XRF Elemental Analysis of the Gold Ore of Gbonkolenken Chiefdom in Tonkolili District of Sierra Leone

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ABSTRACT- Artisanal and Small-scale Gold Mining (ASGM) is one of the oldest mining industries in Sierra Leone; second only to diamond. Sierra Leone gold production was reported at 60.000 kg in Dec 2022. Gold mining has contributed immensely to the economic development of Sierra Leone; especially mining communities as it is one of the most significant employer in the informal sector in country which provides employment for mainly rural youths.

The primary interest of gold miners in Sierra Leone is the extraction of the gold mineral from its ore discarding other precious minerals associated with the gold ore which they are not aware of. Identification of these other minerals from this gold ore could contribute to national economy development.

Artisanal small scale gold miners lack the XRF technology to swiftly analyze rock samples and determine the concentration of valuable elements like gold, silver, copper, and more. Therefore the search for gold leads to the indiscriminate destruction of mining sites that negatively impact the environment. XRF data forms the basis for estimations of the site's economic viability and potential profitability.

There are many techniques used in the identification of minerals or elements from ores, but the most preferred technique for many researchers is the X-ray fluorescence (XRF). XRF is a non-destructive analytical technique that employs the principles of X-ray fluorescence to determine the elemental composition of a material. In the context of gold analysis, XRF is particularly valuable for its ability to quickly and accurately identify the concentration of various elements in a gold ore sample.

The study aims at identifying precious minerals in the gold ores of Gbonkolenken Chiefdom using XRF technique that could contribute to economic development of mining communities and Sierra Leone as a whole.

The results of the qualitative XRF analyses of the samples identified gold, silver, zirconium, tin among the key elements detected. The percentage concentration of the elements were not quantified as the researcher main interest was to know the minerals presents in the samples.

Keywords: X-ray fluorescence (XRF), elements, minerals, analysis, artisanal and small-scale gold mining (ASGM), non-destructive, analytical technique, high-energy radiation, energy-dispersive (ED) XRF.

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INTRODUCTION

Sierra Leone is well known for its vast endowment in minerals, which include diamonds, rutile, bauxite, gold, iron ore, platinum, and zircon, as well as promising petroleum potential. Mining has been the mainstay of the economy since independence, and the government has remained heavily dependent on mineral resources over the years.

In 2021, mining contributed 0.6 percent to GDP, 67 percent of export earnings, 4.1 percent to total government revenues, and 3 percent to employment. The government established the National Mineral Agency under the Ministry of Mines and Mineral Resources in 2012 with a mandate to implement clear policies and regulations, enhance transparency and accountability, and ensure mineral resources support economic and social development. (Sierra Leone Country Commercial Guide, Mining and Mineral Resources 2024-04-17).

The most recognised large scale gold mining method worldwide is hard rock retrieval which uses tunnels underground and machinery in open pits to extract gold. This larger scale enables far greater quantities of gold to be mined as well as other minerals associated with the gold ore. The hard rock retrieval method is not common in Sierra Leone except the Baomahun Gold mine which is located in central Sierra Leone, owned and operated by FC Gold. It is one of the largest pre-production gold assets in the country. The project is expected to pour its first gold in 2025.

Artisanal and Small-scale Gold Mining (ASGM) still remain one of the oldest mining industries in Sierra Leone; second only to diamond. Artisanal and ASGM use rudimentary mining methods that negatively impact the environment and health of mining communities. These methods mostly use elemental mercury which is mixed with gold-containing materials, forming a mercury-gold amalgam which is then heated, vaporizing the mercury to obtain the gold.

Sierra Leone Gold Production was reported at 60.000 kg in Dec 2022. Sierra Leone Gold Production data is updated yearly, averaging 92.000 kg from Dec 1990 to 2022, with 29 observations. The data reached an all-time high of 446.000 kg in 2018 and a record low of 4.000 kg in 1995. This Gold Production data remains active status in CEIC and is reported by U.S. Geological Survey.

It is an important source for job creation, poverty alleviation and broad-based socio-economic development in Sierra Leone. Gold mining has contributed immensely to the economic development of Sierra Leone; especially mining communities as it is one of the most significant employer in the informal sector in country which provides employment for mainly rural youths.

One of the most significant benefits of gold mining is its contribution to the economy. The industry provides jobs for millions of people worldwide, from miners to engineers to logistics personnel. In addition to this, gold mining generates revenue for governments through taxes and royalties, surface rent for mining communities, license fees, customs charges, government community fund, and environmental protection agency support among other benefits.

Gold mining offers a multitude of benefits that extend beyond its economic value. From providing investment opportunities and driving technological innovation to promoting environmental sustainability and fostering social development, the industry plays a significant role in shaping both local communities and the global economy. Responsible mining practices and ongoing efforts to mitigate environmental impacts demonstrate the potential for gold mining to contribute positively to society while continuing to meet the demand for this precious metal in Sierra Leone.

The primary interest of gold miners in Sierra Leone is the extraction of the gold mineral from its ore discarding other precious minerals associated with the gold ore which they are not aware of. Identification of these other minerals from this gold ore could contribute to national economy development.

There are many techniques used in the identification of minerals or elements from ores (Eva et al 2013), the two commonly used ones are X-ray fluorescence (XRF) and X-ray diffraction spectrometry (XRD). XRF is a non-destructive analytical technique that employs the principles of X-ray fluorescence to determine the elemental composition of a material. X-ray diffraction (XRD) is a versatile non-destructive analytical technique used to analyze physical properties such as phase composition, crystal structure and orientation of powder, solid and liquid samples. XRD provides detailed information about the crystallographic structure, chemical composition, and physical properties of a material (Acquafredda 2018). It is based on the constructive interference of monochromatic X-rays and a crystalline sample.

The main difference between XRD and XRF is that XRD can determine the presence and amounts of minerals species in sample, as well as identify phases. XRF will give details as to the chemical composition of a sample but will not indicate what phases are present in the sample. In the context of gold analysis, XRF is particularly valuable for its ability to quickly and accurately identify the concentration of various elements in a gold ore sample.

Based on the advantages mentioned above, the XRF qualitative technique was used to determine the elemental composition of the gold ore of Gbonkolenken Chiefdom in Tonkolili District.

PROBLEM ANALYSIS

Artisanal small scale gold miners lack the XRF technology to swiftly analyze rock samples and determine the concentration of valuable elements like gold, silver, copper, and more. This leads to the indiscriminate destruction of mining sites that negatively impact the environment. XRF data forms the basis for estimations of the site's economic viability and potential profitability. Handheld XRF analyzers are a reliable method to analyze ore samples in open pits and underground mines – achieving the accuracy required to provide defensible information for process oversight, quality assurance, and various other operational decisions (such as grade control).

Therefore, artisanal small scale gold mining (ASGM) is characterized by basic and compromised mining methods with either very limited control of hazards or none. While challenges exist, with wide array of environmental problems in the operational communities including land degradation, loss of land cover, water pollution, and siltation or sedimentation of water bodies. There is little knowledge about health and safety among artisanal and small-scale gold miners (Singo et al, March 2022).

In addition to these environmental problems post by artisanal gold mining, other challenges that small-scale miners face include lack of necessary mining equipment, lack of access to electricity, poor financial credit facilities, lack of expertise, lack of a progressive legal framework, lack of relevant institutions, mining accidents, injuries, and unsafe work practices (Marlene, February 2024).

Artisanal gold mining releases mercury into the environment in its metallic form during amalgamation and as mercury vapor during the burning process. When metallic mercury is used to concentrate the gold, small amounts can be washed out along with the unwanted tailings or sediments (Hilson et al 2006). Mercury attacks the central nervous system, affects brain functioning and, in extreme cases, exposure will lead to death. Despite being commonly overlooked, industrial pollution still poses a significant threat to human health, particularly in the case of artisanal gold mining (Veiga et al 2014).

Aim and Objectives of the Study

The study aims at identifying precious minerals in the gold ores of Gbonkolenken Chiefdom using XRF technique that could contribute to economic development of mining communities and Sierra Leone as a whole.

The objectives is to identify the types of chemical elements or minerals in the gold ores.

LITERATURE REVIEW

XRF spectrometry remains a preferred standard method of geochemical investigation of earth's mineral and chemical compositions due to its ability to rapidly provide a high-resolution assessment of relative variations of most earth elemental compositions (Löwemark et al 2011). Many researchers acknowledged that X-ray fluorescence (XRF) spectroscopy is one of the most widely used and well-established methods of routine estimation of geochemical composition of rocks, sediments and earth material samples (Temitope 2017; Kramar 1997; Ling et al 2017; Tolosana-Delgado & McKinley 2016; Weltje & Tjallingii 2008; Young et al 2916). It has been utilized in the successful investigation of geological, archaeological and industrial samples (Jenkins et al 1995; Young et al 2016).

As a fast technique, XRF precious metal analysis is often used to perform karat, grade, and impurity identification on the spot. Jewelry stores and pawn shops often use XRF precious metal analyzers to accurately authenticate and price the valuable items they buy and sell. In metallurgical processes, XRF ensures the integrity of alloys by confirming their composition. It's a critical step in manufacturing products such as aircraft components, car parts, and structural materials.

The ability of XRF to determine the major oxide/element composition of many earth materials (either in glass discs, powder pellets or bulk powder samples) has made it useful in many laboratory settings (Jenkins et al 1995; Kramar 1997; Young et al.2016,Temitope 2017). XRD analysis provides three types of data namely quantitative, semi-quantitative and qualitative. Qualitative data obtained from XRF results shows what elements are present in a sample, but it does not provide information about the quantity of them. The XRF detector will count the fluorescent X-rays and display this information in a graphical format. Quantitative data provides the additional information lacking in qualitative results. Not only do these results show what elements are present, but also the quantities of these elements. To obtain the most accurate results, calibration of the XRF instruments is important.

According to Sakurai et al (2004), and Weltje et al (2008), the XRF procedure involves inter-linked processes. Most atoms have several electron orbitals (K shell, L shell, M shell, for example). The first process involves the emission of X-rays from the XRF instrument that ignite an electron and knock the ignited electron of an atom out of the inner orbital. The second process is the excitation of the atom and the production of high-energy radiation (photons, protons, electrons, etc.). When X-ray energy causes electrons to transfer in and out of these shell levels, XRF peaks with varying intensities are created and will be present in the spectrum, a graphical representation of X-ray intensity peaks as a function of energy peaks (Zhan et al 2007; Temitope et al 2017).The third process involves the detection and integration of characterized emitted lines to give varying levels of intensity. The last stage in this process is the conversion of the detected line intensities to elemental concentrations (Temitope et al 2017). One can only plot intensities for lines that yield K and/or L lines. These lines refer to the movement of electrons between orbitals within the atom.

EXPERIMENTAL PROCEDURE

Study Area

Gbonkolenken Chiefdom is found in Tonkolili District of Sierra Leone. Its capital is Yele. *Gbonkolenken Chiefdom* has a population of 47,838 with 22,032 male and 25,806 female. Artisanal gold mining is the primary source of income seconded by agriculture and petty trading (Statistics Sierra Leone 2004 Population and Housing Census). Tonkolili District is in the Northern Province of Sierra Leone with a population of 530,776 (Statistic Sierra Leone, 2015). Its capital and largest city is Magburaka.

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Figure 1: Map of Tonkolili District showing Yele, the study area with blue spot

Sample Collection

1kg of gold ore sample was randomly collected from three collection points (CP1, CP2 and CP3) of each of the five gold ore stockpiles (SP) excavated from five mining sites namely Robanka (YEL 1), Makump (YEL 2), Mafarama (YEL 3), Rothain (YEL 4) and Mayaimray (YEL 5). The three samples collected from each stockpile, which was 3kg, were thoroughly mixed and 1kg of sample taken from the homogenous mixture. This gave 1kg of gold ore sample from each mining site as presented in Table 1. The gold ore samples were put into polythene bags and taken to Njala University Quality Laboratory in Sierra Leone for analysis.

Table 1: Sample collection sites

Chiefdom	**Sampled Area**	**Code**	**Weight of sample (kg) from stockpile (SP)**			
			Collection point (CP) from stockpile (SP)			**Mean (kg)**
			CP1	CP2	CP3	
Gbonkolenken Yele	Robanka	YEL1	1	1	1	1
	Makump	YEL2	1	1	1	1
	Mafarama	YEL3	1	1	1	1
	Rothain	YEL4	1	1	1	1
	Mayaimray	YEL5	1	1	1	1

Figure 2: Gold ore extracted from sampled sites

Sample Preparation

The samples collected from the five mining sites were prepared at Njala University Quality Laboratory. The samples were freeze-dried at ~60 °C in a Freeze Drier for 6 days. The dried samples were pulverized into a fine powder with an agate mortar and pestle. 5 gram each of the pulverized ground sample was analyzed using Axios mAX 4kW Sequential XRF Spectrometer.

Instrumentation

X-ray fluorescence analysis instruments can be largely categorized into wavelength-dispersive X-ray spectroscopy (WDX) and energy-dispersive X-ray spectroscopy (EDX). WDX disperses the fluorescent X-rays generated in a sample using an analyzing crystal and a goniometer, resulting in the instrument being large (Guang et al 1990). On the other hand, the detector in EDX has superior energy resolution and requires no dispersion system, which allows the instrument to be smaller in size.

In this study, the energy-dispersive (ED) XRF was adopted in the qualitative elemental analysis of the gold ore samples using the Axios mAX 4kW Sequential XRF Spectrometer with a Vacuum gas system and Ar/CH4 Flow gas. This instrument comprises of an x-ray source, a signal processor, a central processing unit and a detector which work together to process and display results.

DISCUSSION OF RESULTS

As it was a qualitative analysis, the researcher was only interested to know the chemical elements identified by the Axion mAX XRF analyzer on the ore samples as showed in Figures 3 to 8 of the XRF peaks. Each peak uniquely represents an element determined by its KeV values at various K_α, K_β, L_α and L_β lines.

The XRF analysis results show that all the five gold ore samples from the five mining sites have almost the same elements compositions but at different intensity as evident from their peaks.

Robanka (YEL 1): The XRF result of the chemical elements identified for YEL 1 gold ore sample is presented in Figure 3 and Table 2.

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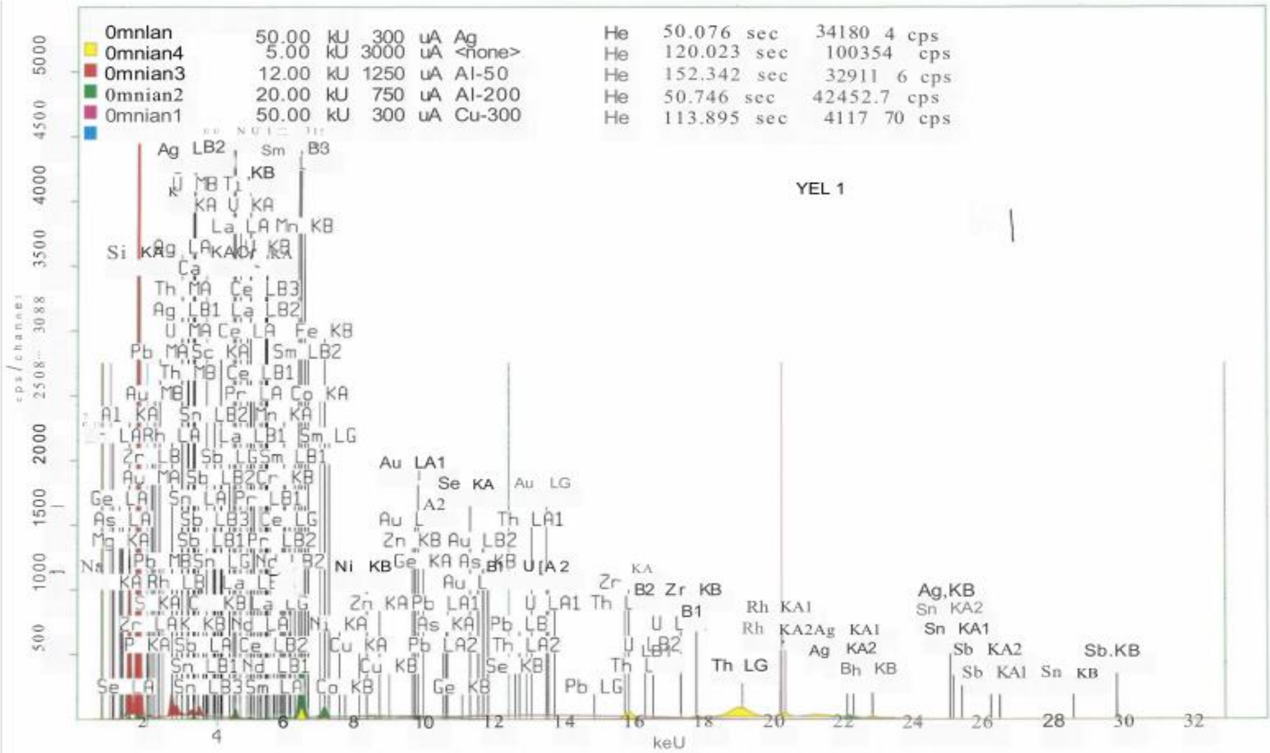

Figure 3: XRF elemental analysis result of Robanka (YEL1)

Table 2: Elements identified in Robanka (YEL1) gold ore sample

Series	Elements identified by XRF									
Transition Metals	Gold (Au)	Silver (Ag)	Zirconium (Zr)	Chromium (Cr)	Iron (Fe)	Cobalt (Co)	Copper (Cu)	Nickel (Ni)	Manganese (Mn)	Rhodium (Rh)
Post-Transition Metals	Lead (Pb)	Tin (Sn)	Aluminu (Al)							
Alkaline Earth Metal	Calcium (Ca)		Magnesium (Mg)							
Alkaline Metal	Potassium (K)		Sodium (Na)	Rubidium (Rb)						
Metalloid	Arsenic (Ar)		German (Ge)	Silicon (Si)	Antimony (An)		Boron (B)			
Reactive Non-Metal	Phosphorus (P)		Selenium (Se)							
Lanthanide	Neodymium (Nd)		Cerium (Ce)	Praseodymium (Pr)						
Actinides	Uranium (U)		Thorium (Th)							

Makump (YEL 2) Gold Ore Sample

The XRF result of the chemical elements identified for YEL 2 gold ore sample is presented in Figure 4 and Table 3.

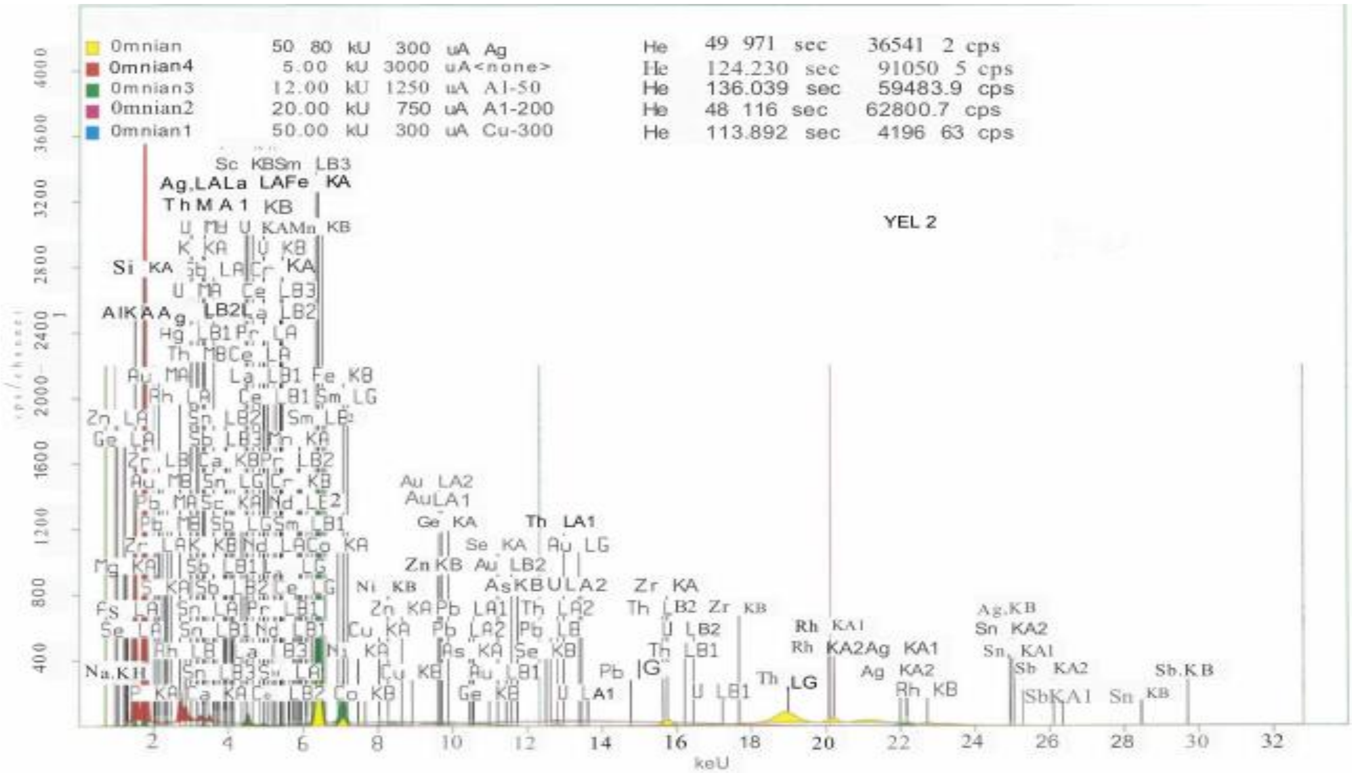

Figure 4: XRF elemental analysis result of Makump (YEL2)

Table 3: Chemical elements identified in Makump (YEL 2) gold ore sample

Series	Elements identified by XRF									
Transition Metals	Gold (Au)	Silver (Ag)	Zirconium (Zr)	Chromium (Cr)	Iron (Fe)	Cobalt (Co)	Copper (Cu)	Nickel (Ni)	Manganese (Mn)	Rhodium (Rh)
Post-Transition Metals	Lead (Pb)	Tin (Sn)	Aluminu (Al)							
Alkaline Earth Metal	Calcium (Ca)		Magnesium (Mg)							
Alkaline Metal	Potassium (K)		Sodium (Na)	Rubidium (Rb)						
Metalloid	Arsenic (Ar)		German (Ge)	Silicon (Si)	Antimony (An)		Boron (B)			
Reactive Non-Metal	Phosphorus (P)		Selenium (Se)							
Lanthanide	Neodymium (Nd)		Cerium (Ce)	Praseodymium (Pr)						
Actinides	Uranium (U)		Thorium (Th)							

Mafarama (YEL 3) Gold Ore Sample

The XRF results for YEL 3 is presented in Figure 5 and Table 4, which shows the key chemical elements identified in the gold ore sample.

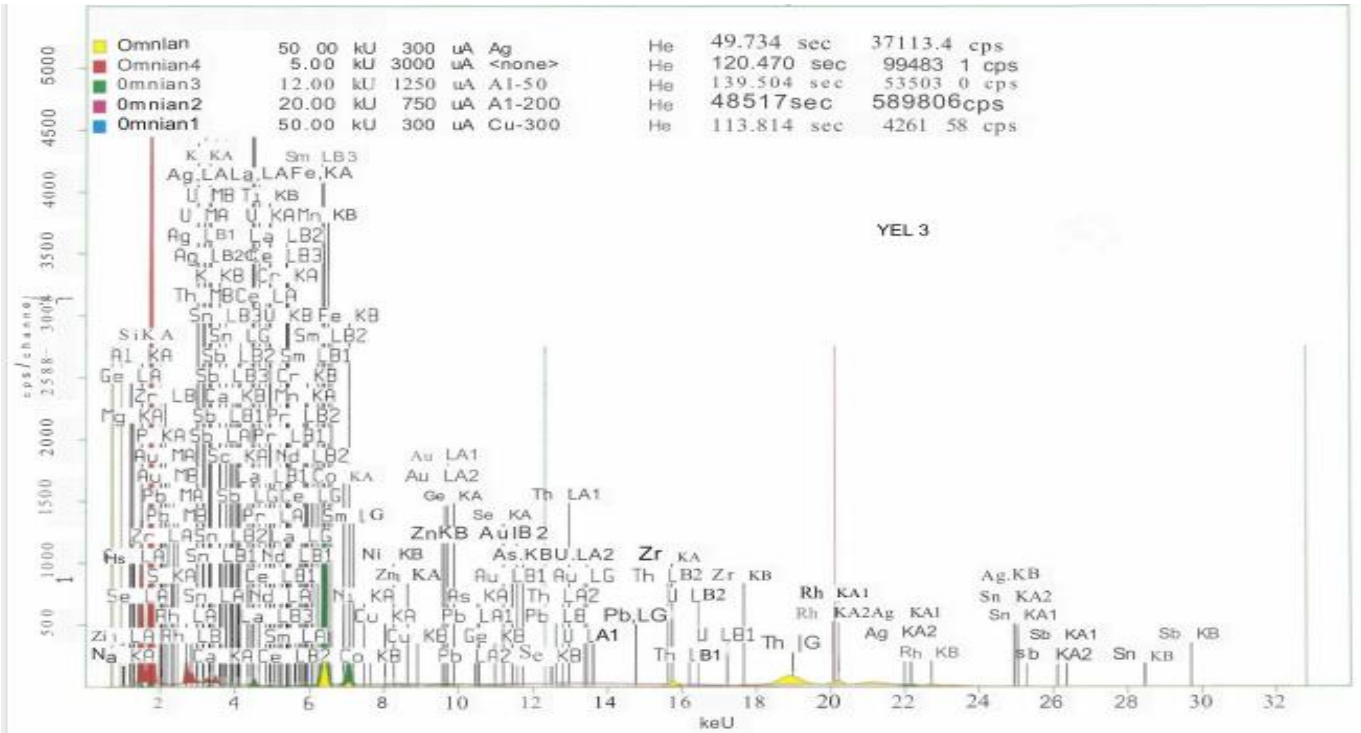

Figure 5: XRF elemental analysis result for Mafarama gold ore sample

Table 4: Chemical elements identified in Mafarama gold ore sample

Series	Elements identified by XRF									
Transition Metals	Gold (Au)	Silver (Ag)	Zirconium (Zr)	Chromium (Cr)	Iron (Fe)	Cobalt (Co)	Copper (Cu)	Nickel (Ni)	Manganese (Mn)	Rhodium (Rh)
Post-Transition Metals	Lead (Pb)	Tin (Sn)	Aluminu (Al)							
Alkaline Earth Metal	Calcium (Ca)		Magnesium (Mg)							
Alkaline Metal	Potassium (K)		Sodium (Na)	Rubidium (Rb)						
Metalloid	Arsenic (Ar)		German (Ge)	Silicon (Si)	Antimony (An)		Boron (B)			
Reactive Non-Metal	Phosphorus (P)		Selenium (Se)							
Lanthanide	Neodymium (Nd)		Cerium (Ce)	Praseodymium (Pr)						
Actinides	Uranium (U)		Thorium (Th)							

Rothain Gold Ore Sample

Figure 6 presents the XRF analysis result for Rothain with Table 5 showing the elements detected by the analyzer.

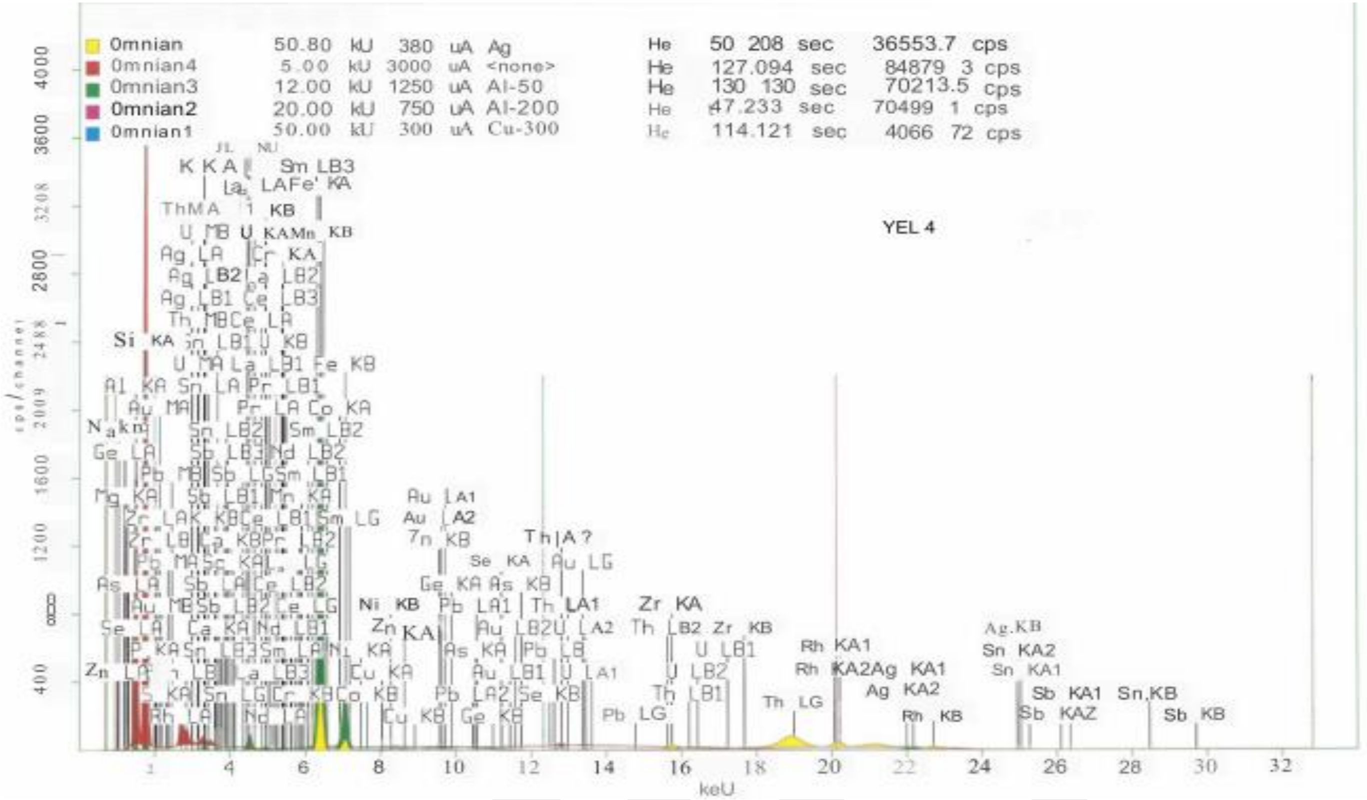

Figure 6: XRF analysis result for Rotain gold ore sample

Table 5: Chemical elements identified in Rothain gold ore sample

Series	Elements identified by XRF									
Transition Metals	Gold (Au)	Silver (Ag)	Zirconium (Zr)	Chromium (Cr)	Iron (Fe)	Cobalt (Co)	Copper (Cu)	Nickel (Ni)	Manganese (Mn)	Rhodium (Rh)
Post-Transition Metals	Lead (Pb)	Tin (Sn)	Aluminu (Al)							
Alkaline Earth Metal	Calcium (Ca)		Magnesium (Mg)							
Alkaline Metal	Potassium (K)		Sodium (Na)	Rubidium (Rb)						
Metalloid	Arsenic (Ar)		German (Ge)	Silicon (Si)	Antimony (An)		Boron (B)			
Reactive Non-Metal	Phosphorus (P)		Selenium (Se)							
Lanthanide	Neodymium (Nd)		Cerium (Ce)	Praseodymium (Pr)						
Actinides	Uranium (U)		Thorium (Th)							

Mayaimray Gold Ore Sample

The XRF analysis result of Mayaimray gold ore sample is presented in Figure 7 followed by Table 6, which shows the element identified from theXRF graph.

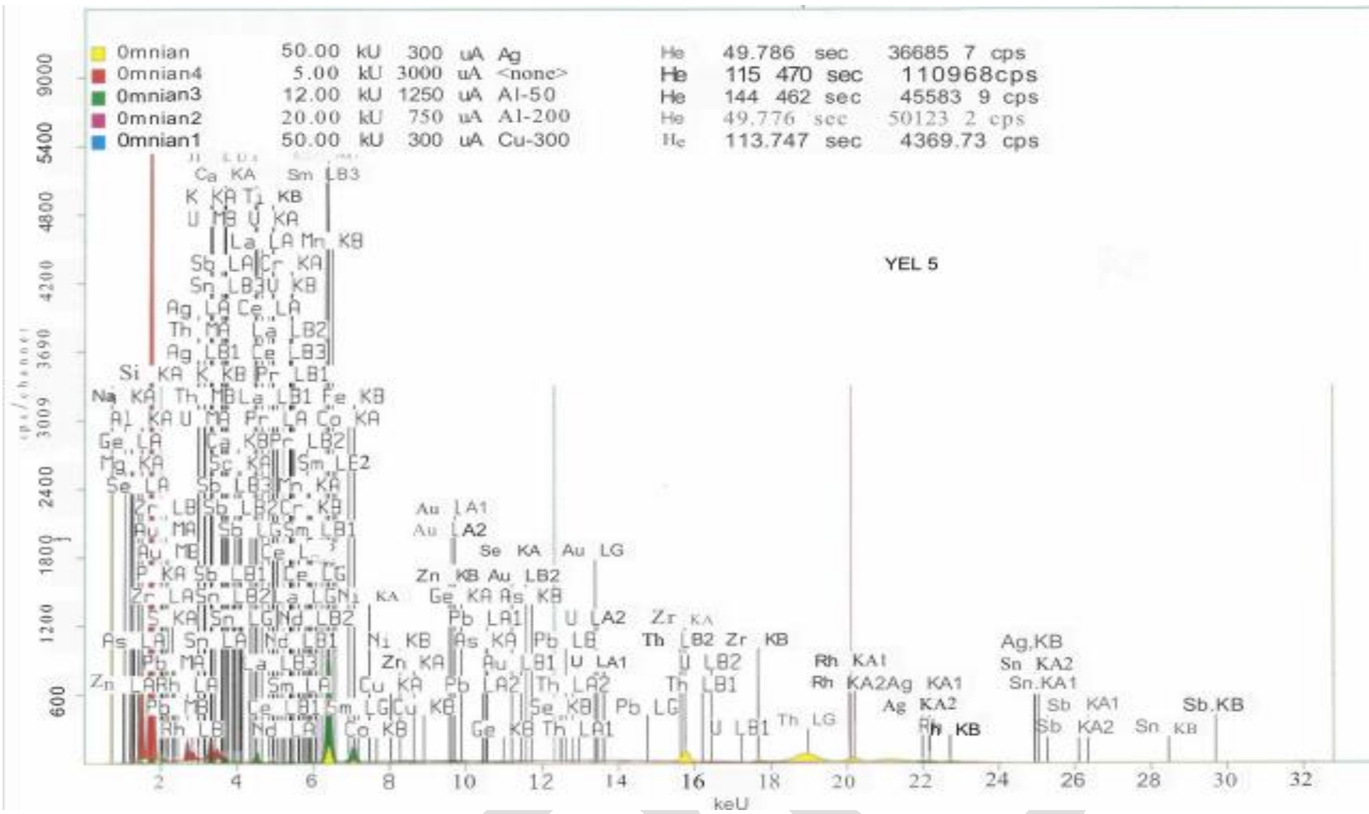

Figure 7: XRF analysis result for Mayaimray gold ore sample

Table 6: Elements identified in Mayaimray gold ore sample

Series	Elements identified by XRF									
Transition Metals	Gold (Au)	Silver (Ag)	Zirconium (Zr)	Chromium (Cr)	Iron (Fe)	Cobalt (Co)	Copper (Cu)	Nickel (Ni)	Manganese (Mn)	Rhodium (Rh)
Post-Transition Metals	Lead (Pb)	Tin (Sn)	Aluminu (Al)							
Alkaline Earth Metal	Calcium (Ca)		Magnesium (Mg)							
Alkaline Metal	Potassium (K)		Sodium (Na)	Rubidium (Rb)						
Metalloid	Arsenic (Ar)		German (Ge)	Silicon (Si)	Antimony (An)		Boron (B)			
Reactive Non-Metal	Phosphorus (P)		Selenium (Se)							
Lanthanide	Neodymium (Nd)		Cerium (Ce)	Praseodymium (Pr)						
Actinides	Uranium (U)		Thorium (Th)							

Table 7: A summary Matrix of elements identified in the five sampled sites

No	Element	Symbol	Atomic #	Series	YEL1	YEL2	YEL3	YEL4	YEL5
1	Gold	Au	79	Transition Metal	X	X	X	X	X
2	German	Ge	32	Metalloid	X	X	X	X	X
3	Arsenic	As	33	Metalloid	X	X	X	X	X
4	Aluminium	Al	13	Post-Transition Metal	X	X	X	X	X
5	Silicon	Si	14	Metalloid	X	X	X	X	X
6	Magnesium	Mg	12	Alkaline Earth Metal	X	X	X	X	X
7	Silver	Ag	47	Transition Metal	X	X	X	X	X
8	Potassium	K	19	Alkaline Metal	X	X	X	X	X
9	Thorium	Th	90	Actinides	X	X	X	X	X
10	Lead	Pb	82	Post-Transition Metal	X	X	X	X	X
11	Zirconium	Zr	40	Transition Metals	X	X	X	X	X
12	Phosphorus	P	15	Reactive Non-Metal	X	X	X	X	X
13	Tin	Sn	50	Post-Transition Metal	X	X	X	X	X
14	Antimony	Sb	51	Metalloid	X	X	X	X	X
15	Samarium	Sm	62	Lanthanide	X	X	X	X	X
16	Chromium	Cr	24	Transition Metals	X	X	X	X	X
17	Boron	B	5	Metalloid	X	X	X	X	X
18	Neodymium	Nd	60	Lanthanide	X	X	X	X	X
19	Cerium	Ce	58	Lanthanide	X	X	X	X	X
20	Manganese	Mn	25	Transition Metal	X	X	X	X	X
21	Iron	Fe	26	Transition Metal	X	X	X	X	X
22	Cobalt	Co	27	Transition Metal	X	X	X	X	X
23	Copper	Cu	29	Transition Metal	X	X	X	X	X
24	Rubidium	Rb	37	Alkaline metals	X	X	X	X	X
25	Selenium	Se	34	Reactive Non-Metal	X	X	X	X	X
26	Nickel	Ni	28	Transition Metal	X	X	X	X	X
27	Praseodymium	Pr	59	Lanthanides	X	X	X	X	X
28	Manganese	Mn	20	Transition Metal	X	X	X	X	X
29	Rhodium	Rh	45	Transition Metal	X	X	X	X	X
30	Uranium	U	92	Actinides	X	X	X	X	X
31	Calcium	Ca	20	Alkaline Earth Metal	X	X	X	X	X
32	Sodium	Na	11	Alkaline Metal	X	X	X	X	X

CONCLUSION

Sierra Leone is well known for its vast endowment in minerals, which include diamonds, rutile, bauxite, gold, iron ore, limonite, platinum, chromite, coltan, tantalite, columbite, and zircon, as well as promising petroleum potential. In 2021, mining contributed 0.6 percent to GDP, 67 percent of export earnings, 4.1 percent to total government revenues, and 3 percent to employment. Sierra Leone Gold Production was reported at 60.000 kg in Dec 2022.

Artisanal and Small-scale Gold Mining (ASGM) is one of the oldest mining industries in Sierra Leone; second only to diamond. The primary interest of gold miners in Sierra Leone is the extraction of the gold mineral from its ore discarding other precious minerals associated with the gold ore which they are not aware of. Identification of these other minerals from this gold ore could contribute to national economy development.

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Artisanal small scale gold miners lack the XRF technology to swiftly analyze rock samples and determine the concentration of valuable elements like gold, silver, copper, and more. XRF data forms the basis for estimations of the site's economic viability and potential profitability.

The study aims at identifying precious minerals in the gold ores of Gbonkolenken Chiefdom using XRF technique that could contribute to economic development of mining communities and Sierra Leone as a whole.

The study was conducted in five mining communities in Gbokolenken Yele Chiefdom in Tonkolili District where gold ore samples were collected and XRF analysis done at Njala University Quality Laboratory. The results of the qualitative XRF analyses of the samples identified gold, silver, zirconium, tin among the key elements detected. The percentage concentration of the elements were not quantified as the researcher main interest was to know the minerals presents in the samples.

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