Te, As, and Sb serving as potential pathfinder elements in the Londoni areas (see Figure 10). There is a strong association of Cu ore with Zn and Au (Figure 9). While other elements are present in trace amounts, Tellurium (Te), Arsenic (As), and Antimony (Sb) have the potential to indicate Cu-Zn-Au polymetallic mineralization (Figure 10). Furthermore, the data in Table 2 shows a strong correlation of Pb with Au and Zn (r = 0.51 and r = 0.81, respectively), while Zn also exhibits strong correlations with Se and Te (r = 0.85 and r = 0.58). These correlations emphasize Pb, Se, and Te as primary pathfinder elements for the exploration of Au and Zn in the Londoni areas. Moreover, the use of As and Sb as pathfinders in the search for Au should be considered, given that these elements correlate significantly with Pb (Table 2). Studies of soil and stream sediment geochemistry by Mvile et al. (2021), (2023); Kalimenze et al. (2023) and Nunoo et al. (2023) have also demonstrated the presence of similar pathfinder elements in the area. To maximize economic gains in this poly-metallic mineralized zone, priority should be given to recovery processes employed by ASSM, which facilitate the concurrent recovery of Cu and Zn with Au.

Table 2: Correlation matrix of Ore minerals/metals and their pathfinder element of Londoni areas

Metal	Au	Cu	Zn	As	Pb	Se	Hg	Ag	Te	Sb
Au g/ton	1									
Cu ppm	-0.3	1								
Zn ppm	0.12	-0.19	1							
As ppm	0.26	-0.31	-0.13	1						
Pb ppm	0.51	-0.47	**0.81**	0.08	1					
Se ppm	-0.04	-0.44	**0.85**	-0.17	**0.82**	1				
Hg ppm	-0.26	-0.11	0.14	-0.85	0.12	0.43	1			
Ag ppm	0.43	-0.16	0.39	-0.24	**0.73**	**0.59**	0.41	1		
Te ppm	-0.07	-0.18	**0.58**	0.03	**0.71**	**0.81**	0.27	**0.71**	1	
Sb ppm	-0.02	-0.21	0.24	0.27	**0.53**	**0.55**	0.1	**0.62**	**0.91**	1

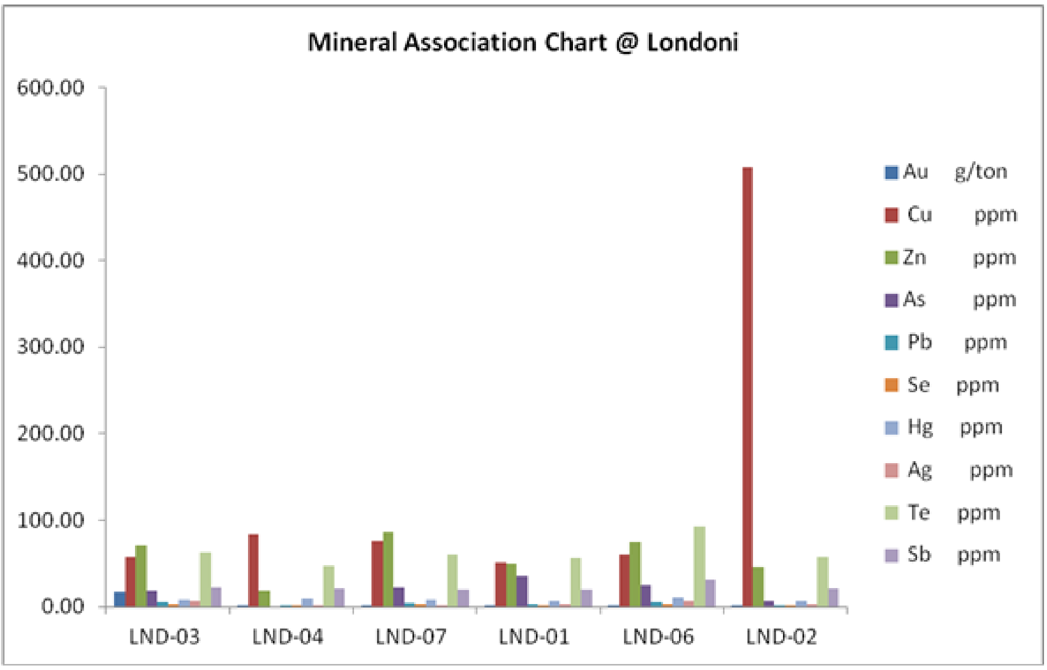

Figure 9: Mineral association graph at the Londoni site

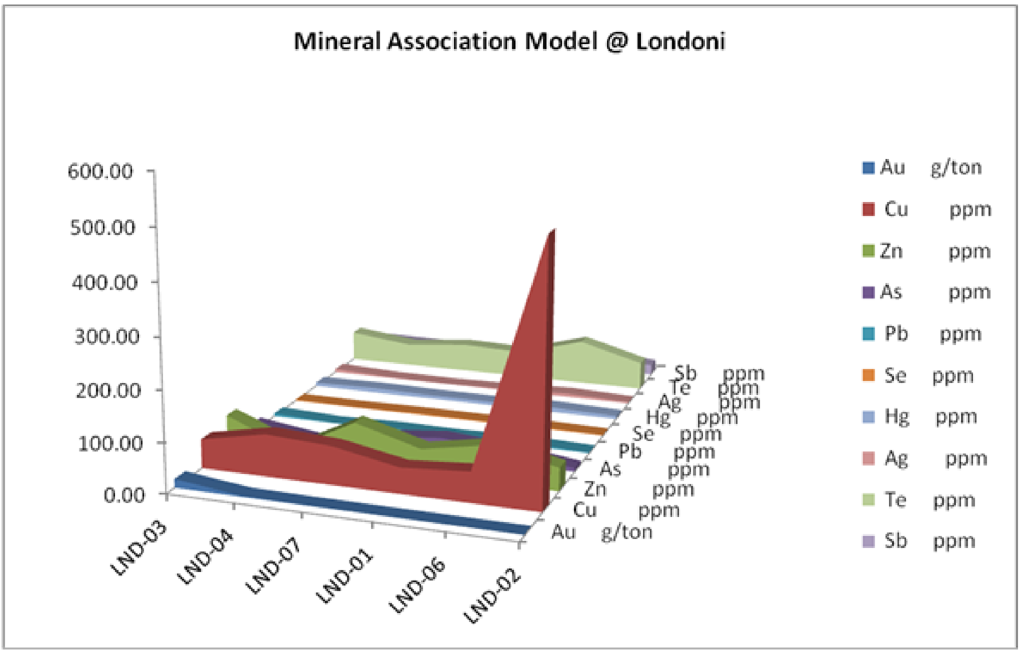

Figure 10: Displaying a polymetallic gold-copper-zinc deposit model with potential pathfinder

4.2.3 Muhintiri and Mpetu Muhintiri site; The analysis of the samples revealed negligible gold occurrences, with values reaching a maximum of only 0.17 g/t. This could be attributed to inadequate or erroneous sampling methods employed by the artisanal workers during sample collection, likely owing to challenges in accessing the mineralized zone in the pit. Although the area demonstrates the presence of Cu, Zn, As, Te, and Sb in close association, as indicated in Figure 11, the existence of small-scale gold mines in the area suggests the presence of gold occurrences, although in trace amounts. This implies that the gold present in this area possibly constitutes a polymetallic Au-Cu-Zn deposit, with As, Te, and Sb serving as pathfinder elements for exploring the gold, as depicted in Figure 12. The two sites within the area share similar geological settings and are thus likely to possess comparable mineralization associations, as illustrated in Figure 13, as well as deposit models, as depicted in Figure 14.

In the Muhintiri area, Zn is closely associated with Cu and As, while Te and Sb also display a close association, as shown in Figure 11. Despite the very low Au values, with a maximum of 0.17 g/t, As, being a well-known pathfinder of Au, strongly correlates with Zn and Cu, suggesting the polymetallic occurrence of Au-Zn-Cu in the area, with Te and Sb, as well as As, serving as the main pathfinder elements, as indicated in Figure 12. A similar elemental association of As, Zn, and Cu, as well as Te and Sb, is observed in the Mpetu – Muhintiri areas, as shown in Figures 13 and 14. The correlation matrix in Tables 3 and 4 reveals that in the Muhintiri site, defined by the Muhintiri and Mpetu-Muhintiri areas, the occurrence of Au can be delineated using As, Se, and Pb as pathfinder elements. Additionally, Cu can be explored with As, Ag, and Zn as its pathfinder elements in the area owing to its substantial correlation values with those elements, while Zn can be delineated using Pb, Te, As, and Sb as the main pathfinder elements in the Muhintiri areas according to Tables 3 and 4. The pathfinder elements of the Muhintiri area are similar to those found in other greenstone belts in West Africa, as previously documented by Béziat et al. (2016) and Sunkari et al. (2019).

Table 3: Correlation matrix of Ore minerals/metals and their pathfinder element of Muhintiri areas

Metal	**Au**	**Cu**	**Zn**	**As**	**Pb**	**Se**	**Hg**	**Ag**	**Te**	**Sb**
Au g/ton	1									
Cu ppm	-0.35	1								
Zn ppm	-0.39	0.41	1							
As ppm	**0.96**	-0.25	-0.24	1						
Pb ppm	-0.21	0.34	**0.86**	0.02	1					
Se ppm	**0.7**	0.14	0.27	**0.7**	0.21	1				
Hg ppm	0.34	**0.56**	0.4	0.33	0.31	**0.83**	1			
Ag ppm	0.3	**0.69**	0.46	0.39	0.39	0.8	**0.86**	1		
Te ppm	-0.23	0.43	**0.92**	-0.08	**0.91**	0.36	**0.57**	**0.5**	1	
Sb ppm	-0.28	0.5	**0.88**	-0.24	**0.61**	0.47	**0.68**	**0.6**	**0.84**	1

Table 4: Correlation matrix of Ore minerals/metals and their pathfinder element of Mpetu-Muhintiri areas

Metal	**Au**	**Cu**	**Zn**	**As**	**Pb**	**Se**	**Hg**	**Ag**	**Te**	**Sb**
Au g/ton	1									
Cu ppm	-0.33	1								
Zn ppm	0.39	**0.73**	1							
As ppm	0.18	**0.86**	**0.98**	1						
Pb ppm	0.96	-0.16	**0.5**	0.31	1					
Se ppm	0.46	0.14	**0.56**	**0.5**	0.3	1				
Hg ppm	**0.84**	0.07	**0.71**	**0.57**	**0.77**	**0.83**	1			
Ag ppm	-0.35	**0.88**	**0.67**	**0.79**	-0.3	0.49	0.2	1		
Te ppm	0.41	-0.18	0.23	0.15	0.17	**0.93**	**0.69**	0.25	1	
Sb ppm	0.51	-0.69	-0.22	-0.35	0.24	**0.62**	0.49	-0.31	**0.84**	1

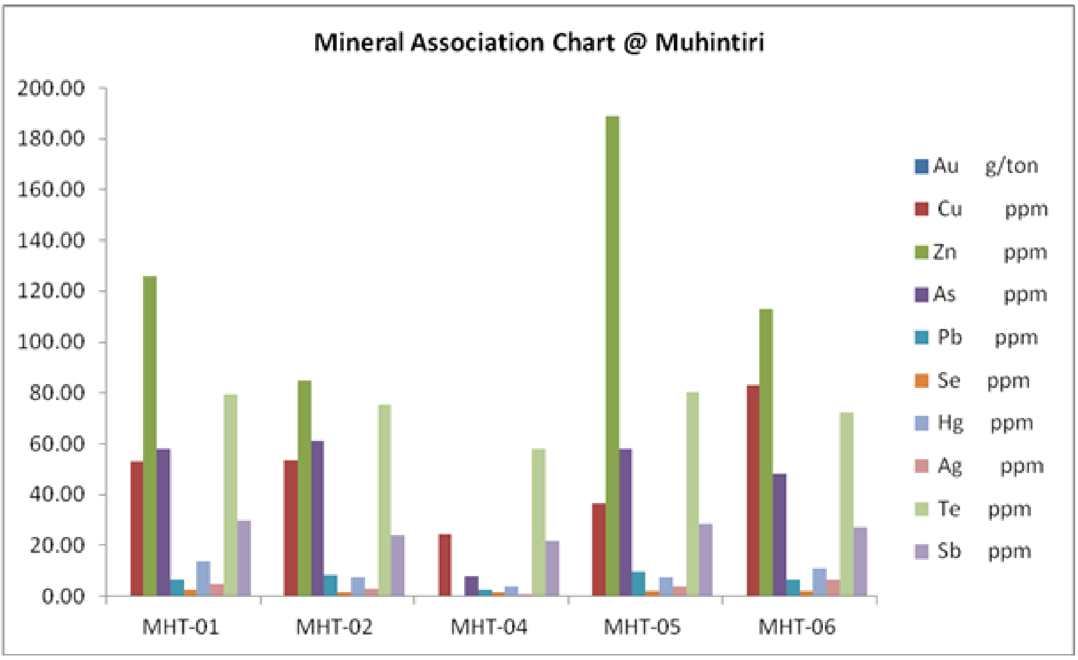

Figure 11: Mineral association graph at Muhintiri

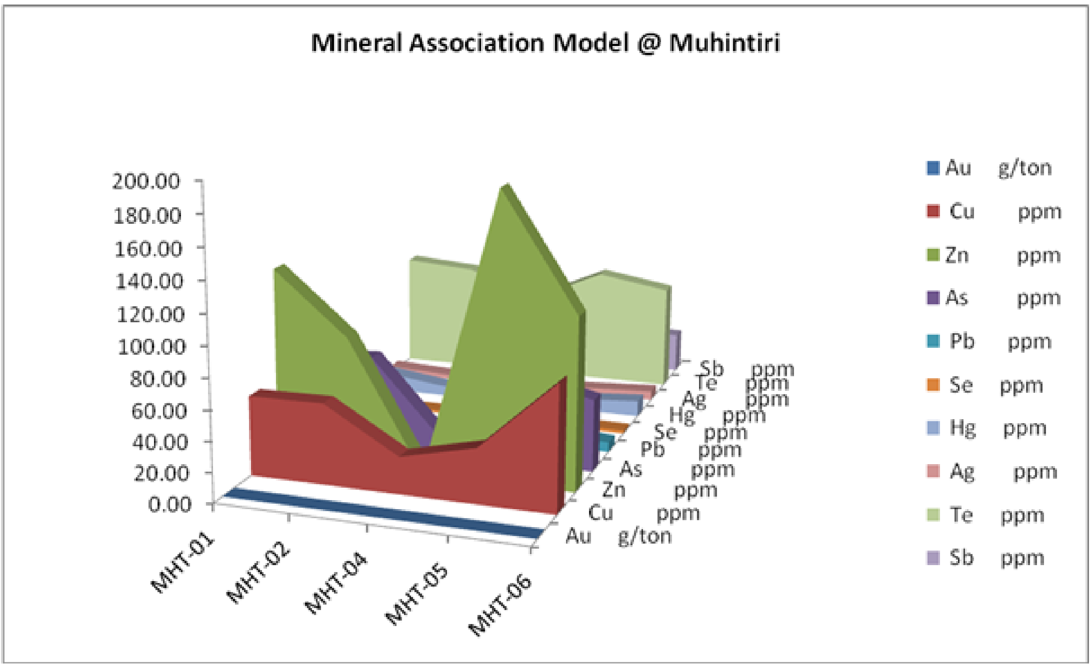

Figure 12: A potential Au-Cu-Zn deposit model at Muhintiri with As, Te & Sb as pathfinder elements

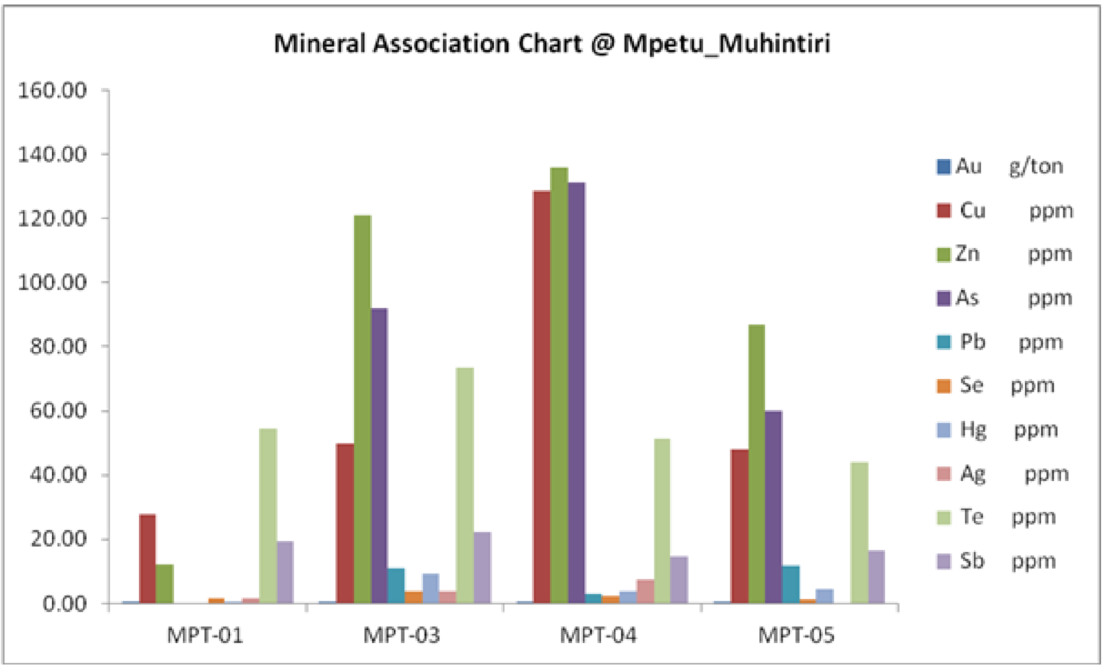

Figure 13: Mineral association graph at Mpetu Muhintiri

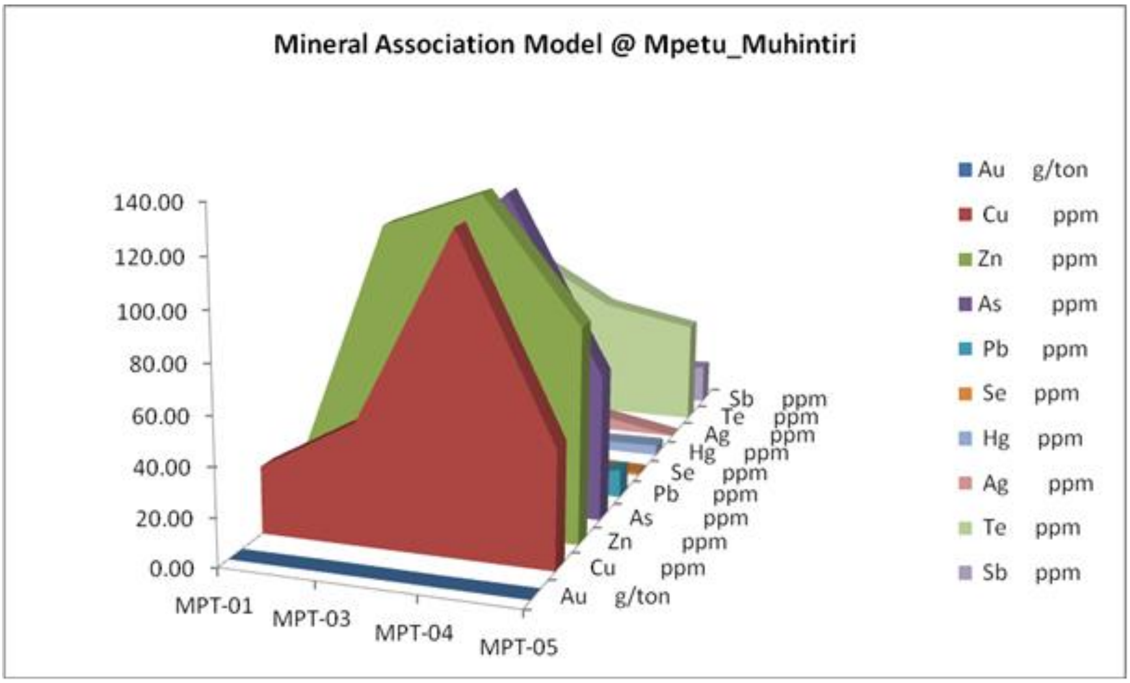

Figure 14: A potential Au-Cu-Zn deposit model at Mpetu Muhintiri with As, Te & Sb as pathfinder elements

4.2.4 Sambaru site; The profound occurrence of gold as a predominant ore in the Sambaru premises has garnered substantial interest, showcasing grades of up to 119.8 g/t from ore samples. This mineral exhibits a distant association with Cu and Zn but demonstrates a close correlation with As (refer to Figure 15). Arsenic plays a crucial role as the primary pathfinder element for gold exploration in the vicinity, as depicted in the model (Figure 16), implying the presence of a gold-arsenic (Au-As) metallic deposit. The Sambaru site displays noteworthy enrichment in Au, with grades measuring up to 119.8 g/t. The coexistence of Au with As, Cu, and Zn (refer to Figure 15) in the area accentuates Arsenic's significance as the principal pathfinder element in the pursuit of Au (Figure 16) in the Singida Region. Furthermore, the Misigiri-Kirondatal areas manifest substantial Au concentration levels, reaching approximately 6.92 g/t. The heightened Au content is discernible from the prominent peak of Arsenic (Figure 17) conjoined with Cu and Zn. Analogous to the Samburu area, the Misigiri-Kirondatal region summarizes a polymetallic mineralized zone with As serving as the pathfinder element in the quest for an Au-Cu-Zn (Figure 18) deposit. The correlation analysis (refer to Table 5) unveils selenium (Se) and mercury (Hg) as the pathfinders for the occurrence of Au and As for Zn. While As does not act as a pathfinder for Au in the Sambaru area, it assumes the primary pathfinder role for Zn, though with a moderate correlation coefficient (r = 0.50).

Table 5: Correlation matrix of metals and their corresponding pathfinder elements in the Sambaru areas

Metal	**Au**	**Cu**	**Zn**	**As**	**Pb**	**Se**	**Hg**	**Ag**	**Te**	**Sb**
Au g/ton	1									
Cu ppm	-0.07	1								
Zn ppm	0.07	0.42	1							
As ppm	0.04	0.07	**0.5**	1						
Pb ppm	-0.09	0.33	-0.2	-0.25	1					
Se ppm	**0.58**	-0.11	0.08	-0.12	0.08	1				
Hg ppm	**0.53**	0.05	0.18	-0.3	0	0.73	1			
Ag ppm	0.38	-0.2	0.13	-0.31	-0.34	-0.02	0.24	1		
Te ppm	-0.01	0	0.32	-0.02	-0.4	-0.4	-0.01	**0.58**	1	
Sb ppm	0.06	-0.49	-0.04	-0.51	-0.35	0.09	0.27	**0.72**	0.27	1

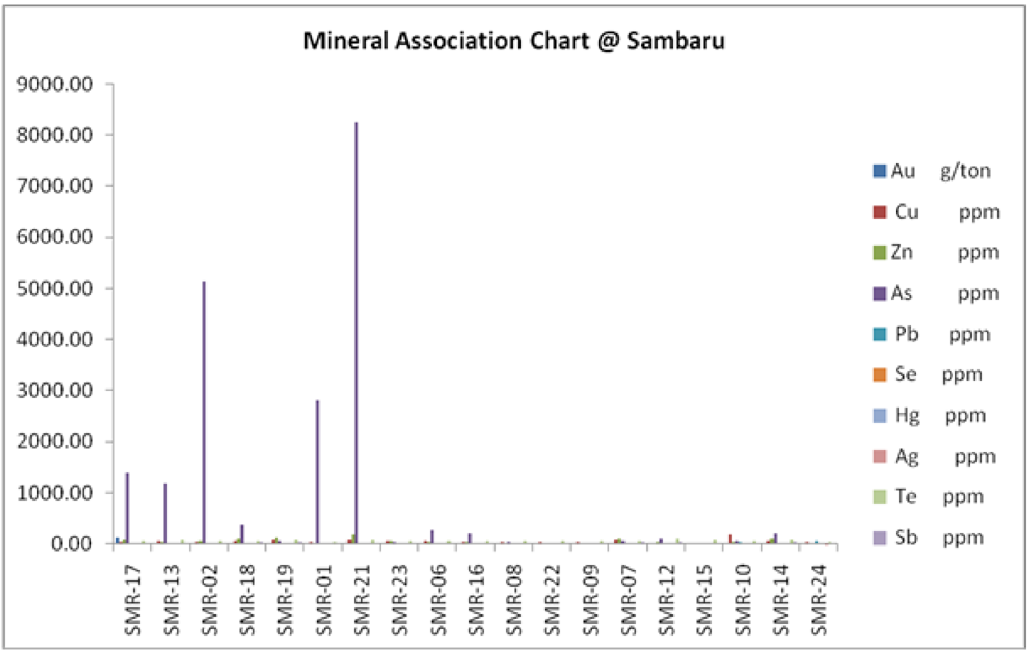

Figure 15: Mineral association graph at Sambaru

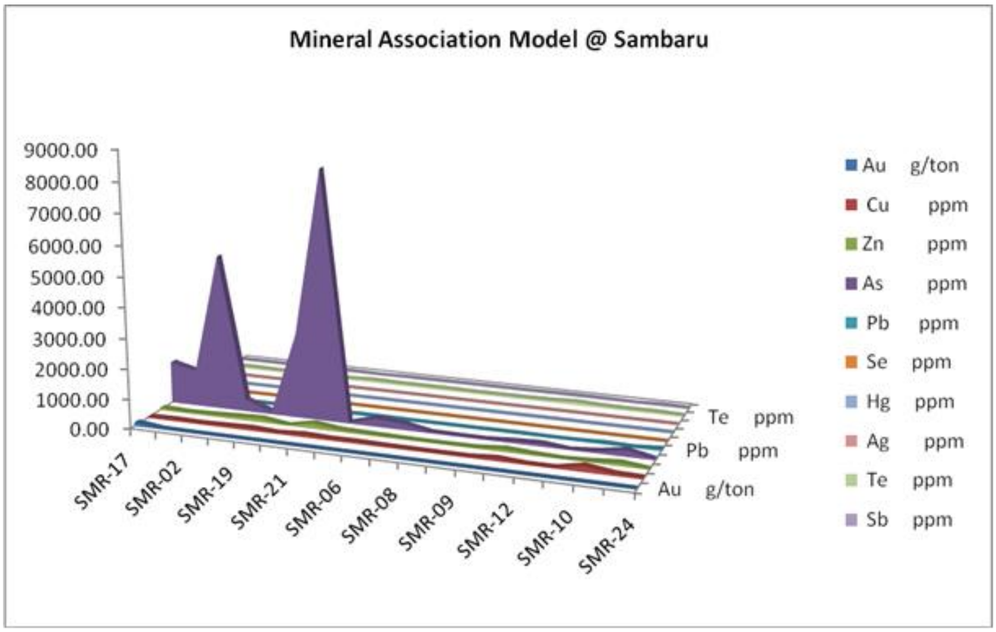

Figure 16: Presenting a gold deposit (Au-As deposit) model, with arsenic serving as a pathfinder element

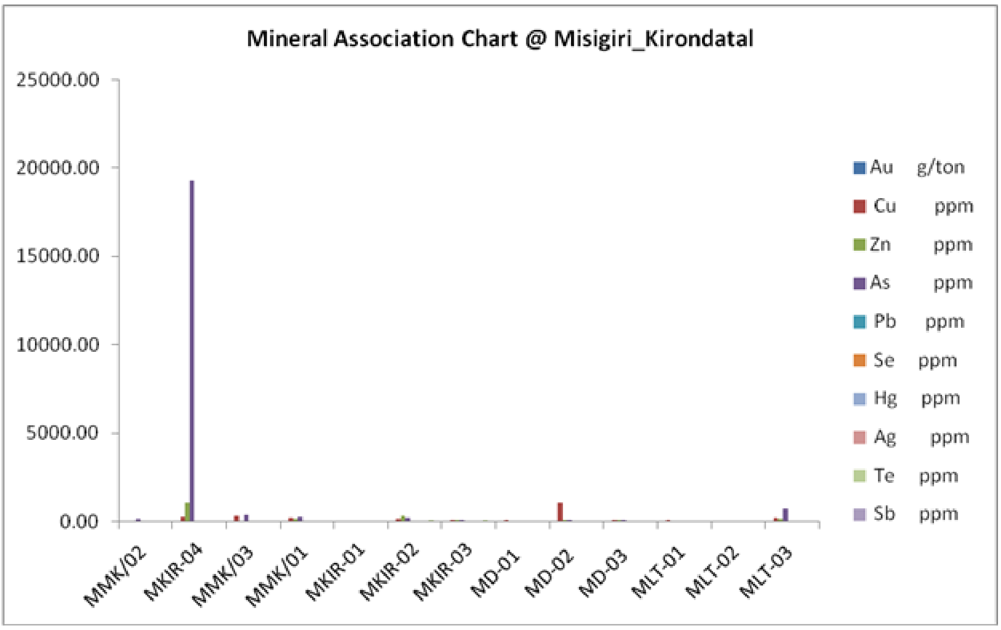

Figure 17: Mineral association graph at Misigiri-Kirondatal

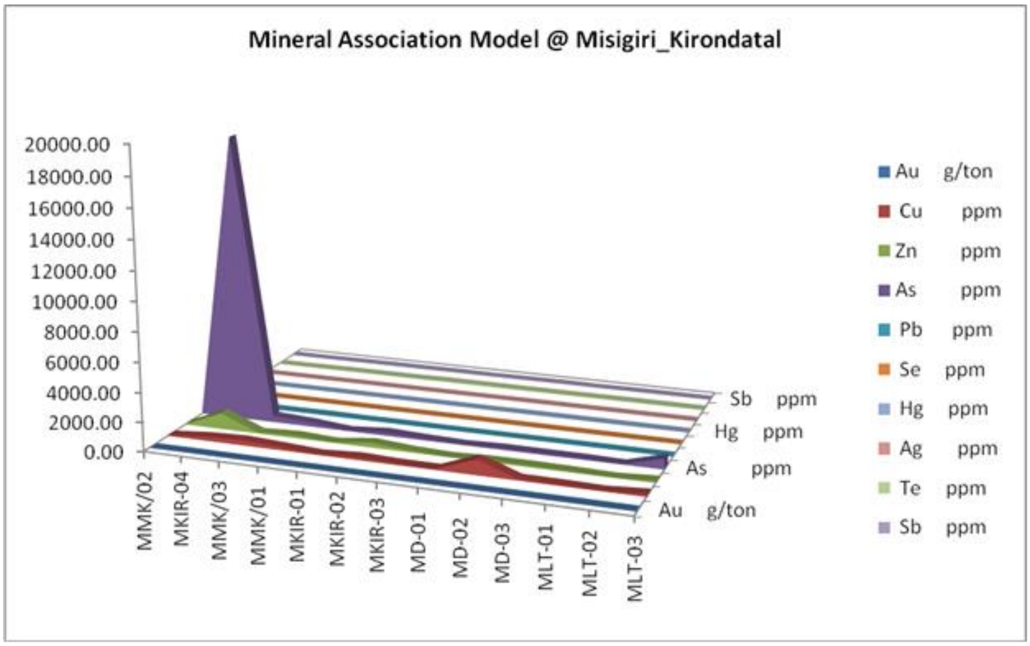

Figure 18: Presenting a potential polymetallic gold-copper-zinc deposit model with arsenic as the pathfinder element

4.2.5 Mpambaa site; The mineral being investigated is gold, which has been found to have a grading of up to 1.55 g/t based on the obtained data. Gold is commonly associated with Cu and Zn (refer to Figure 19), along with trace amounts of other elements such as As, Pb, Se, Hg, Ag, Te, and Sb. The deposit appears to exhibit characteristics of a polymetallic Au-Cu-Zn deposit (refer to Figure 20). The specific pathfinder elements at this location are yet to be determined, as most trace elements occur in similar proportions. The Mpambaa site presents maximum Au values of 1.55 g/t. Zn is found alongside Cu (refer to Table 6), indicating a typical polymetallic mineralized zone. Well-defined pathfinder elements for the presence of Zn and Cu have not been identified (Table 6). However, Au demonstrates a reasonable correlation with Pb and to some extent with Ag.

The Maluga-Kinampanda site is notable for its significant gold concentrations, with levels reaching up to 2.58 g/t of Au. Cu, Zn, and As are closely associated, suggesting the mineralization of Au-Cu-Zn along with As, Te, mercury (Hg), and Sb as the pathfinder elements. Maluga-Kinampanda is primarily characterized by a polymetallic mineralized zone of Au-Cu, with the potential occurrence of Zn also warranting further exploration (see Table 7). The Au-Cu occurrence does not exhibit clear pathfinder elements, except for some indications of arsenic, though insignificant (r = 0.38). Conversely, Zn can be delineated using Pb, Se, Ag, and Sb (refer to Table 7) as the pathfinder elements in the search for Zn mineralization in the Maluga-Kinampanda area. The primary focus at Maluga-Kinampanda is gold, which can be found in ore grading up to 2.58 grams per ton. Gold is associated with Cu, Zn, As, and Te, with a limited relation to Sb and Hg (refer to Figure 21). It is considered to be a polymetallic deposit containing gold, copper, and zinc, with arsenic and tellurium serving as indicator elements (see Figure 22).

Table 6: The correlation matrix of metals and their corresponding pathfinder element in Mpambaa areas
areas

Metal	**Au**	**Cu**	**Zn**	**As**	**Pb**	**Se**	**Hg**	**Ag**	**Te**	**Sb**
Au g/ton	1									
Cu ppm	-0.31	1								
Zn ppm	-0.25	**0.99**	1							
As ppm	0.43	-0.19	-0.18	1						
Pb ppm	**0.52**	-0.21	-0.19	0.21	1					
Se ppm	-0.22	-0.29	-0.35	-0.09	0.39	1				
Hg ppm	-0.49	-0.2	-0.21	-0.13	-0.08	0.07	1			
Ag ppm	0.49	0.25	0.28	0.23	0.18	-0.2	-0.84	1		
Te ppm	-0.51	0.07	0.06	-0.18	-0.8	-0.42	0.14	-0.14	1	
Sb ppm	-0.18	0.12	0.1	0.43	-0.55	-0.19	-0.24	0.07	0.25	1

Table 7: Correlation matrix of metals and their corresponding pathfinder element of Maluga-Kinampanda areas

Metal	**Au**	**Cu**	**Zn**	**As**	**Pb**	**Se**	**Hg**	**Ag**	**Te**	**Sb**
Au g/ton	1									
Cu ppm	**0.88**	1								
Zn ppm	-0.37	-0.35	1							
As ppm	0.38	0.38	-0.74	1						
Pb ppm	-0.23	-0.36	**0.76**	-0.6	1					
Se ppm	-0.34	-0.37	**0.76**	-0.86	0.36	1				
Hg ppm	0.27	0.12	-0.92	**0.7**	-0.5	-0.77	1			
Ag ppm	-0.4	-0.45	**0.81**	-0.93	**0.83**	**0.73**	-0.65	1		

Metal	Au	Cu	Zn	As	Pb	Se	Hg	Ag	Te	Sb
Te ppm	-0.02	-0.21	-0.43	0.61	0.07	-0.75	**0.67**	-0.39	1	
Sb ppm	-0.41	-0.46	**0.83**	-0.95	**0.78**	**0.8**	-0.7	**0.99**	-0.46	1

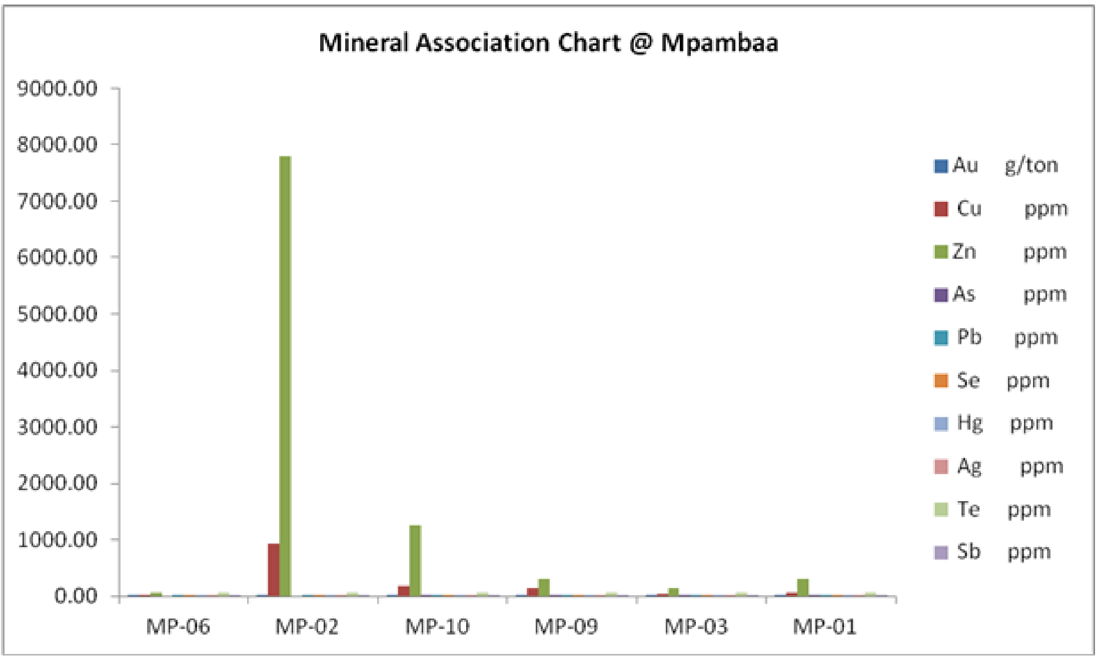

Figure 19: Mineral association graph at Mpambaa

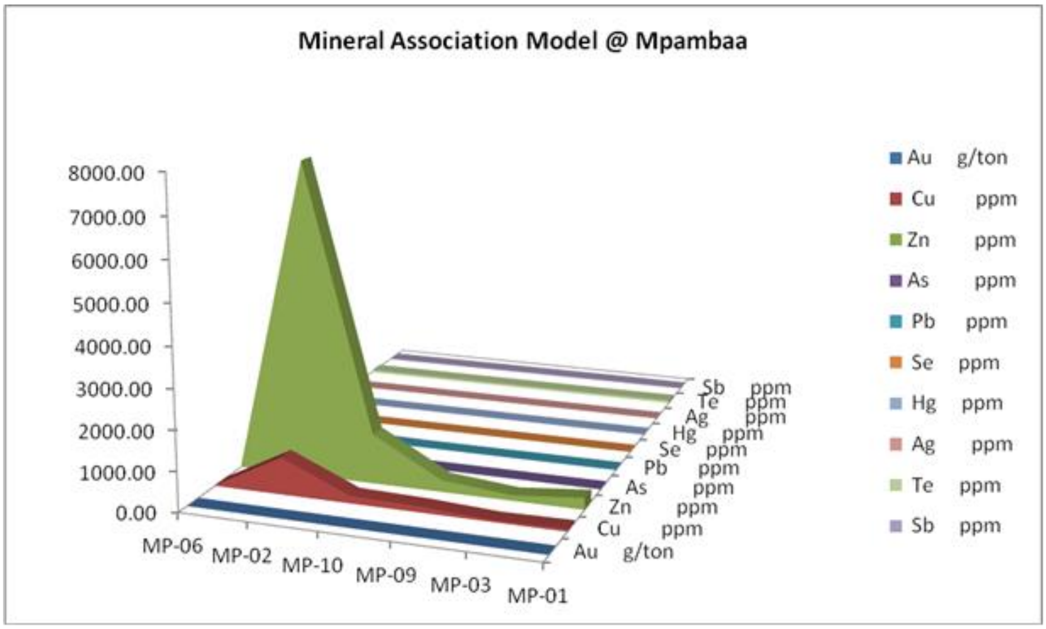

Figure 20: Presenting a polymetallic Au-Cu-Zn deposit model at Mpambaa

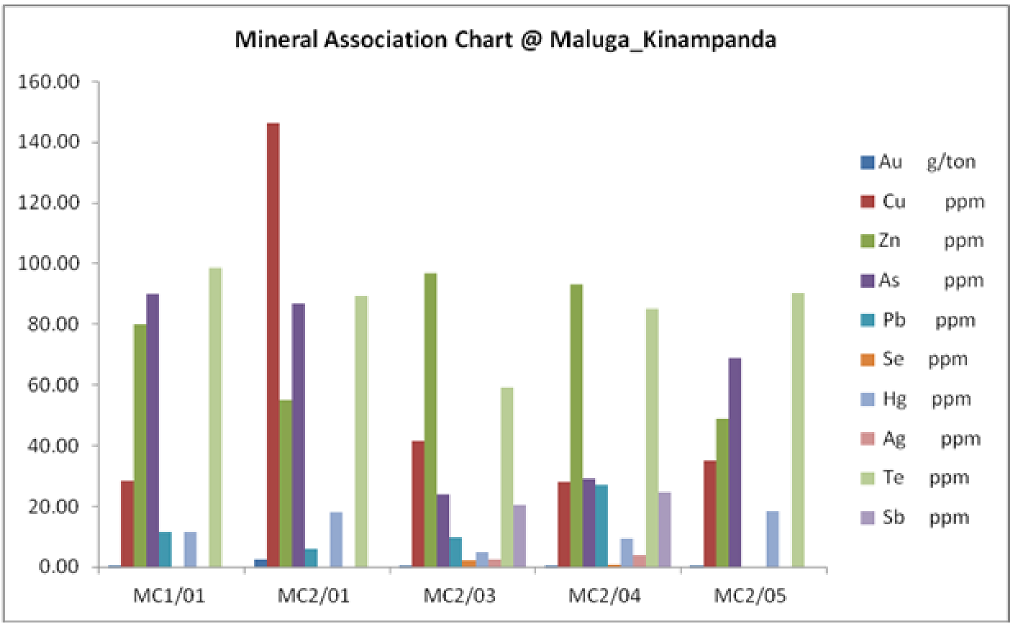

Figure 21: Mineral association graph at Maluga – Kinampanda

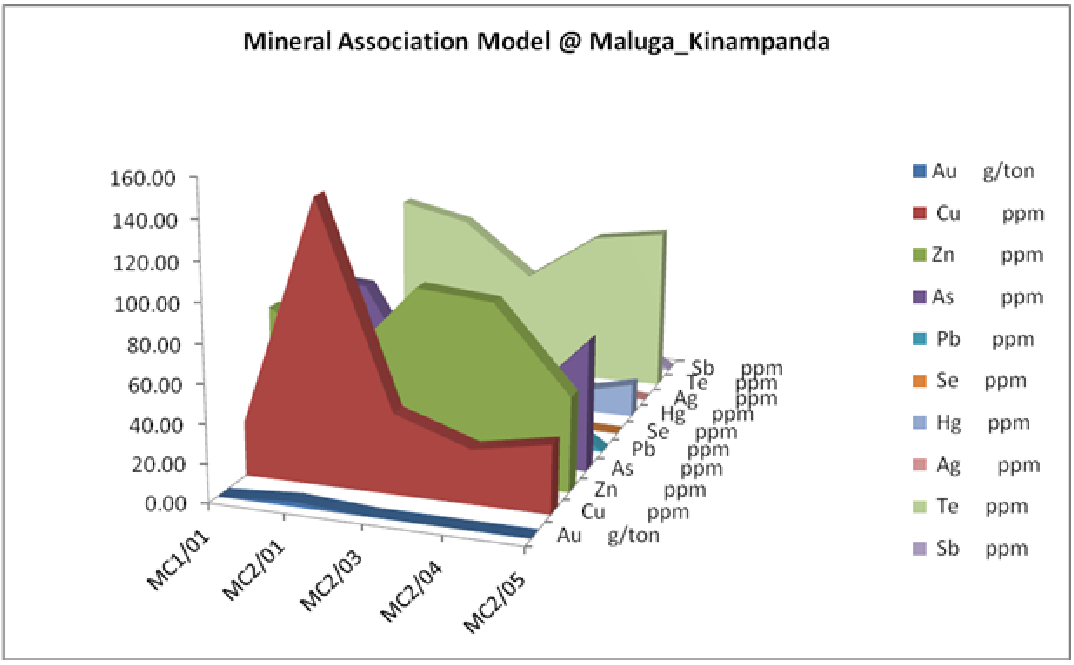

Figure 22: Presenting a polymetallic Au-Cu-Zn deposit model with As and Te as pathfinder elements

4.3. Study of tailing and the implication to extraction efficiency

The analysis of tailings from all surveyed localities revealed the utilization of substandard beneficiation methods during the mineral extraction processes. This is evident from the significant quantities of gold grades found in the tailings (refer to Table 8 and Figure 23), notwithstanding the initial ore grade of the processed material being indeterminate.

Specifically, the Ibaga tailings (IB-08) exhibited the presence of approximately 2.5% or 25000 ppm Cu, 1.32 g/t Au, and 0.2% Zn. In the case of Mpambaa, the tailings revealed the existence of up to 2.32 g/t Au, while Misigiri-Kirondatal tailings contained up to 3.48 g/t Au. Correspondingly, Sambaru exhibited up to 3.19 g/t, Londoni 8.12 g/t, Muhintiri 0.76 g/t, and Maluga-Kinampanda up to 2.67 g/t Au in tailings. These findings emphasize the necessity for enhanced gold and mineral extraction techniques in the small-scale mining industry in Singida, Tanzania. Tailings from various sites showed high levels of gold concentration (refer to Table 8), indicating the inefficiency of the extraction process. The exploration of alternative processing methods is imperative for optimizing metal extraction in the region. Noted the abbreviations stand for wherever applicable; IB – Ibaga, MP – Mpambaa, MC – Maluga, MD/MLT/MKIR/MMK – Misigiri Kirondatal, MHT – Muhintiri, LND – Londoni and SMR – Sambaru sites.

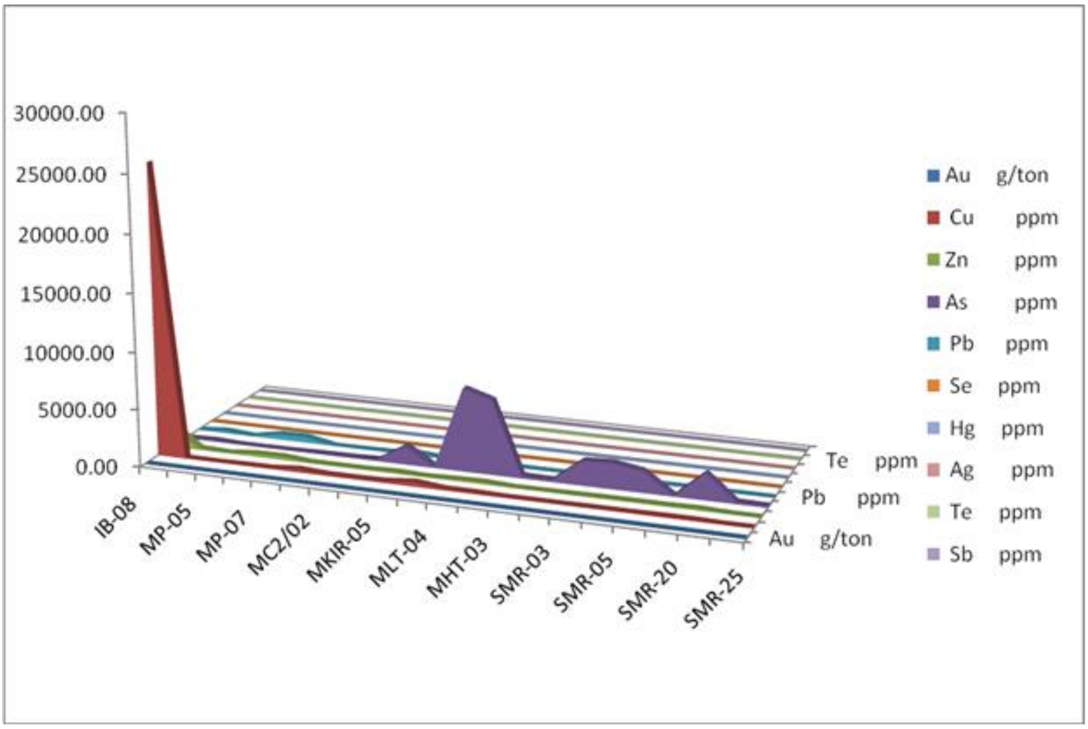

Figure 23: Displaying the retrieved minerals found in various tailing samples within the study areas

Table 8: Concentration levels of Au in tailings with corresponding elements from the study area

Sample ID	Au g/ton	Cu ppm	Zn ppm	As ppm	Pb ppm	Se ppm	Hg ppm	Ag ppm	Te ppm	Sb ppm
IB-08	1.32	25348.71	1979.00	55.00	18.55	5.08	0.00	0.00	64.97	0.00
MP-04	2.32	40.80	136.00	114.00	206.07	1.24	3.24	3.84	57.86	25.72
MP-05	2.30	19.11	38.00	0.00	12.90	1.31	0.98	4.74	59.10	20.90
MP-08	1.79	54.17	258.00	0.00	466.00	1.76	2.11	3.95	56.54	16.14
MP-07	1.65	62.30	279.00	19.00	495.01	2.06	7.79	1.62	43.58	16.55
MC1/02	2.67	258.03	69.00	73.00	5.43	0.00	10.47	0.00	75.17	0.00
MC2/02	0.14	109.62	61.00	82.00	0.00	0.00	13.39	0.00	77.41	0.00
MMK/04	3.48	107.84	66.00	145.00	36.01	3.02	5.18	6.72	61.93	22.44
MKIR-05	3.18	137.29	140.00	1634.00	218.40	1.71	12.53	6.71	66.65	21.98
MD-04	3.40	377.49	52.00	77.00	19.82	2.62	3.26	2.68	62.00	23.69
MLT-04	2.48	110.89	119.00	7228.00	17.31	3.80	4.66	12.73	81.45	38.58
MLT-05	5.87	103.59	167.00	6452.00	40.93	4.40	5.55	4.26	66.61	32.40
MHT-03	0.76	30.40	29.00	234.00	5.41	2.46	10.33	4.90	66.49	23.05
LND-05	8.12	38.01	43.00	180.00	3.26	1.42	2.28	1.75	61.19	25.36
SMR-03	0.37	38.07	55.00	2158.00	5.34	1.29	4.50	3.30	65.17	21.40
SMR-04	0.52	50.46	81.00	2259.00	7.88	1.81	6.76	2.41	55.86	19.81
SMR-05	1.54	46.25	79.00	1851.00	7.44	1.45	9.01	2.57	61.47	23.12
SMR-11	1.78	70.07	75.00	69.00	23.42	2.17	9.18	3.48	65.63	25.12
SMR-20	3.19	76.09	121.00	2330.00	4.66	6.46	21.29	0.00	44.16	18.46
SMR-26	2.93	12.97	24.00	172.00	8.07	0.86	7.46	4.10	63.69	23.67
SMR-25	2.28	25.99	19.00	126.00	7.20	1.41	6.36	0.46	64.07	21.48

4.4 The mineralization style and the implication to geological gaps

The geological characteristics of the Ibaga region exhibit a typical gold-copper-zinc mineralization style, as confirmed by previous research conducted by Ngole et al. (2016); Laizer et al. (2024); and Laizer and Mulibo (2024). The mineral deposits are delimited by syngenetic volcanic-massive sulfides (VMS) and sedimentary exhalative (SEDEX) formations. The VMS genetic model is deemed more plausible due to the prevalence of the Cu-Zn association, unlike the common Pb-Zn association found in SEDEX. Additionally, copper ore is observed to be hosted in sheared country rock in certain areas. The presence of stains or veinlets of minerals such as malachite, bornite, and azurite in some parts further supports the dissemination of copper. The gold mineralization at Mpambaa is linked to thin shear zones (less than 1m thick) striking NE-SW and exhibiting sub-vertical to vertical dipping within an Archaean quartz porphyry environment in the greenstone rocks. Previous studies have reported moderate gold grades of up to 1.55 g/t (Leger, 2015; Ngole et al., 2016; Laizer et al.,2024; Laizer and Mulibo 2024), whereas the current study has revealed gold grades reaching up to 2.32 g/t. The mineralization assemblage in this area typically demonstrates gold-copper-lead-zinc anomalies.

Figure 24: Typical Cu Ore at Ibaga; SEDEX and VMS respectively (Photo courtesy by Kalimenze

In the Muhintiri region, gold mineralization is found in sheared metavolcanic and metasedimentary rocks of the Archaean age, with major faults, primarily oriented in the NE-SW and some in NW-SE directions, potentially influencing the mineralization patterns. The mineralization assemblage in this area exhibits gold-lead-zinc anomalies. The gold mineralization in Kirondatal-Misigiri is lithologically controlled and is predominantly hosted in partially sheared greenstone rocks. The association of gold mineralization with base metal anomalies suggests a gold-copper-zinc mineralization style. Previous studies by Harris (1961), Laizer et al., (2024), and Laizer and Mulibo (2024) have indicated the presence of quartz reef mineralization along shear zones in this area, and the gold deposit is hosted in auriferous veins in mafic volcanic rocks of basaltic composition present in the shear zone (Mkinga, 1997; Ngole et al., 2016; Laizer et al.,2024; Laizer and Mulibo 2024). However, the precise nature of ore paragenesis remains unclear and calls for further investigation.

Sambaru and Londoni are characterized by gold mineralization primarily confined to quartz veins and reefs within highly sheared country rocks. The primary mineralization occurs in highly sheared cataclastic to mylonitic rock units (Figure 25), with quartz veins and reefs oriented in the NW-SE direction. The mineralization style in this area is characterized by a gold-pyrite-mica association, with arsenopyrites and pyrites being the most common sulfide ores (Semkiwa et al., 2013). Additionally, idiomorphic pyrite grains are frequently found within the quartz veins. These characteristics are crucial in understanding and interpreting the geological significance of the area. This academic review reflects the diverse geological contexts and mineralization styles evident across the studied regions (Semkiwa et al., 2013), providing a comprehensive understanding of the gold-copper-zinc mineralization patterns and their associated geological features. According to Semkiwa et al. (2013), most ASSM working grounds have several veins with a general trend of about 310° and a dip of nearly 80°. There are significant values of gold occurring in the country rock, as evidenced in one of the visited sites, where the country rock and quartz vein yielded 7.5 g/t and 11.1 g/t of gold respectively.

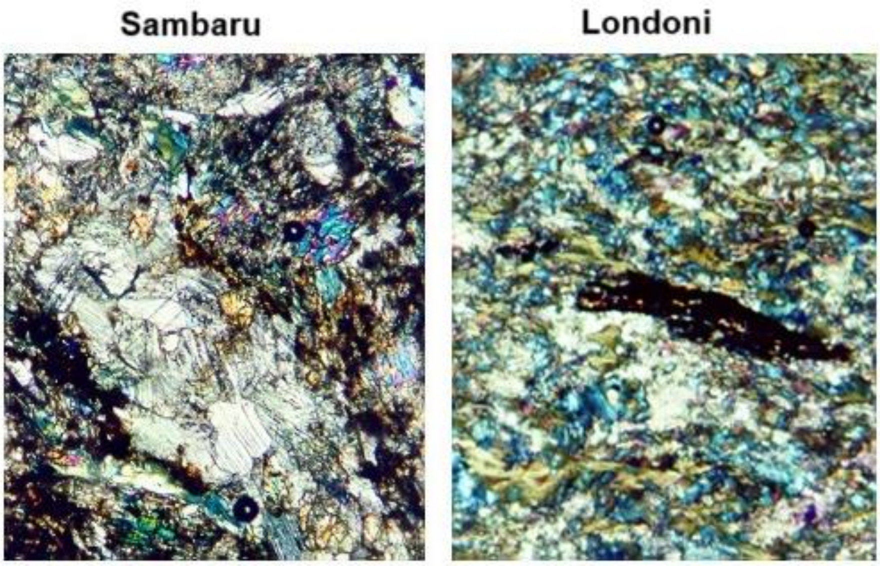

Figure 25: Typical Au ore at Sambaru and Londoni respectively (photo courtesy by Kalimenze 2016 – Not to scale)

5. Conclusion

The study in the Singida region sought to elucidate the factors impacting mineralization in the ASSM working sites within this geographic area. It is main objectives included the characterization of mineralization and associated ore minerals, as well as the evaluation of potential reasons for the low resource recovery in the region to enhance mineral recovery methods. The findings have revealed that gold mineralization in the area is predominantly influenced by specific geological structures, except in the Londoni area where different structures govern it.

Moreover, the Singida Region delineates poly-metallic mineralization of gold, copper, and zinc. Key pathfinder elements contributing to this mineralization encompass copper, arsenic, lead, and antimony, supplemented by contributions from mercury, silver, and tellurium. It has been observed that the current ore processing and metal recovery methods in the region may be suboptimal, as significant quantities of gold values are discernible in tailings. The identified pathfinder elements bear a resemblance to those found in other greenstone belts across Africa and may offer valuable insights for countries grappling with similar challenges in the extraction of economically viable mineral deposits.

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7. Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

8. Authors contributions

Mr. John Kalimenze played a pivotal role in spearheading the endeavor. His responsibilities included meticulous planning, organizing, coordinating, and overseeing the implementation of fieldwork for data collection. Additionally, he prepared the initial draft and composed the final manuscript. Dr. Benatus Mvile made significant contributions by precisely revising the initial manuscript, conducting comprehensive data analysis, interpreting the results, and playing an integral role in crafting the final manuscript.

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