Addis Ababa University

College of Natural and computational science

School of Earth Science

Mineralogical, Geochemical and Textural characterization of Akobo Gold deposit for ore beneficiation, South Western Ethiopia.

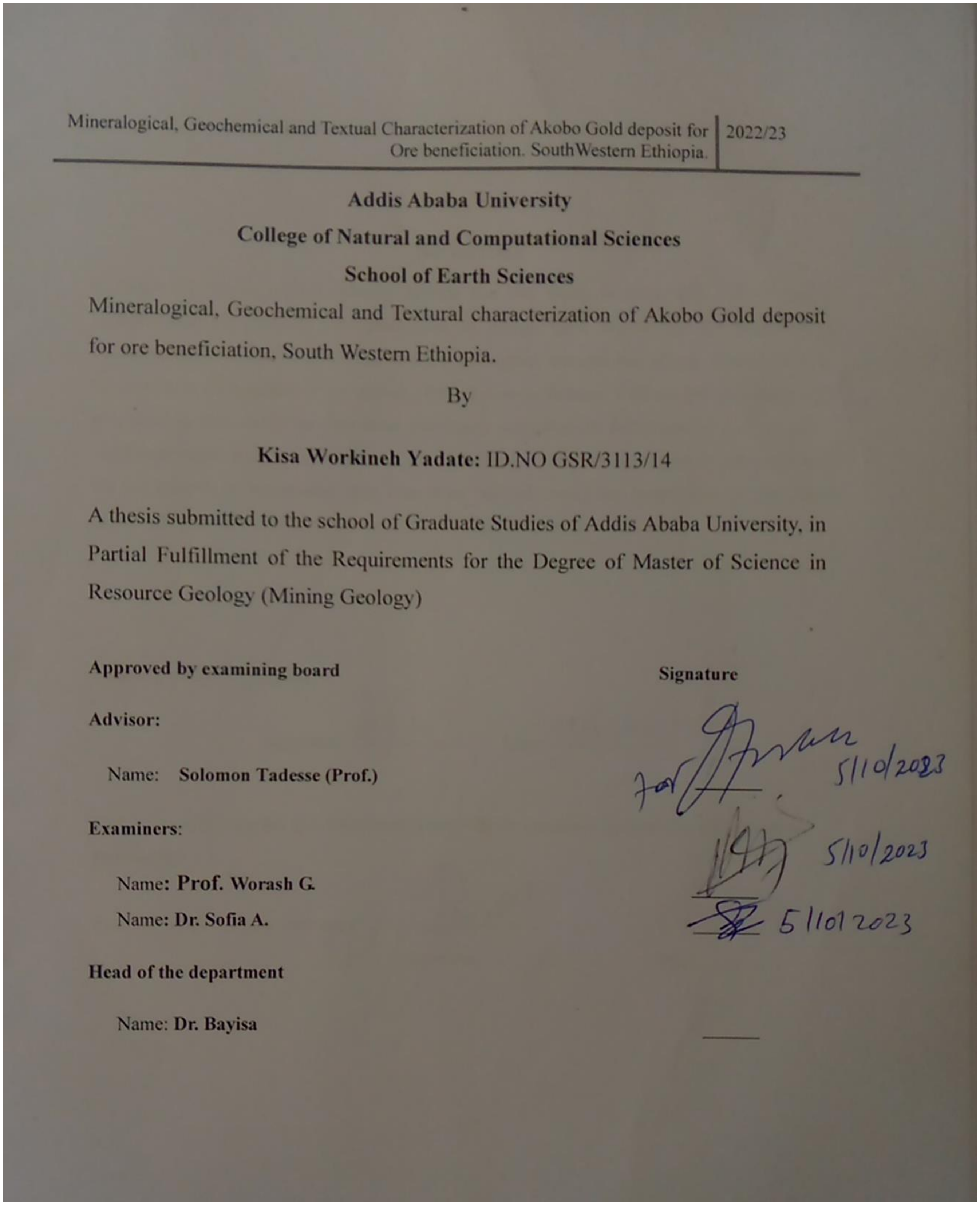
A Thesis Submitted to School of Earth Sciences of Addis Ababa
University in Partial Fulfillment of the requirements for the Degree of
Master of Science in Mining Geology

By: Kisa Workineh Yadate: ID NO GSR/3113/14

Advisor: Solomon Tadesse (Prof.)

Addis Ababa, Ethiopia

Oct, 2023



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A thesis submitted to the school of Graduate Studies of Addis Ababa University, in Partial Fulfillment of the Requirements for the Degree of Master of Science in Resource Geology (Mining Geology)

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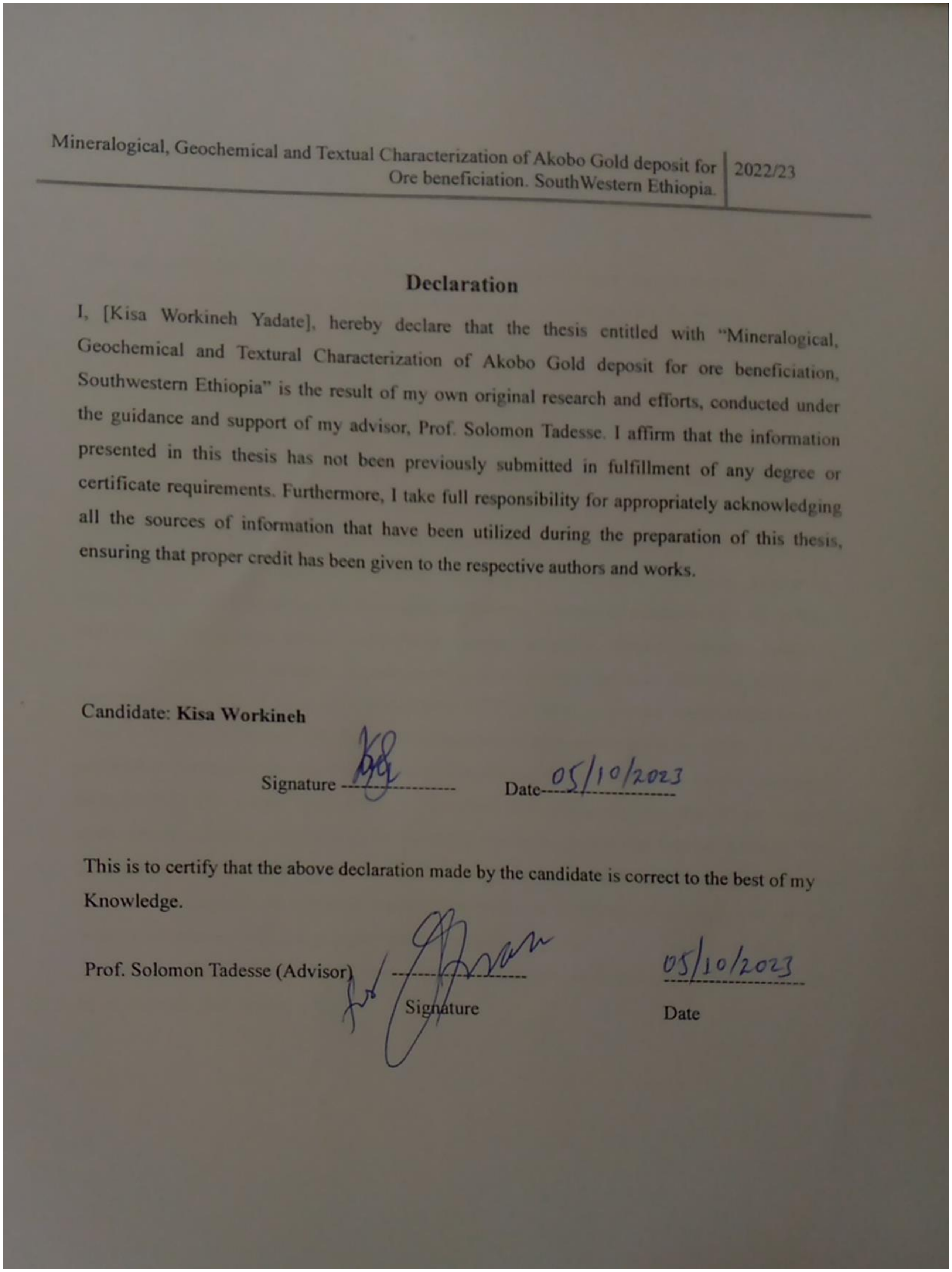

Declaration

I, [Kisa Workineh Yadate], hereby declare that the thesis entitled with "Mineralogical, Geochemical and Textural Characterization of Akobo Gold deposit for ore beneficiation, Southwestern Ethiopia" is the result of my own original research and efforts, conducted under the guidance and support of my advisor, Prof. Solomon Tadesse. I affirm that the information presented in this thesis has not been previously submitted in fulfillment of any degree or certificate requirements. Furthermore, I take full responsibility for appropriately acknowledging all the sources of information that have been utilized during the preparation of this thesis, ensuring that proper credit has been given to the respective authors and works.

Candidate: **Kisa Workineh**

Signature ---------------- Date 05/10/2023

This is to certify that the above declaration made by the candidate is correct to the best of my Knowledge.

Prof. Solomon Tadesse (Advisor) ------------------ 05/10/2023

Signature Date

Abstract

Gold, a precious metal since ancient times, was one of the first metals used by humans due to its availability in placer deposits. However, efficient gold ore processing faces challenges in achieving optimal gold recovery. Inadequate mineral and geochemical characterizations of the ore contribute to inefficient processing. The objective of the project was to assess the mineralogy and geochemical properties of the Akobo gold deposit in order to identify effective treatment methods for optimal gold recovery. Various methods such as optical microscopy, XRD, ICP-AES/MS and SEM are used to evaluate the mineralogy, geochemistry and texture of the gold deposit. The Akobo gold deposit is hosted in metavolcanics and metasedimentary rock, with common alterations including talc alteration, carbonatization, and silicification. Gold mineralogy identified in the area includes krennerite, montbrayite, buckhornite, austobite, calaverite, nagyagite and gold phosphorus thallium selenide. Gangue minerals associated with gold include magnetite, arsenopyrite, pyrite, chalcopyrite, quartz, actinolite, chlorite, siderite, cubanite, covellite, stibnite, and bertherite. Geochemical analysis showed that gold concentration ranged from 0.001 ppm to 9.76 ppm, silica ranged from 26.2% to 58%, iron oxide concentration ranged from 3.79% to 19.3% and the maximum concentration of titanium oxide is 2.47%. The gold particles in the deposit are encapsulated in gangue minerals and range in size from submicroscopic to microscopic (as it ranges from 20µm to 2mm). Most grain size ranges from 50µm to 100µm (about 41%). The Akobo gold deposit is classified as a refractory ore due to its mineral composition, consisting mainly of telluride along with some sulfide and selenide minerals. The processing of this refractory gold requires pretreatment methods such as roasting, bio-oxidation, and pressure oxidation to minimize losses. Comprehensive metallurgical testing is necessary to select a suitable and efficient gold processing method.

Key words: *Gold ore mineralogy, Roasting, Pre-treatment, Amalgamation, Flotation, Telluride, Refractory ore, Free milling.*

Acknowledgment

I am glad for the chance to thank the Almighty GOD for his guidance and blessings over the course of my thesis.

Undertaking research projects of this nature presents significant challenges, often necessitating the assistance of numerous individuals and organizations in addition to my own efforts. Without the support and collaboration of these individuals and organizations, this research project could not have been accomplished.

I am eternally grateful to my esteemed advisor, Professor Solomon Tadesse, for his exceptional guidance, unwavering encouragement, and invaluable contributions that have played a pivotal role in the successful completion of this thesis. It is beyond words to express the depth of my gratitude for his meticulous mentorship and support.

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Last but certainly not least, I want to express my heartfelt gratitude to my family, especially my brothers, Mr. Kumsa Workineh and Mr. Gudeta Workineh, for their unwavering encouragement and support throughout this journey. I am also immensely thankful to all my classmates who, in various ways, provided assistance. Your contributions have played a vital role in helping me overcome challenges and ultimately complete this research project.

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Table of Contents

List of Figures:

List of Tables:

Acronyms

ALS	Australian Laboratory Services
ANS	Arabian Nubian Shield
ASTU	Adama Science and Technology University
CIL	Carbon In Leach
CIP	Carbon In Pulp
EIGS	Ethiopian Institute of Geological Surveys
EMRDC	Ethiopian Mineral Resources Development Corporation
GIS	Geographic Information System
GPS	Global Positioning System
IOCG	Iron-Oxide-Copper-Gold deposit
LIMS	Laboratory Information Management Systems
LOI	Loss Of Ignition
ICP-AES/MS	Inductively Coupled Plasma Atomic Emission Mass Spectroscopy
QEMSCAN	Quantitative Evaluation of Minerals by Scanning Electron Microscopy
XRD	X-Ray Diffraction
SEM	Scanning Electron Microscope
USGS	United States Geological Survey

CHAPTER ONE

INTRODUCTION

1.1. Background

Gold has been cherished for its beauty and practical attributes since ancient times (Butterman & Iii, 2005). Beyond its aesthetic value, gold gained significance as a crucial industrial metal in the late 20th century due to its exceptional electrical conductivity, corrosion resistance, and desirable physical and chemical properties (Christie & Brathwaite, 2009; Izatt et al., 2014). Its occurrence as a free metal in placer deposits likely made it one of the earliest metals employed by humans, as it could be retrieved without complex separation techniques. The form in which gold exists in ore deposits determines the appropriate recovery methods to be employed (Butterman & Iii, 2005).

Gold exhibits a variety of deposit types, distinguished by their geometry, host rock characteristics, mineralization form, and associated minerals (Nguimatsia et al., 2017). These deposits contribute to global gold production in different proportions. Among them, placer and Orogenic gold deposits are the most abundant, followed by porphyry and epithermal deposits (Frimmel, 2008).

The liberation of gold during processing from gold deposits is influenced by various factors, including the mineralogy of the gold ore, the characteristics and particle size of the gold-bearing mineral, the textural relationship between gold and gangue minerals, including economically valuable sulfides such as sphalerite, galena, and chalcopyrite, as well as the composition of the gangue mineral (Spry et al., 2004).

Ethiopia's geological conditions have been favorable for the formation of various mineral deposits, including gold (Au), Tantalum, Platinum, Phosphate, iron ore, bauxite, and more (Tadesse et al., 2003). In Ethiopia, there are several instances of placer gold occurrences, as well as the Lega Dembi primary gold mining area, originating from Precambrian basement rocks associated with granitic intrusions. These gold mineralization are found in intensely sheared, hydrothermally altered greenschist facies volcano-sedimentary rocks within the Megado and Kenticha belts in the southern part of the country (Deksissa & Koeberl, 2004), as well as in the Meli, Weri, and Werkamba areas in the northern part (Abraham et al., 2015), and the granitoids of Western Ethiopia (Belete et al., 2002). Unlike Southern Ethiopia, there is no documented record of primary gold mining in Western Ethiopia, except for irregular placer and alluvial gold mining activities (Oljira & Warkisa, 2020). One of the recently discovered gold deposits in southwestern Ethiopia is the Akobo gold deposit. The Akobo deposit, located in the Gambela region, is situated within a narrow greenstone sub-belt, which has shown great potential for gold exploration in recent years. The geological setting of Akobo comprises mafic schists, meta-ultramafic rocks, meta-sedimentary schists, as well as undifferentiated schists and gneisses (Sjoberg & Tamene, 2019).

The Akobo gold deposit, located in the southwestern greenbelts of Ethiopia in the Gambela region of Dima woreda, has recently been discovered by ETNO mining companies. The deposit is now progressing towards the mining production stage. Despite the presence of unpublished reports on the geology and genesis of the deposit in the area, there is a lack of detailed mineralogical and geochemical characterization of the gold ore. Therefore, it is crucial to understand the mineralogy and geochemical properties of the deposit as it approaches the processing phase. This project focuses primarily on studying the mineralogical factors to ensure effective and efficient processing, minimizing potential gold losses associated with mineralogy and geochemistry during ore processing. The mineralogy, geochemical, and textural characteristics are being assessed using various methods such as optical microscopy, X-ray diffraction (XRD), inductively coupled plasma atomic emission spectroscopy/mass spectrometry (ICP-AES/MS), and scanning electron microscopy (SEM).

1.2. Statement problem

Gold ore processing often faces challenges in achieving optimal gold recovery. One of the main causes of processing inefficiency is the lack of implementation of thorough mineralogical and geochemical characterization and evaluation of the gold ore (Bargawa & Hardiyanto, 2017). Merely knowing the metal grades within a mineral deposit is insufficient. Once it is determined that the grades are economically viable, understanding the in-situ properties of the target minerals and their association with gangue minerals becomes crucial. The most efficient processing route for gold extraction is closely linked to the inherent mineralogical features of the specific gold ore being processed (Adams, 2005; Chryssoulis & McMullen, 2016). Therefore, it is of utmost importance to accurately characterize the mineralogical nature of the ore to be processed, including a detailed analysis of the precious metal phases (gold deportment) and the characteristics of the gangue minerals.

A thorough understanding of the mineralogy of gold ore is crucial for efficient recovery and mineral processing. While it is widely recognized that the direct mineralogy of gold can significantly impact processing outcomes, the challenges and costs involved in conducting comprehensive characterizations of gold-bearing ores often result in mineralogical analysis being overlooked until processing issues arise (Goodall & Scales, 2007). As the Akobo gold mineralization progresses towards the production stage, obtaining accurate information regarding the geological setting and mineralogy of the gold and associated gangue minerals becomes paramount for successful gold recovery and efficient mineral processing.

Hence, this study aims to comprehensively characterize the mineralogy of the deposits and assess how specific attributes of the ore minerals will impact gold recovery during processing. By gaining a deep understanding of the ore's mineralogical composition, we can anticipate its behavior during processing and extraction. The primary objective of this project is to characterize the mineralogy and geochemical properties of the gold ore in order to identify the most effective and efficient processing methods, leading to optimal gold recovery

1.3. Research questions

The research aims to address the following key questions:

- What are the various mineralogical compositions of the gold ore found in the Akobo gold deposit?

- What are the specific properties of the gold ore that can have an impact on its beneficiation process?
- How can we determine the most suitable and efficient gold ore processing methods by considering its mineralogical, geochemical, and textural characteristics?

1.4. Description of the study area

1.4.1. Location and Accessibility

The project area is situated in the southwestern part of Ethiopia, specifically within the Gambela region, Dima Woreda. This region is part of the southern extension of the Western Greenstone Belt, which is a significant geological formation within Ethiopia. The Western Greenstone Belt itself is a component of the larger Arabian Nubian Shield, a geological region known for its mineral-rich deposits.

Geographically, the project area is bounded by the coordinates 0721386 m to 0740913 m E in terms of longitude and 0696176 m to 0717550 m N in terms of latitude (Fig. 1.1). To access the project area, one can travel from the capital city of Addis Ababa. The distance from Addis Ababa to the project site is approximately 690 kilometers, and this journey can be made via an asphalt road. Additionally, there is a 30-kilometer stretch of gravel road that leads to Dima town. The main route from Addis Ababa to Dima town passes through Weliso, Welkite, Jima, Bonga, Mizan, Biftu, and finally reaches Dima. Once in Dima town, access to the project area is facilitated by dirt roads. Maximum and minimum elevation of the area is 2200 and 600 meter respectively (Fig 1.2).

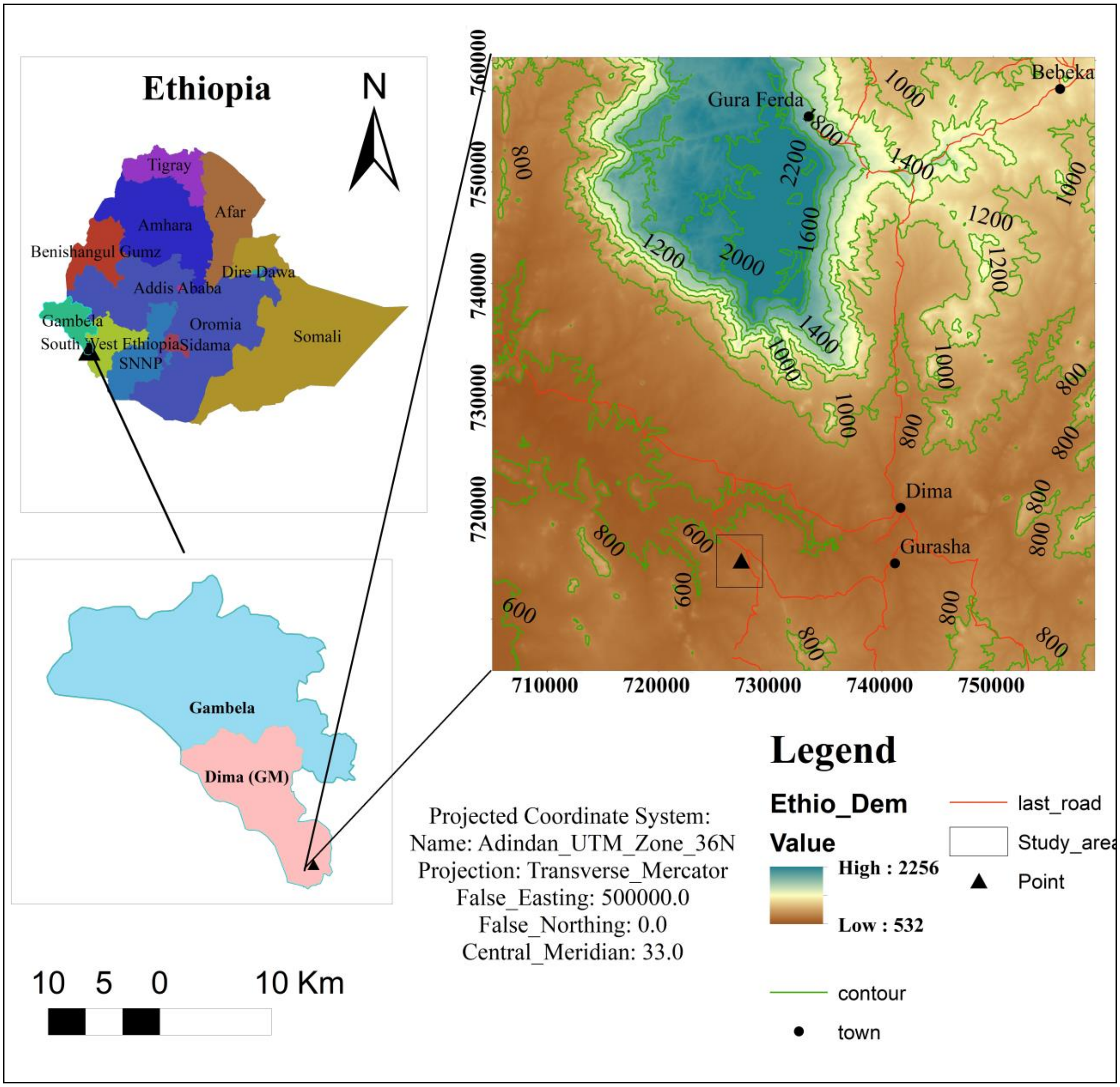


Figure 1.1: Location map of the study area.

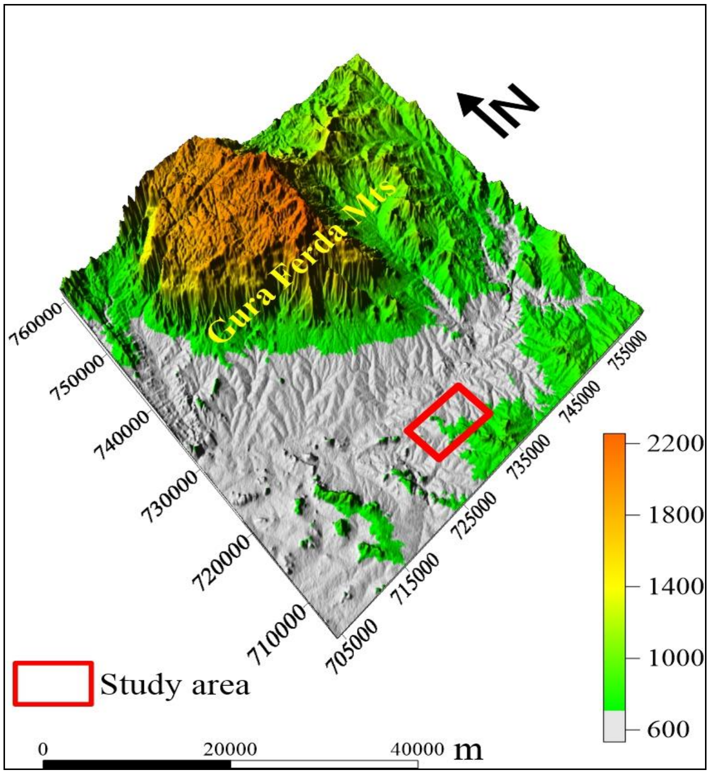


Figure 1.2: Physiographic map of the area

1.4.2. Climate and Vegetation of the area

The Akobo gold deposit area, located within Dima Woreda of the Gambela region in southwestern Ethiopia, experiences a specific climate and vegetation pattern influenced by its geographical location.

The region falls within a tropical climate zone, characterized by distinct wet and dry seasons. The wet season typically occurs from June to September, during which the area receives the majority of its annual rainfall. The dry season spans from October to May, characterized by lower precipitation levels and higher temperatures. Temperatures in the area are generally warm to hot throughout the year. Average temperatures range from around 35.31°C and 22.47°C (Fig.1.3), with higher temperatures often experienced during the dry season (35.31 °C).

The vegetation in Dima Woreda is predominantly characterized by savanna and woodland biomes. The specific vegetation types include grasslands, scattered trees, and patches of dense woodland. Acacia trees are common in the region. The vegetation composition is adapted to the prevailing climate conditions, with drought-resistant plants and trees that can thrive in the seasonal rainfall patterns. (**source**:https://en.climate-data.org/afric/ethiopia/gambela-1651/r/january-1/#climate-table-year).

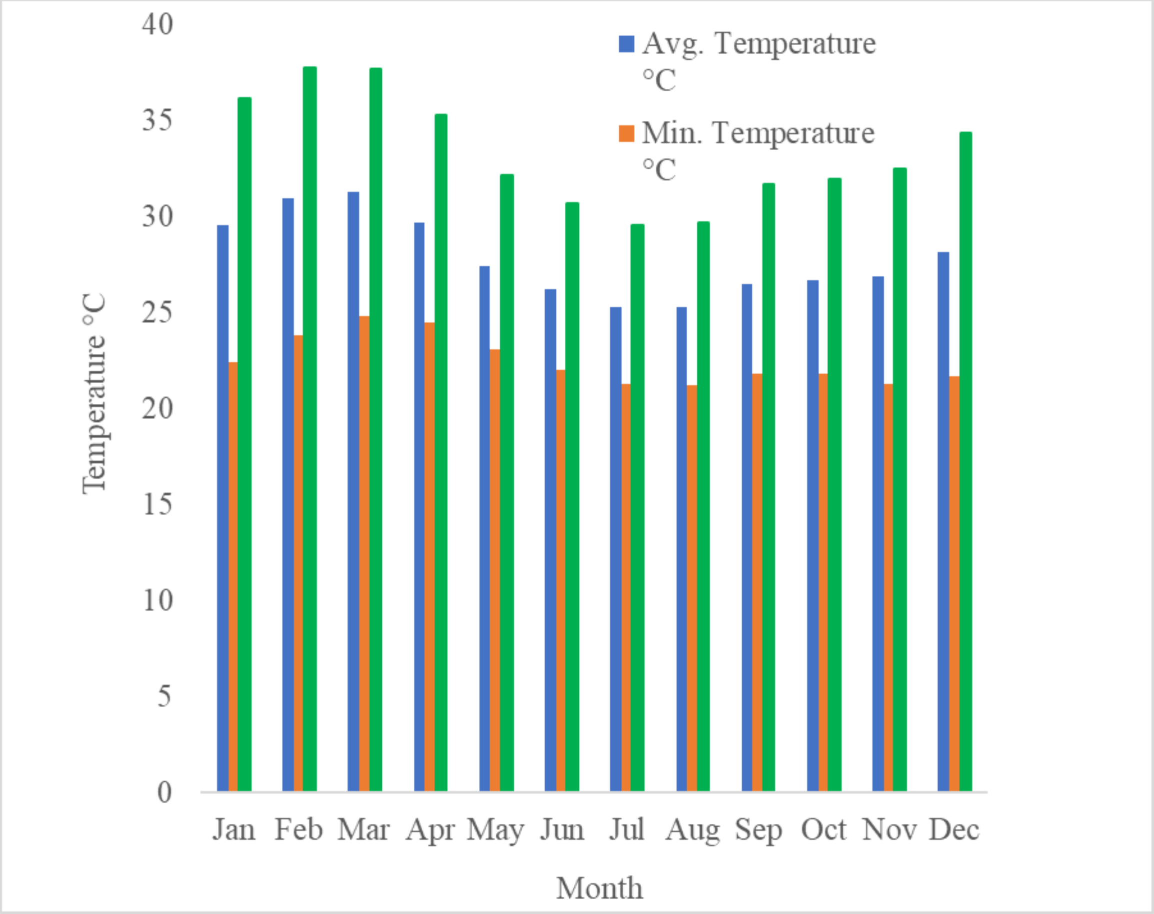


Figure 1.3: Minimum, Average and Maximum temperature of the study area

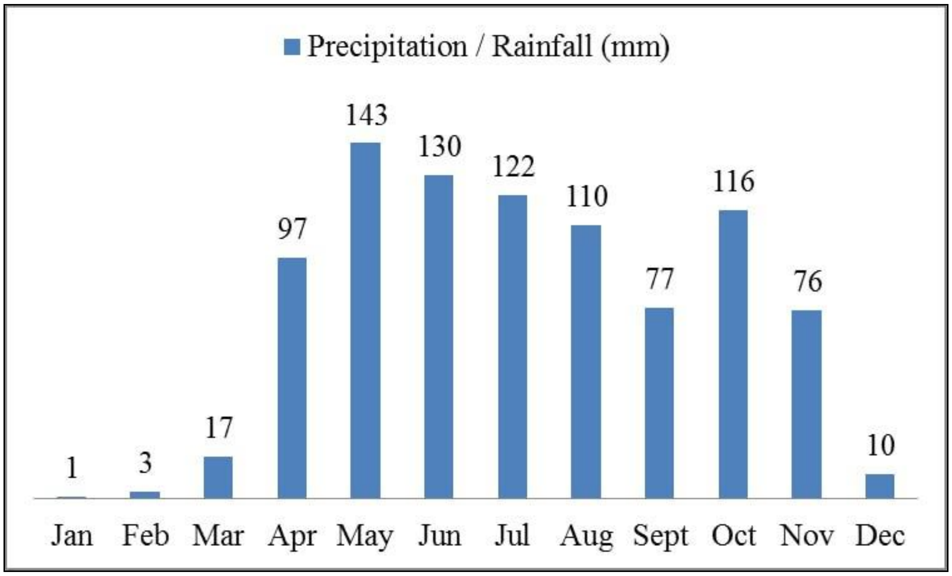


Figure 1.4: Mean monthly rainfall of the area

1.5. Objectives

1.5.1. General Objectives

The main objective of this research work is characterization of the mineralogical, geochemical and textural amenability of Akobo gold deposit.

1.5.2. Specific Objective

The specific objectives of the proposed research are:

- ➢ To accurately identify the mineralogy of the gold ore and associated minerals
- ➢ To describe gold ore texture
- ➢ To describe the geochemical association of element with gold ore
- ➢ To describe the effects of mineralogy, geochemical and textures of the gold ore to the different gold processing

1.6. The outputs of the research

The followings are the final results of the study:

- ✓ What is the gold ore mineralogy in the area?
- ✓ The ore texture and association of gold ore with the gangue minerals

- ✓ The composition of the gold ore
- ✓ The effects of gold mineralogy, ore texture and mineral association on the gold processing

1.7. Significance of the research

The mineralogical and geochemical characterization of the gold deposit enables to design effective methods of the gold extraction and selecting the efficient gold mineral processing methods. As mineralogy is the key factor for mineral processing, understanding the behavior of gold occurrence and its association helps for recovery the gold metals with the suitable methods. Most of the time characterizing the deposit's mineralogy is done after the low recovery and problem happens in processing; so, this research is very significant to fill the gap the related with gold mineralogy and geochemical properties of the new discovered deposit in the advanced stages. The ETNO mining companies and similarly other companies can understand the importance of detailed mineralogical and geochemical characterization for getting the required gold metals during processing and reduce the losses of the metal that happens due to mineralogy. It also fills the gap that occurred due to lack of mineralogical characterization of the gold ore before processing designing as most of characterization is done after problem happens in processing and recovery of the metals. Finally, it opens the door for different scholars and researchers to conduct various researches to know the effect of ore mineralogy for designing and planning flow sheets for newly discovered deposit.

1.8. Scope of the Study.

This study primarily focuses on the geochemical, mineralogical, and textural characterization of the Akobo gold deposit in order to understand its processing. This is done by sampling the rock that hosts the gold and analyzes those materials. Characterization of those materials is done by common analytical methods like optical microscope, X-ray diffraction, scanning electron microscope and inductive coupled plasma atomic emission spectrometry (ICP-AES). The projects try to identify the different gold ore mineralogy, textures, and association of other minerals with gold and the composition of the Akobo gold deposits. The processing technique for this deposit can finally be determined using those factors.

1.9. Limitation of the Study

As characterization of gold ore minerals for processing is essential in designing and implementing the process flow sheets, metallurgical test should be needed. For this purpose, an enormous number of samples could be analyzed so that you can confidently select appropriate methods of processing. Not only this, but also the quantitative analysis is required like quantitative x-ray diffraction which is too sophisticated techniques. One of the challenges for this project is getting the sophisticated methods of analysis due to their economic factors (costs of laboratory) within the limited budget. There is no metallurgical test done to improve characterization of the gold deposit. Getting sufficient samples is also another challenge that I faced although some core samples are collected. The financial issue as generally one of the obstacles for effective and efficient methods of characterization for selecting the processing methods.

1.10. Gold production in the world

According to Symeonidis (2023), gold was one of the first metals mined since it is readily extracted in its natural state, is attractive and imperishable (a noble metal), and can be used to create wonderful products. The first gold miners were the Sumerians, who were working deposits in modern-day Iran by 3800 B.C., and the Egyptians, who had organized gold mining on a large scale by at least 3000 B.C. In ancient civilizations, gold was mostly used to brightly decorate temples and monarchs' tombs. Following the fall of the Roman Empire, gold coinage completely disappeared as a form of legal money (Misra, 2000). Gold coinage first appeared much later, approximately 700 B.C.

According to Garside (2023), the world's gold mine reserves are thought to be around 50,000 metric tonnes (Fig. 1.6), with some minor annual changes. The biggest estimated reserves are in Australia, Russia, and South Africa, as illustrated in Fig. 1.5. After the global financial crisis of 2008, gold production from mines surged steadily. With a peak of 2,560 metric tonnes in 2010, the production of gold from mines worldwide has routinely been above 3,000 metric tonnes since 2015. Around 3,000 metric tonnes of gold were produced worldwide in 2021. In terms of global gold mining, China now holds the first spot, followed by Australia and Russia (Garside, 2023).

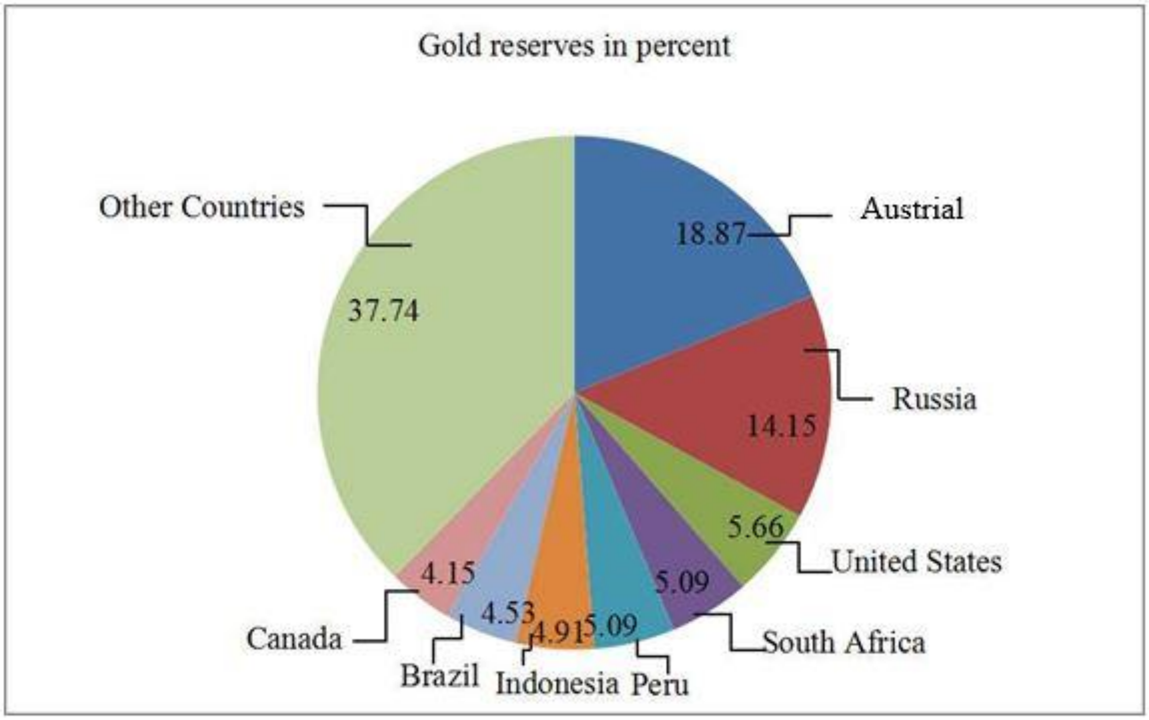


Figure 1.5: Gold mine reserves worldwide as of 2022, broken down by country (*Source: Garside, 2023)*

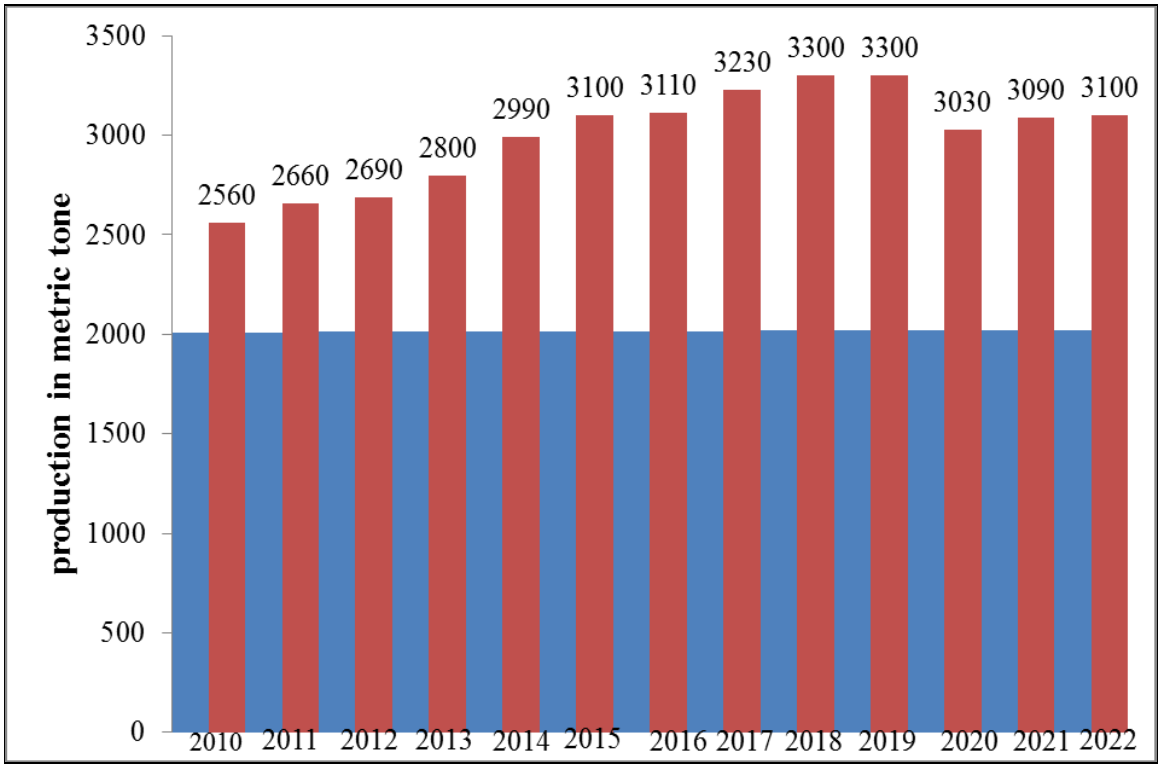


Figure 1.6: Global gold production from 2010 to 2022. (Source: (Garside, 2023)

1.11. Ethiopia's gold production and history

Ministry of Mines, Petroleum and Natural Gas (MoMP, 2020) reported gold occurrences are widespread in Ethiopia. Exploitation of placer gold reportedly dates back at least 3,500 years. Over the subsequent millennia, gold has been extracted nearly continuously to this day, although not always in large quantities

Since the establishment of the Ethiopian Institute of Geological Surveys (EIGS) in 1983 and later the Geological Survey of Ethiopia, various geological mapping and mineral exploration projects have been undertaken by the government. Current gold deposits of economic interest have been outlined in several localities of Ethiopia that belong to the Arabo-Nubian shield of late Proterozoic age, developed as a result of Pan-African tectono-thermal orogeny (MoM, 2023)

Precambrian occurrences are being explored and exploited in the southern, western and northern greenstone belts of Ethiopia. Precambrian rocks are the most important repositories for gold deposits in three greenstone belts (**Fig. 1.7**). These are the northern, western, and southern greenstone belts. The Southern greenstone belt includes the separate Adola Kenticha, Ageremariam, Arero and Moyale areas, which are associated with gold mineralization (Worash & Solomon, 2015).

The western greenstone belt stretches more than 600 kilometers from Akobo-SW Ethiopia, and its average width varies from 50 to 200 kilometers. This belt comprises chlorite, sericite and graphitic schist, phyllites, quartzites, and andesitic to rhyolitic volcanics, hosting auriferous veins and alteration zones. The belt comprises major regions of Gambela, Western Wollega, and Benishangul Gumuz, which include gold prospects at Chamo, Akobo, Guraferda, Gezana, Tumet, Godare, Baro, Ankori, Tulu Kapi, Tulu Kami, Dimma, Baruda, Oda Godare, Mengie, Ashashire, Dul, Gambella mountain, Indaka, Bekoji Motisha, Suken, Egambo, Kilaji, Wombera, Metekel (Jilaye), Guba and other sites (MoM, 2023)

The third major greenstone belt in northern Ethiopia comprises several meta-volcano sedimentary belts and sub-belts, bounded by mafic-ultramafic rocks, hosting gold and base-metal occurrences. The primary gold occurrences of Terakimti, Adi Zeresenay, Zager, Asgede, Mia Koka, and Niraqque as well as the base metals of Tsehafi Emba and others are identified by GSE.

Primary gold sources were discovered in the 1980s during detailed exploration in the Adola gold field (Legadembi and Sakaro) primary gold deposits (are the only primary gold mines) and many other primary gold occurrences by EMRDC (Solomon Tadesse, 2009; Worash & Solomon, 2015). However, a number of others gold mines, including Tulu Kapi, Dish, Jilaye and Akobo in Segele area (western Ethiopia), Okote (southern Ethiopia), and Meli (northern Ethiopia) are in operations (MoM, 2023).

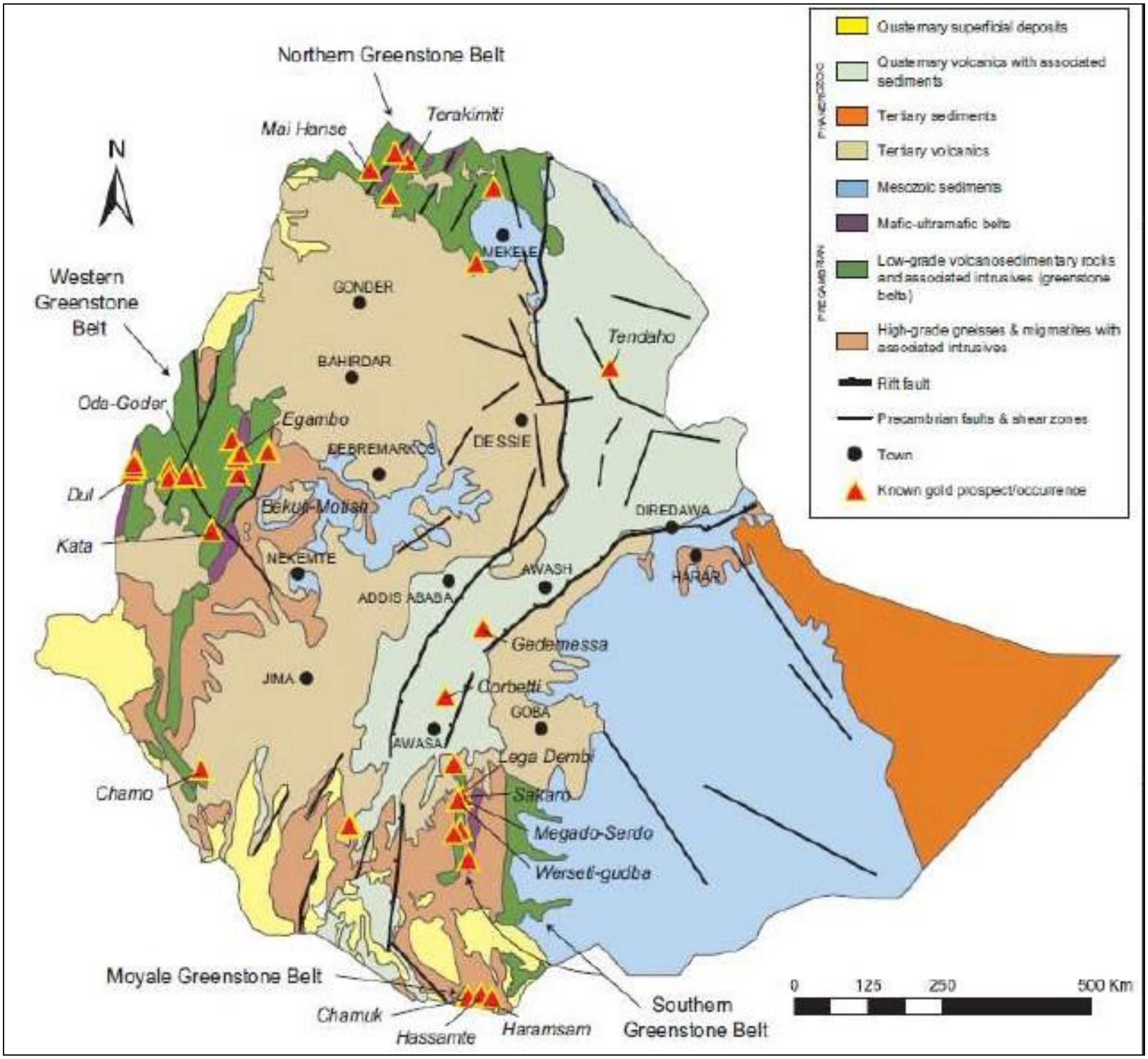


Figure 1.7: The distribution of principal gold prospects and occurrences in Ethiopia.

(*Source: MoM, 2023).*

CHAPTER TWO

LITERATURE REVIEW

2.1. Gold ore mineralogy

Gold, being an inert metal, is not commonly found in a wide range of naturally occurring compounds. Its occurrence in gold ores is primarily in the form of native gold, electrum (a gold-silver alloy), and gold alloys (Vaughan, 2004). However, there are other forms of gold that can be present, such as "invisible" gold, gold tellurides, gold selenides, and gold sulfides (Petruk, 2000; Vaughan, 2004)

According to Jordan (2023), approximately 70% to 75% of the gold in a deposit is typically in the form of native gold, while around 20% occurs as tellurides. The remaining 5% to 10% is in the form of "invisible" gold, which has either been incorporated into the crystal structure of various minerals or exists as tiny particles.

Based on their mode of occurrence, gold can be classified into three categories: microscopic gold, sub-microscopic gold, and surface-bound gold (Vaughan, 2004; Zhou & Wang, 2003). Microscopic gold, also known as visible gold, includes gold alloys, gold tellurides, gold sulfides, gold selenides, gold sulfo-tellurides, gold sulfo-selenides, and other similar minerals (Zhou et al., 2004) as in table 1.

Microscopic gold is commonly found in many gold ores and constitutes the primary form of gold in non-refractory gold ores (Vaughan, 2004). Sub-microscopic gold, also known as invisible gold, refers to gold particles that are not visible under an optical microscope. Instead, these particles require the use of a scanning electron microscope (SEM) for detection (Chryssoulis & McMullen, 2016). In gold ores, sub-microscopic gold is typically found as discrete particles with a diameter smaller than 0.1 µm, residing within sulfide minerals, primarily pyrite and arsenopyrite.

On the other hand, surface-bound gold refers to gold that has been adsorbed onto the surfaces of other minerals during the mineralization process or subsequent oxidation and metallurgical processing. Similar to sub-microscopic gold, surface gold is not visible under optical or electron microscopes and can only be detected using techniques such as laser Inductively Coupled Plasma Mass Spectrometry (LIMS) (Zhou et al., 2004). The primary carriers of surface gold in the ore include FeOx (iron oxides), stained quartz, carbonaceous matter, and clay minerals.

Table 1: Gold ore mineralogy (modified from (Petruk, 2000; Zaghlol, 2020)

2. Native elements, alloys and metallic compounds	**Formula**	**3. Tellurides**	**Formula**
✓ Native gold (<20 mol% Ag)	Au	✓ Calaverite	$AuTe_2$
✓ Electrum (20–80 mol% Ag)	(Au,Ag)	✓ Krennerite	$(Au,Ag)Te_2$
✓ Palladian gold (porpezite)	(Au,Pd)	✓ Muthmannite	(Au,Ag)Te
✓ Rhodian gold (rhodite)	(Au,Rh)	✓ Petzite	Ag_3AuTe_2
✓ Iridic gold	(Au,Ir)	✓ Sylvanite	(Au,Ag)2Te4
✓ Platinum gold	(Au,Pt)	✓ Kostovite	$CuAuTe_4$
✓ Gold amalgam	(Au,Ag)Hg	✓ Montbrayite	$(AuSb)_2Te_3$
✓ Weishanite	$(Au,Ag)_3Hg_2$	✓ Nagyagite	$(Pb(Pb,Sb)S_2)(Au,Te)$
✓ Maldonite	Au_2Bi	✓ Bilibinskite	$Au_3Cu_2PbTe_2$
✓ Auricupride	Cu_3Au	✓ Bezsmertnovite	$Au_4Cu(Te,Pb)$
✓ Tetra-auricupride	AuCu	✓ Bogdanovite	$(Au,Te,Pb)_3(Cu,Fe)$
✓ Hunchinite	Au_2Pb	✓ Buckhomite	$AuPb_2BiTe_2S_3$
4. Sulfide and selenide		**5. Silicates/Other**	
✓ Uytenbogaardite	Ag_3AuS_2	✓ As chloritea	$(Mg,Al,Fe)_{12}((Si,Al)_8O_{20})(OH)_{16}$
✓ Fischesserite	Ag_3AuSe_2	✓ Auroantimonate	$AuSbO_3$
		✓ Aurostobite	$AuSb_2$
✓ Petrovskaite	AuAg(S,Se)		
✓ Criddleite	$TlAg_2Au_3Sb_{10}S_{10}$		
✓ Penzhinite	$Ag,Cu)_4Au(S,Se)_4$		

2.2. Description of gold ore Mineralogy and Geochemistry: Implications for Processing and Significance

The identification of the minerals present in the ore is an important initial step in establishing a processing scheme for a new ore. Identifying the constituent minerals alone is frequently insufficient to lead a beneficiation process (Petruk, 2000). Even in simple ores, the amenability of a mineral assemblage to beneficiation is determined not only by the minerals' composition and abundance but also by their textures, size ranges, surface conditions, and modes of occurrence. Many fine-grained or complicated ores went unexploited for many years because they were not suited to the beneficiation technologies available at the time or because their mineralogical features were not fully recognized (Day, 2002).

Mineralogical characterization is an essential step in the design and implementation of metallurgical extraction techniques and mine planning generally. Valuation of a mineral deposit typically involves a generic study of the grade of the interesting elements present in a particular mineral deposit, but a more in-depth study of mineralogy can add value to the mining operation (Echeverry Vargas & Rojas Reyes, 2021) . In the context of gold mining, understanding how gold occurs, its granulometry, and mineralogical relationships is a key factor in minimizing losses due to insufficient recoveries, or in the recognition and design of processes, considering the presence of minerals detrimental to the various extraction (Echeverry Vargas & Rojas Reyes, 2021; Ogundare et al., 2014) .

Mineralogy, mineral associations, and gold ore have recently been recognized as essential components of any gold evaluation project (Goodall, 2008). As stated by Goodall (2008) several studies have shown that a better understanding of sample mineralogy, as well as information on gold ore, might improve the applicability of the results. In recent years, gold ore characterization has been extensively used in process formulation and optimization; consequently, characterization of gold in a deposit is critical, as it aids in determining extraction and processing (Echeverry Vargas & Rojas Reyes, 2021).

Based on processing, there are three separate gold types (Fig. 2.1): free milling, complex (double refractory), and refractory (in increasing order of processing difficulty) (Youlton et al., 2021); however, complex ores are included in refractory ores in various literatures.

Free milling ores: All ores that readily produce gold by cyanidation and have no variables that complicate or minimize extraction efficiency are considered free milling ores. Free-milling ores have a gold recovery of 90% or more (Marsden & House, 2006; Zhou et al., 2004; Zhou & Cabri, 2004).

Complex ores: are ores with high gold recoveries but only under modified or more intensive leaching conditions. Complex ores are classified as either preg-robbing or reactive (Youlton et al., 2021). In leaching, preg-robbing ores include material capable of absorbing gold-cyanide complexes. However, clays are assumed to have a limited potential for preg-robbing (Goodall et al., 2005; Miller et al., 2005; Vaughan, 2004). Preg-robbing is mostly carbonaceous (particularly elemental and organic carbon). Any ore that contains material that interacts with reagents necessary for efficient gold leaching is referred to as reactive ore. These reactive compounds are often cyanicides (they react with cyanide and decrease its available concentration) or oxygen consumers (Asamoah et al., 2014; Youlton et al., 2021). Pyrhotite, copper minerals (excluding chalcopyrite) such as chalcocite, malachite, azurite, and cuprite, as well as most base metal minerals including iron, arsenic, antimony, zinc, nickel, and cobalt are examples of these minerals (Aylmore & Muir, 2001; Karimi et al., 2010).

Refractory ores are deposits from which acceptable gold recoveries cannot be obtained using standard procedures, or deposits that yield low gold recoveries or yield appropriate gold recoveries only with the use of significantly more reagents or more complex pre-treatment processes (Youlton et al., 2021; Zhou et al., 2004). There are two types of refractory ores: those with physically and chemically locked gold, both of which render the gold unavailable to lixiviants. The proportion of gold recovered was used to classify the degree of refractoriness (table 2).

Table 2: Classification of refractory gold ores depending on degree of refractoriness (Asamoah et al., 2014; Suratman, 2017).

Classification of refractory gold ores	Recovery of gold
• Free milling	More than 95%
• Mildly refractory	80 - 95%
• Moderately refractory	50 - 80%
• Highly refractory	Less than 50%

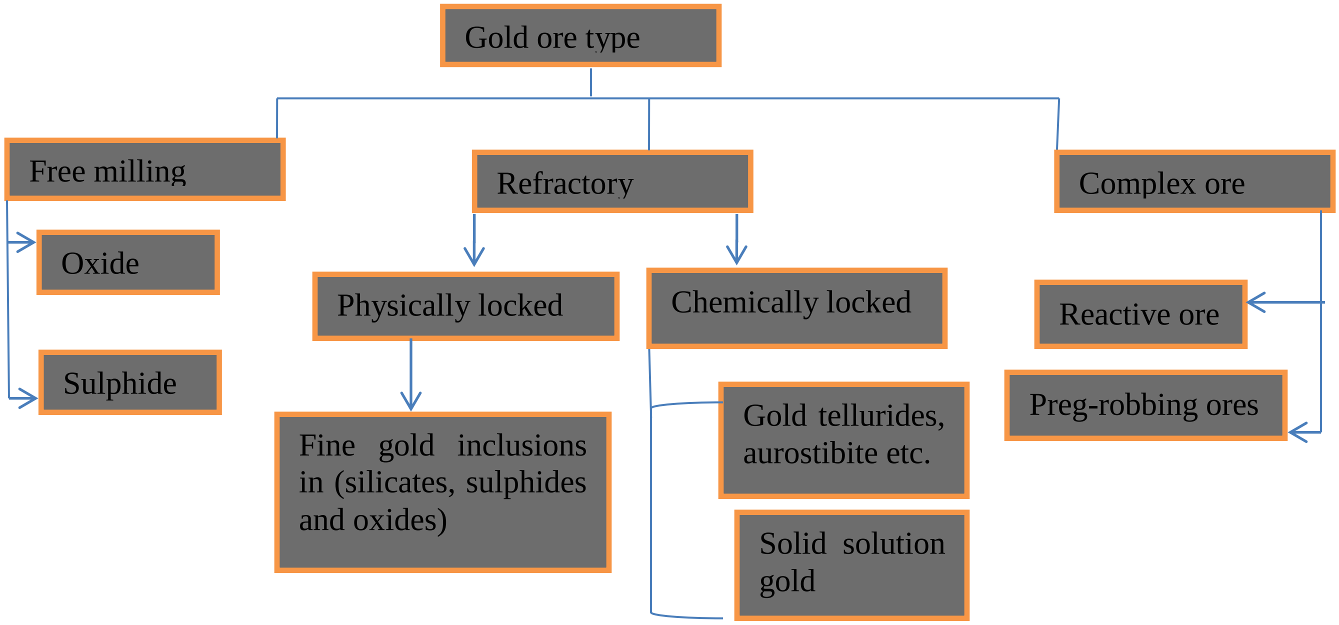


Figure 2.1: Gold ore classification depending on processing (La Brooy et al., 1994; Youlton et al., 2021)

Gold ores may be categorized into 12 categories based on mineralogical features and mineral processing processes required (Zhou, 2016; Zhou et al., 2004), as shown in table 3. In general, the first six gold-ore types in table 3 are more free-milling, whereas the last six ore types are more refractory, and the refractoriness rises from top to bottom. Because of the presence of carbonaceous materials and sub-microscopic gold, carbonaceous sulphide ores are considered the most challenging to process. To obtain adequate gold recoveries, this type of ore must be pre-treated before gold extraction.

Table 3: Classification of gold ore types. Adapted from (Zhou et al., 2004)

More refractory

1. Placers
2. Quartz vein-lode ores
3. Oxidized ores
4. Silver-rich ores
5. Copper sulfide ores
6. Iron oxide copper-gold ores
7. Iron sulfide ores
8. Arsenic sulfide ores
9. Antimony sulfide ores
10. Bismuth sulfide ores
11. Telluride ores
12. Carbonaceous sulfide ores

More free-milling

2.2.1. Common reasons of ore refractoriness

The refractoriness of gold ore changes with gold mineralization. These mineral associations develop as a result of gold mineral leaching, concentration, and deposition in the earth's crust (Asamoah et al., 2014). Refractory gold ores may also be categorized into the following categories based on gangue mineral association (Asamoah et al., 2014; Zhou & Cabri, 2004):

- Locked gold
  - Physically locked gold
  - Chemically locked gold
- Reactive gangue minerals
- Adsorption of gold

2.2.1.1. Physically Locked Gold

According to Asamoah et al (2014), gold in this group resides in the free state, occluded and/or dispersed, within the gangue minerals (silicates, sulphides, and oxides), as shown in **Fig. 2.2**.

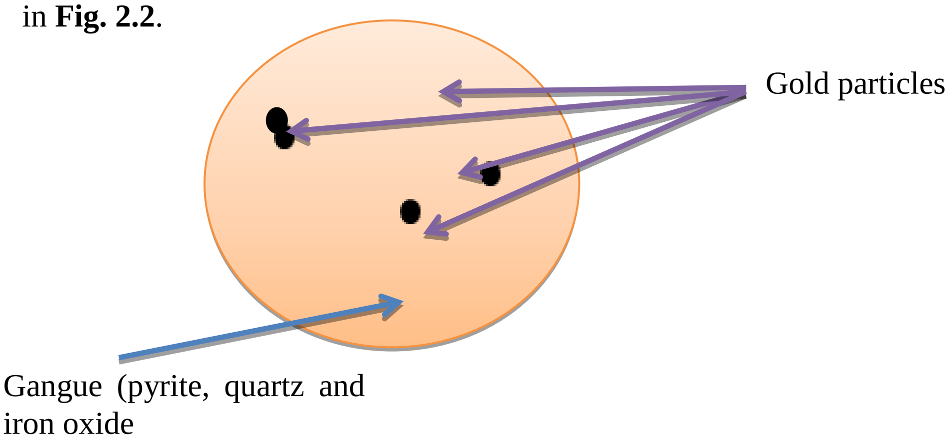


Figure 2.2: Diagram showing physically trapped gold in pyrite, quartz, and/or iron oxide (Asamoah et al., 2014).

2.2.1.2. Chemically locked gold

Gold tellurides, aurostibite, aurocupride, and maldonite are examples of chemically bound gold minerals (Vaughan, 2004). Chemically locked gold can also refer to gold that exists as a solid solution within specific minerals, implying that atomic gold exists within crystal lattices (Vaughan & Kyin, 2004). Solid solution gold may be found in arsenopyrite and, to a lesser extent, pyrite (Vaughan, 2004; Vaughan & Kyin, 2004).

2.2.1.3. Reactive gangue minerals

The recovery of gold in the cyanidation process is frequently accompanied by the leaching of additional species (sulphides and sulph-arsenides, primarily those of copper, silver, antimony, and arsenic) (Mlaki et al., 2013; Asamoah et al., 2014). These side reactions reduce the free cyanide and oxygen essential for gold extraction. According to studies, the stoichiometric quantity of free cyanide required for most gold recovery techniques is 1% of the total ingested (Petre et al., 2008). Both cyanide- and oxygen-consuming components are known as "cyanicides" (Karimi et al., 2010).

2.2.1.4. Adsorption of Gold

Carbonaceous compounds and other surface-active gangue minerals (e.g., clay, silicates, etc.) are ore components susceptible of gold adsorption. When aurocyanide (Au (CN)2-) is adsorbed by carbonaceous particles in the ore, it is referred to as "preg-robbing" (Dunne et al., 2012). Carbonaceous materials can be found throughout an ore body or in separate pods or veins within a deposit. Preg-robbing capability varies greatly across carbonaceous ores. Mild preg-robbing ores may be able to adsorb 1 g/t Au ore, whereas severe preg-robbing ores may be able to adsorb > 500 g/t Au ore (Dunne et al., 2012).

2.3. Characterizing the Textural Features of Gold Ores for Optimizing Gold Extraction

It is widely recognized in the mining sector that textural features may result in heterogeneity in mineral processing behavior. According to (Bonnici, 2012), the integration of mineralogical and textural parameters observed at different scales is critical in relating geological qualities to mineral processing behaviors.

Texture has traditionally been defined in process mineralogy by particle sizes and grain spatial distribution, and it is utilized as a parameter to determine a particular number of textural classes (Díaz et al., 2019). Textural classes can be defined using several characteristics such as mineral abundance, ore/mineral distribution, mineral form, mode of occurrence of the mineral of interest, or mineral relationships (Tungpalan et al., 2015).

"All textural parameters of the ore influence mineral processing, but mineral grain size and bonding between grains are the major variables determining mineral breaking and mineral liberation," according to Petruk (2000). Mineral grain size, specifically grain size distribution of sulphides and gangue minerals, as well as mineral association is expected to have the greatest influence on processing behavior.

The release of gold for metallurgical recovery is determined by gold particle sizes, gangue mineral identity, and gold textural interaction with gangue minerals. Gravitational methods can extract coarse-grained gold, but fine-grained gold can be partly released by fine grinding and recovered by flotation, cyanidation, and/or amalgamation (Hausen, 2000).

The following are the primary textures for gold in gold deposits (Petruk, 2000):

I. Gold may be found in fractures and microfractures in rocks, as well as veinlets and microveinlets in minerals.

II. Gold in interstitial spaces between mineral grains and at mineral grain boundaries, occurring:

  a) between grains of the same mineral and

  b) between grains of two or more distinct minerals

III. Gold encased in a host mineral (encapsulated gold)

2.3.1. Gold Sizes

According to Chryssoulis & McMullen (2016), gold particles are generally divided arbitrarily into five sizes: extremely fine, fine, medium, coarse, and very coarse (table 4). Within the same deposit, the gold grain size varies greatly in certain occurrences, ranging from very fine to coarse, and in others it is more uniform, falling within one or two size classes.

Table 4: Arbitrary categorization of gold grain sizes (Chryssoulis & McMullen, 2016).

Classification	Gold particle size range (μm)
Very fine	˜2-<0.1
Fine	˜20-2
Medium	˜200-20
Coarse	˜500-200
Very coarse	>500

2.3.2. Associated Gangue Minerals

An optical microscope and an x-ray diffractometer are often used to identify gangue minerals along with gold. Gold is associated with a wide range of common gangue and mineraloid phases, including quartz, chalcedony, opaline and jasper phases, carbonate and sulphate minerals, clays, carbonaceous and organic phases, sulphides, heavy minerals, ferruginous oxides, oxide copper, and other base-metal minerals (Hausen, 2000; Mlaki et al., 2013). Depending on the metallurgical process, such gangue stages frequently alter the physical and/or chemical recoveries of gold.

2.4. Gold Processing Techniques

In contrast to base metal ores, which are normally treated with froth flotation, gold ores are commonly treated using a variety of methods such as gravity separation, flotation, and cyanidation (Zhou, 2016). Pretreatment is required before leaching for refractory gold ores, in which gold typically resides as submicroscopic gold in sulphide minerals and is combined with carbonaceous elements in certain deposits, making gold ore processing more complex and ore characterization more important.

As stated earlier there are three main classification of gold ores based on their processing: free-milling, refractory, and complex (*Gold Extraction*, 2012).

Placers, quartz vein gold ores, oxidized ores, and silver-rich ores are often free-milling, and gold can be extracted using gravity and/or direct cyanide leaching. Some epithermal deposits are free-milling (such as the oxidized section), but the majority of them include considerable quantities of sulphides containing gold as micrometer-sized inclusions or submicroscopic gold and are therefore refractory (Zhou & Cabri, 2004).

The following unit operations are employed in gold recovery procedures (Bulatovic, 2010):

1. **The gravity pre-concentration method**: this is mostly used to extract gold from placer deposits containing coarse native gold. Gravity is frequently utilized in combination with flotation and/or cyanidation
2. **Hydrometallurgical methods:** are often used to extract gold from oxidized deposits (heap leach), low-grade sulphide ores (cyanidation, CIP, CIL), and refractory gold ores (biological decomposition followed by cyanidation).
3. A combination of **pyrometallurgical (roasting)** and **hydrometallurgical route** is used for highly refractory gold ores (carbonaceous sulphides, arsenical gold ores)

and ores having impurities that result in substantial cyanide consumption and must be removed prior to cyanidation.

4. **The flotation method** is a method frequently applied for gold recovery from gold-containing copper ores, base metal ores, copper nickel ores, platinum group ores, and many other ores when conventional techniques are ineffective. Flotation is also used to remove interfering impurities before hydrometallurgical treatment (i.e., carbon pre-float) and to upgrade low-sulphide and refractory ores for further processing. Flotation is said to be the most cost-effective method of gold concentration.

In other cases, gold amalgamation is used in addition to those methods. They are briefly addressed below:

2.4.1. Gravity Concentration

Gravity concentration is the earliest gold recovery technique (Adams, 2005; Bath et al., 2013). Gravity concentration is commonly employed to extract free gold as well as gold coupled with heavier minerals, such as numerous sulphide and titanium minerals. Depending on their mineralogy, the resulting concentrates may be processed by direct cyanidation, smelting, amalgamation, flotation, or extensive cyanide leaching (Fig. 2.4).

Gravity separation equipment often used includes a shaking table, spiral chute, and jigging concentrator. Gravity separation equipment's performance is highly connected to the size and shape characterizations of gold particles (McGrath et al., 2015). Gold particles with finer grain sizes are more difficult to recover (Wang et al., 2019).

2.4.2. Hydrometallurgy

The leaching of a desired metal into a solution, followed by the concentration and purification of the solution, and ultimately the recovery of the metal or its compounds, are all hydrometallurgical processes (Medina & Anderson, 2020). Because of its cheap operating costs, simplicity of usage, and environmentally friendly gold recovery techniques, hydrometallurgy is a popular way of processing gold and other noble and nonferrous metals (Faraji et al., 2021; Fedotov et al., 2022). One of the most notable instances of early hydrometallurgy-based operations was the leaching of gold and silver ore.

The most popular method for extracting gold from low-grade ore is cyanidation, which involves converting the gold to a water-soluble coordination complex (Petruk, 2000). It is the most often used gold extraction leaching procedure (*Gold Cyanidation - Wikipedia*, n.d.). Only native gold, electrum, and auricupride are readily cyanidable gold minerals, as shown in Table 5 (Adams, 2005; Chryssoulis & McMullen, 2016). Under conventional leaching circumstances, Sylvanite [$AuAgTe_4$], calaverite [$AuTe_2$], and maldonite [Au_2Bi] are refractory to direct cyanidation, needing additional modified conditions to release all or part of their gold content (Chryssoulis & McMullen, 2016).

Table 5: Response of the most prevalent gold mineral to direct cyanidation (Adams, 2005; Chryssoulis & McMullen, 2016)

Gold minerals	Rate	Dissolution (%)
✓ Native gold [$Au_{>}0.8\ Ag_{<}0.2$]	Fastest	100
✓ Electrum [$Au_{<}0.8\ Ag_{>}0.2$]	Fast	100
✓ Aurocupride [AuCu]	Fast	100
✓ Sylvanite	Slow	100
✓ Calaverite [$AuTe_2$]	Slow	480
✓ Maldonite [Au_2Bi]	Slow	0–20
✓ Aurostibite [$AuSb_2$]	0	0
✓ Auroantimonate [$AuSbO_3$]	0	0

2.4.3. Flotation

The extraction of gold by flotation process is based on the difference in physical and chemical features of the ore surface and is processed by flotation reagents to make the valuable mineral stick to the bubble in order to achieve gold extraction (*Extraction of Gold by Flotation Process*, 2019).

Flotation is typically used to extract gold from sulphide-mineral gold-bearing ores such as porphyry copper, base metal, and copper-gold ores (Petruk, 2000). The gold is typically extracted from the copper concentrate by smelting and electrolysis. Gold floats easily in sulphide flotation cells, especially copper flotation cells. As a result, all of the released gold, as well as a large portion of the unliberated but exposed gold, is recovered in copper concentrates.

Collectors increase gold's inherent floatability. Collectors used in the gold industry (for example, xanthate) create a concentrate comprising free gold as well as high quantities of sulphide minerals related to the gold (Forrest, 2001). The broad flotation principle is depicted in **Fig. 2.3.**

Flotation is also the most effective method for recovering gold from base metal ores and PGM ores containing gold (Bulatovic, 2010). Flotation is the most cost-effective beneficiation process, excluding gravity preconcentration.

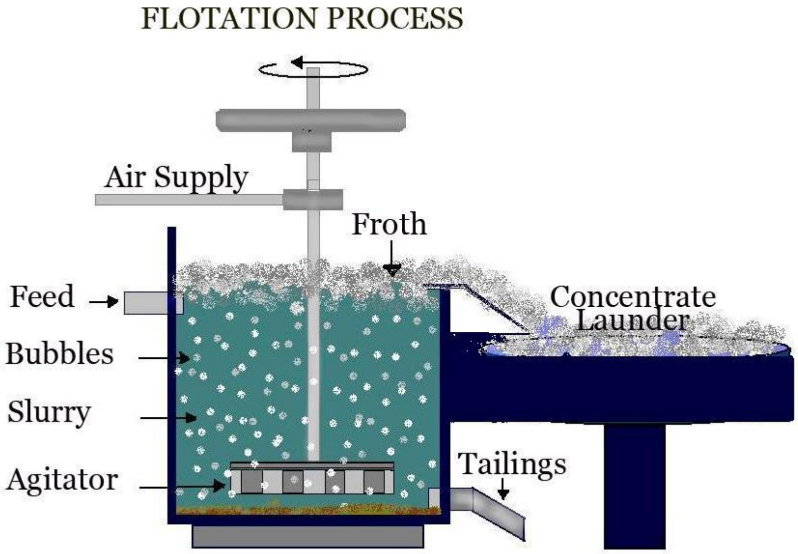


Figure 2.3: Flotation in Mining. Image credit from miningeducation.blogspot.com

The flotation method has the advantage of liberating gold values at a relatively coarse particle size (28 mesh), which implies that ore processing costs are reduced (Eugene & Mujumdar, 2009). Because the chemicals used for flotation are usually non-toxic, tailings disposal costs are low.

2.4.4. Amalgamation

This gold extraction process from ore is appropriate for treating primary quartz vein deposits as well as oxidized ores containing coarse gold. The amalgamation process of gold extraction from ore is an ancient and widespread gold extraction method (Shirley, 2022). When mercury comes into contact with gold particles in sediments or crushed ore, it creates amalgam, a soft combination of around 50% mercury and 50% gold. Heat is used to evaporate the mercury from the amalgam, leaving the gold behind (Eugene & Mujumdar, 2009). Several parts of this process release mercury into the air, water, and soil.

According to Eugene & Mujumdar (2009), this approach is used for the treatment of coarser gold (30 microns in diameter or higher). Due to the extremely toxic nature of mercury and the process's inferior performance when compared to available alternatives, it has fallen out of favour with major mining companies; however, the process is still widely used by artesian mines in third-world countries and at small mines due to its simplicity (Adams, 2005).

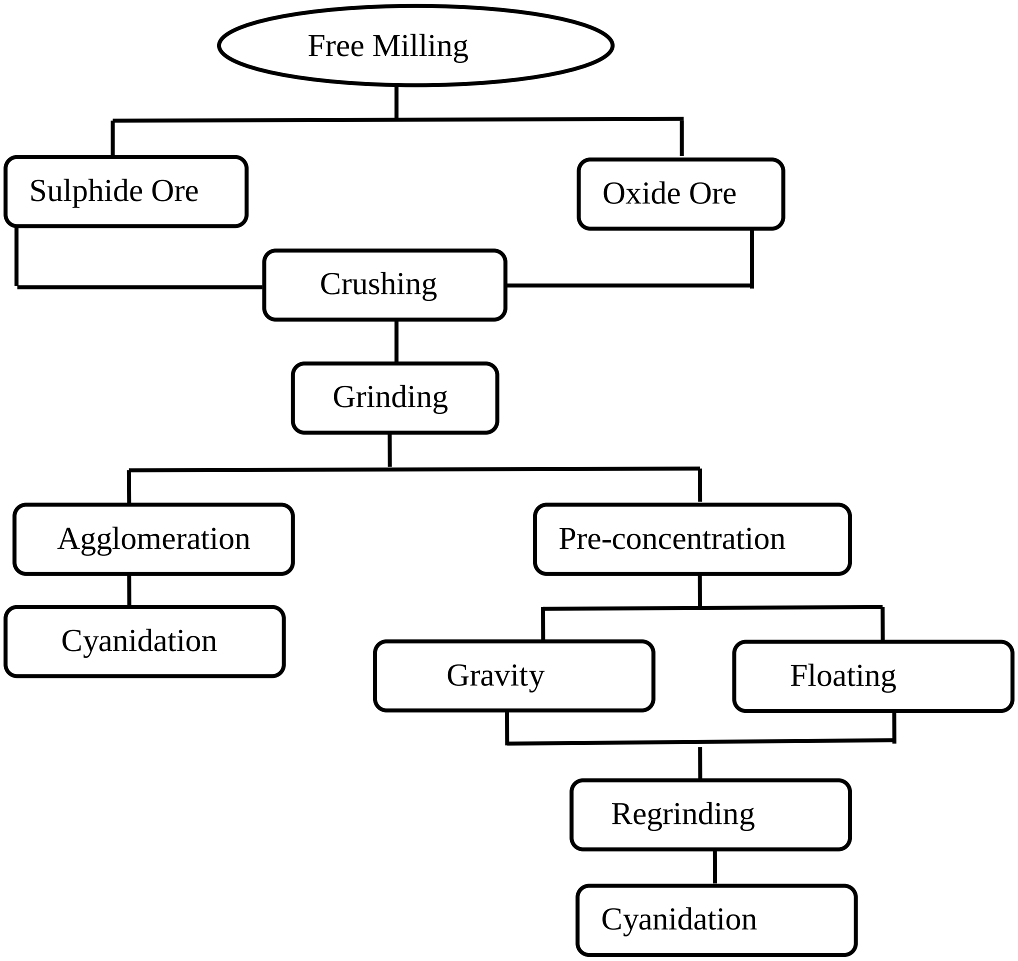


Figure 2.4: A typical free-milling gold-bearing ore processing (Ilyas & Lee, 2018)

2.5. Pretreatment Methods for Refractory and Complex (Double Refractory) Ore

Thermal treatment (roasting), pressure oxidation, bio-oxidation, physical treatment, and chemical treatment are the most frequent pretreatment methods in refractory gold ore **(Fig. 2.5**). Other than chemical treatment, the following approaches are described:

2.5.1. **Roasting**

The most frequent oxidative method, roasting, involves heating ores or concentrates below their fusion point when in contact with air, oxygen, water vapor, carbon, sulphur, or chlorine (Zhang et al., 2010). Roasting has been used for almost a century to oxidize refractory sulphide, arsenical, carbonaceous, and telluride ores and concentrates, according to (Marsden & House, 2006). It has shown excellent use across a wide spectrum of materials with varying sulphur content and other mineralogical features.

Certainly! However, it is worth noting that the roasting process does have a drawback. It generates substantial amounts of gas emissions containing harmful pollutants such as sulphur dioxide and arsenic trioxide. In order to meet environmental regulations, it is essential to eliminate these emissions before they are released into the atmosphere (Petruk, 2000). As environmental regulations become increasingly stringent, the expenses tied to gas treatment procedures for roasting have significantly risen. Consequently, it is expected that this trend will persist, potentially leading to a decline in the utilization of roasting as a method for processing gold ores and concentrates. This decline can be attributed to the escalating costs associated with adhering to the regulations.

2.5.2. Pressure Oxidation

Pressure oxidation is a viable method for treating refractory sulfide and arsenic ores and concentrates. However, it is generally not suitable for handling carbonaceous materials unless additional measures are taken to reduce their ability to adsorb gold, such as using carbon-in-leach (CIL) or chlorination techniques (Ng et al., 2020). Despite having a relatively high initial investment and operational expenses, the process is effective in rapidly oxidizing the majority of sulfide and arsenic minerals in the input material, typically exceeding 90%. From an environmental perspective, the process is favorable due to its minimal generation of harmful gases, and any arsenic present in the feed can be precipitated as a relatively stable solid compound known as Fe (III) arsenate.

Pressure oxidation is a method of hydrometallurgy that is considered to have better environmental acceptability compared to pyrometallurgical processes like roasting. However, roasting is still utilized in cases where carbonaceous ores are present because pressure oxidation does not eliminate active carbon in the same way that roasting does (Chryssoulis & Cabri, 2013).

2.5.3. Bio-oxidation

Bio-oxidation is a more promising approach for pre-treating gold telluride. It serves as an alternative to roasting for refractory gold concentrates and offers the advantage of eliminating the release of toxic gaseous emissions (Zhang et al., 2010). Method harnesses the natural action of acidophilic chemo lithotrophic bacteria to expedite the oxidation of sulfides, including pyrite and arsenopyrite, thereby liberating the gold or gold telluride that is trapped within their particles (Zhang et al., 2010) It has also been successfully employed in the treatment of arsenic flotation concentrates.

2.5.4. Chlorination

Chlorination is a technique employed to make gold-adsorbing carbonaceous ore constituents inactive before cyanide leaching. These constituents, often referred to as preg-robbing, can be effectively treated using this method. Additionally, chlorination has been utilized for the oxidative leaching of telluride ores. However, it is generally unsuitable for materials with high sulphur content, typically exceeding approximately 0.5% S to 1.0% S, due to the consequent high consumption of chlorine (Ng et al., 2020).

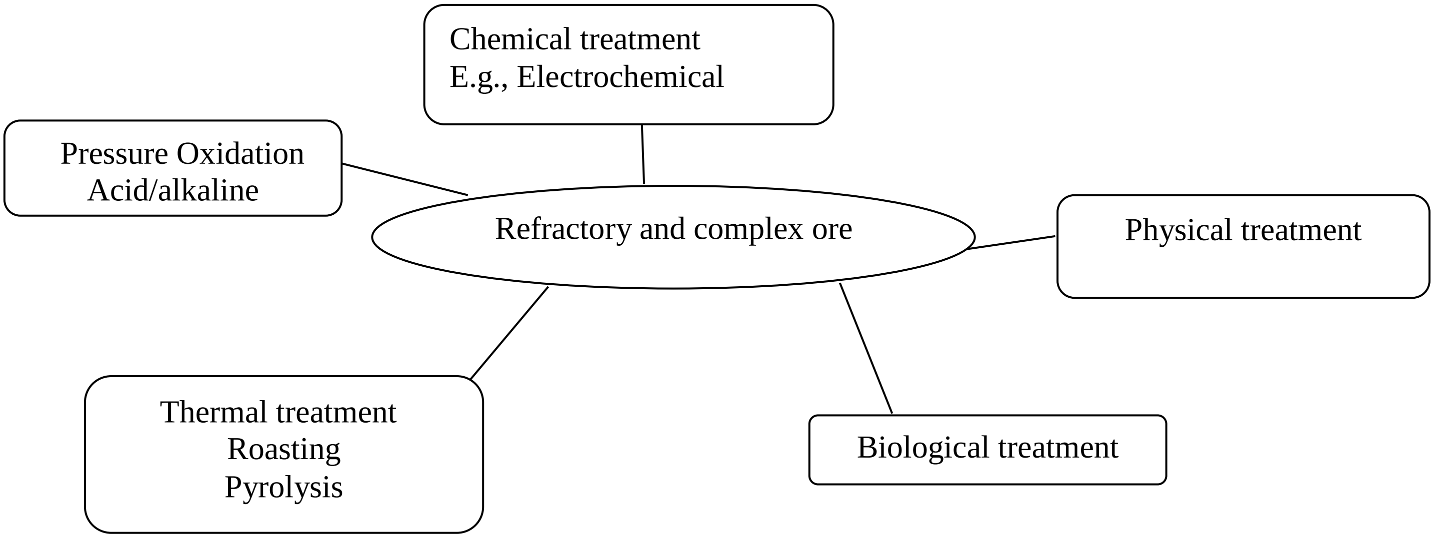


Figure 2.5: Possible pre-treatment procedures for processing the refractory and or complex gold ores for achieving an efficient recovery of gold in leaching operation (Ilyas & Lee, 2018).

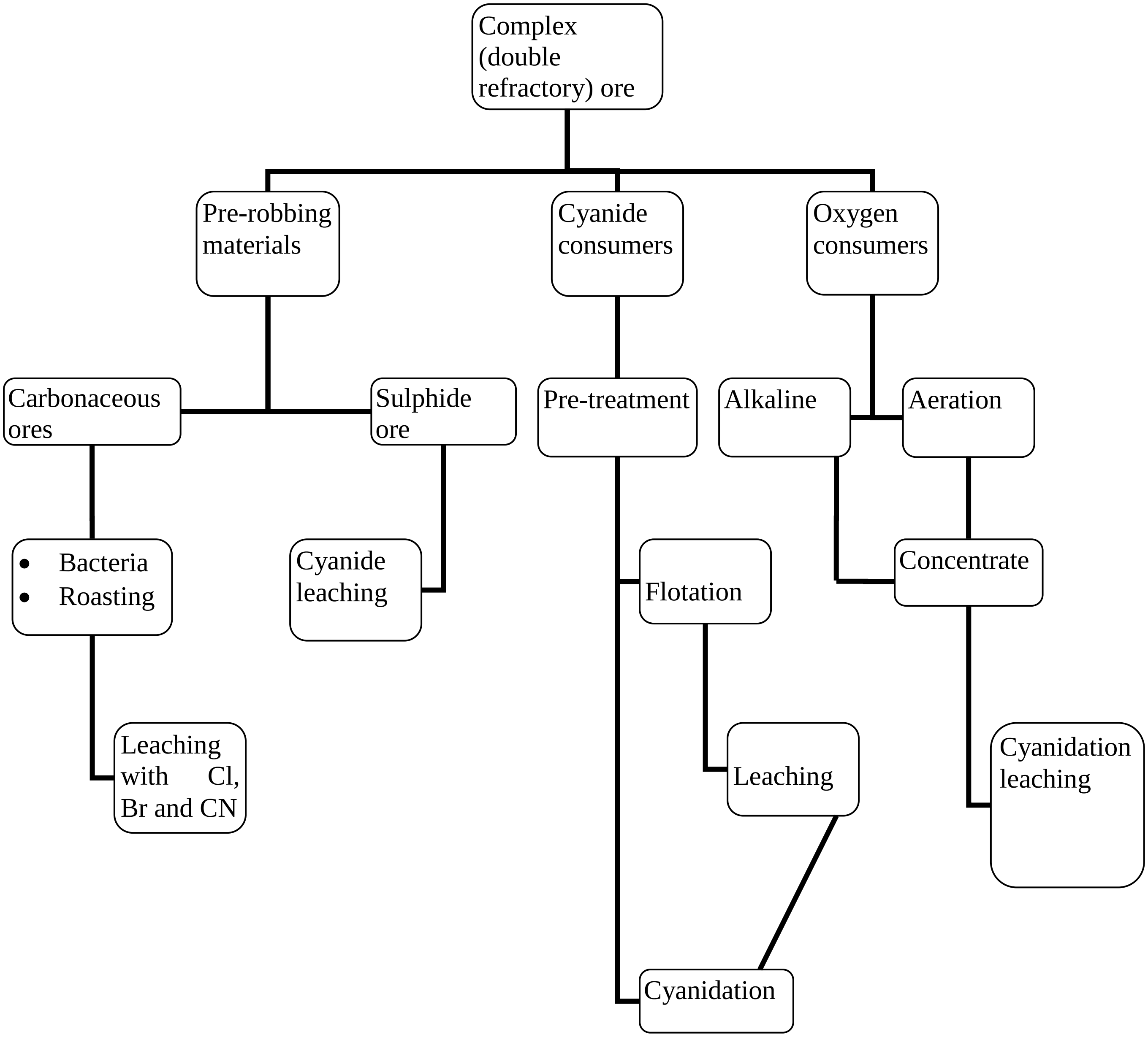


Figure 2.6: Complex (double refractory) gold containing ores are classified by processing (Ilyas & Lee, 2018).

2.6. Regional Geology

The metavolcano-sedimentary rock sequence uncovered in Akobo represents an extension of Ethiopia's Southern Western Greenstone Belt, which forms part of the larger Arabian Nubian Shield (ANS) (**Fig. 2.7)**.

Orogenic gold and gold-bearing VMS are the most abundant gold-deposit types in the Arabian Nubian Shield (Johnson et al., 2017). According to Johnson et al (2017) orogenic-gold occurrences within the Nubian Shield are extensive in their distribution. These occurrences are characterized by the presence of native gold or gold-sulfide-telluride assemblages disseminated within silicified, brittle-ductile shear zones. The ore mineralogy comprises pyrite ± arsenopyrite ± chalcopyrite ± sphalerite ± tellurides, embedded in a matrix of quartz ± carbonate. The hosting shear zones are attributed to the period of strike-slip shearing, and shortening that characterized the late Cryogenian-Ediacaran epoch. This geological phase encompassed tectonic escape, extension, and orogenic collapse within the shield. These shear zones and quartz veins are found within granitoid plutons, as well as in adjacent regions of sheared and highly altered volcano-sedimentary and/or ultramafic rocks. In the northern reaches of the Nubian Shield, the predominant shear structures align with the northwest-trending Najd fault system. As we move further south, they encompass the north-trending Hamisana and Oko shortening zones, along with the Keraf suture (Zoheir et al., 2019). In Eritrea and Ethiopia, they feature north-trending sinistral and dextral shear zones occurring within, and at the margins of, greenstone belts.

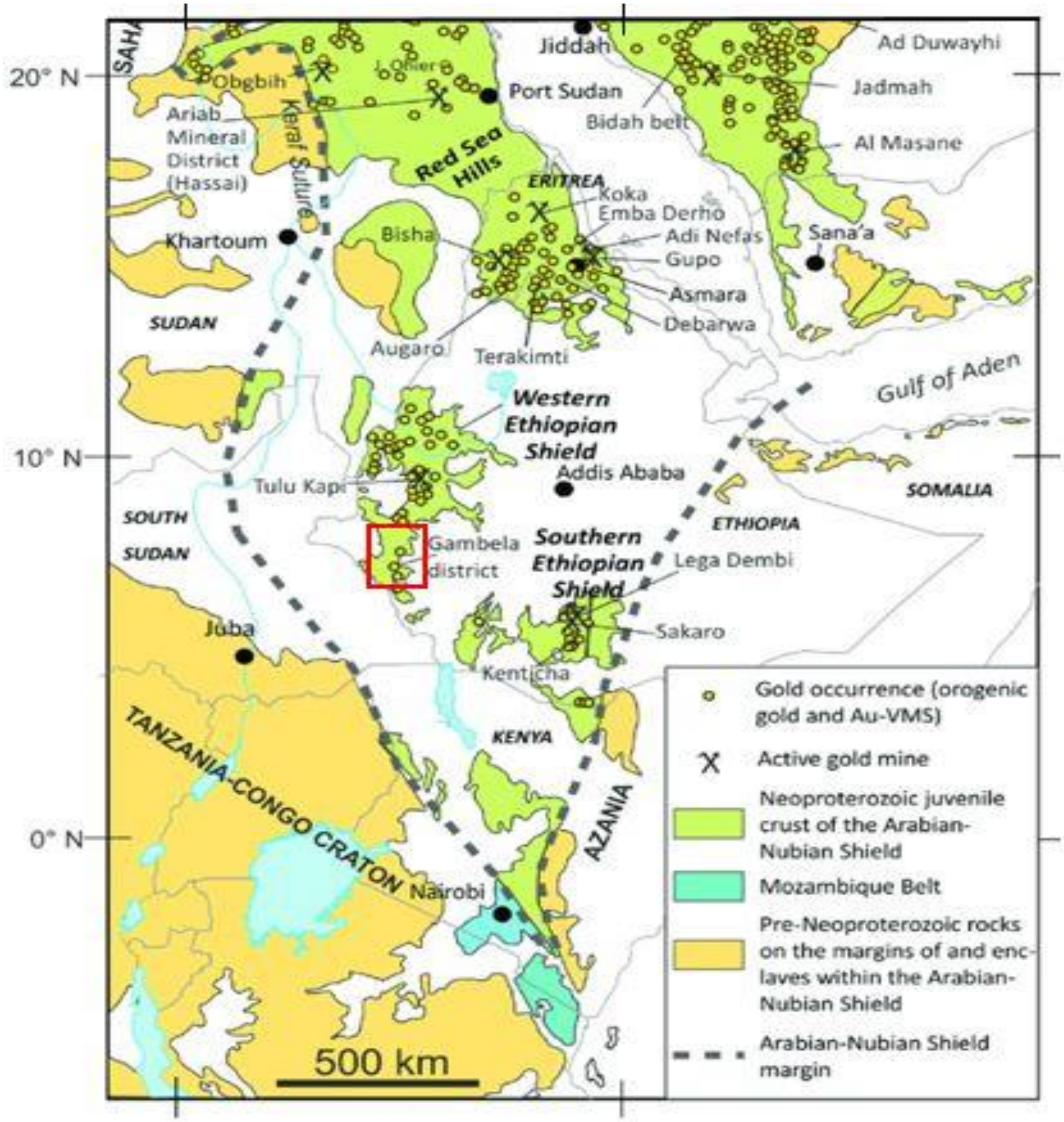


Figure 2.7: Distribution of gold occurrences plotted on a simplified map of the Arabian-Nubian Shield (modified after, Zoheir et al., 2019).

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1. Materials

The primary materials being examined in this study are rock samples, including chip samples and borehole samples, as well as gold ore samples. A total of 26 samples, amounting to approximately 48 kg in weight, were collected from the study area. The size of the samples was adjusted based on the specific analytical methods and cost considerations required for analysis. The samples were obtained from various sources, including 13 boreholes, 8 pits, 4 trenches, and 1 outcrop. It is worth noting that only one chip sample was taken from the outcrop, which exhibited magnetite mineralization.

Various field equipment and tools were utilized for sampling, collecting, labeling, analyzing, and processing the data obtained in this study. These include:

- *Geological field kits*: These kits consist of essential tools such as GPS devices, geological hammers, hand lenses, sample bags, notebooks, and markers.
- *Geological and Geochemical software*: A range of software applications were employed, including ArcGIS 10.8 for spatial analysis and mapping, Match XRD for X-ray diffraction analysis, Grapher for graphing and visualization, Google Earth Pro for satellite imagery and geospatial data, Surfer for contouring and surface mapping, Global Mapper for geospatial data management, and SPSS for statistical analysis.
- ICP-AES/MS analytical instrument for determining the elemental composition of various samples (whole rock geochemistry), including gold analysis and REE.
- X-Ray Diffraction for identifying the mineralogical composition.
- *Optical Microscope*: optical microscope was used for the microscopic examination of samples.

- *Digital camera*: A digital camera was employed to capture high-resolution images of the samples, providing visual documentation for further analysis and reference.

3.2. Methodology

In order to accomplish the objectives outlined above, a comprehensive approach will be undertaken, combining field-based observations with analytical laboratory techniques. The geological methodology will involve a thorough description of the deposit, along with the collection of representative samples from both mineralized and unmineralized rock formations for subsequent analysis.

Various analytical methods will be employed to characterize the gold deposits in terms of their mineralogy, texture, and geochemistry. These methods include the use of an optical microscope for detailed examination of sample features, X-ray diffraction to identify mineral phases, ICP-MS/AES for elemental analysis, and a scanning electron microscope (SEM) for high-resolution imaging and further mineralogical characterization.

3.2.1. Geological Method.

This method played a crucial role in conducting an in-depth description of the gold mineralization in the area. The geological approach involved a comprehensive assessment of the deposit, as well as the collection of representative samples from both mineralized and unmineralized rock formations for subsequent analysis.

Over a period of approximately two weeks, a total of 26 samples were precisely gathered. These samples were obtained from various sources, including 13 samples from drill cores, 8 samples from pits, 4 samples from trenches, and 1 chip sample extracted from an outcrop. The mineralization styles observed in the area are closely associated with shear zones, as the deposit falls within the category of orogenic gold deposits located in the western greenstone belts of Ethiopia.

The altered ultramafic rock serves as the host rock for the gold mineralization, which is influenced by shear movements in a northwest-southeast direction. These movements have resulted in the formation of localized zones oriented in an east-west direction, creating favorable conditions for the deposition of gold in narrow zones and characterized by intense shearing. These geological features affecting the mafic-ultramafic body were observed during the fieldwork activities.

Additionally, the collected samples were appropriately labeled to ensure ease of identification during subsequent analysis. This labeling process facilitates efficient handling and tracking of the samples throughout the analytical procedures.

3.2.2. Analytical Methods.

By this method those collected samples are analyzed using different analytical laboratory. The different analytical methods to be used are Optical Microscope, X-Ray Diffraction (XRD), inductively coupled plasma atomic emission spectroscopy (ICP-AES/MS) and Scanning Electron Microscope (SEM). Overall description of those methods is as the follows: -

3.2.2.1. Optical Microscope analysis

For mineralogical characterization of the ores/rocks, optical microscopy is an invaluable tool (Cornelis & Anthony, 2013). For this, polished sections of ores are prepared. The minerals are identified basically from their optical properties. From the collected samples during the field work, 11 core and pit samples indicating mineralization were selected for polished section preparation and they were sent to the Ethiopian Geological Survey Central Laboratory. After preparation of the polished section, the detailed description of these polished sections was carried out using reflected light Microscope School of Earth sciences, Addis Ababa University.

Sometimes it becomes difficult to identify all the minerals using only the optical microscope because there are cases where the optical properties of one mineral very closely resemble another. In such cases the help of advanced characterization techniques such as X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM).

3.2.2.2. X-ray diffraction and ICP-AES/MS

XRD is used for the identification of the mineralogy of samples from various parts of an ore body or mineral process stream. It can identify which minerals are present and in what amount (Bunaciu et al 2015). Inductively coupled plasma-atomic emission spectrometry/mass spectrometry (ICP-AES/MS) is a potentially powerful tool in chemical phase analysis of gold in batch mode, especially applicable to the low-grade gold ores with gold content of far below detection limit of the other methods, but it has not been used in gold phase analysis of gold ores (Zhao Liang-Cheng et al, 2018).

For this purpose, six samples are selected for XRD analysis; the sample preparation is done in Ethiopian Geological Institute. About 8kg of samples are entirely crushed and those grain size less than 75µm sent to ASTU for XRD and the result is described. And 12 samples are prepared for whole rock chemistry (major and trace element as well as base metal analysis) and gold by ICP-AES/MS in ALS Ireland laboratory. The sample preparation is done in Addis Ababa at ALS. The samples were crushed to 70% less than 2mm, riffled to split off 1kg and the splits were pulverized to 75 microns. The pulverized samples were shipped to ALS Services, whole rock analysis using ME-MS81d, a code given by ALS services PLC to represent combination of ICP-MS and ICP-AES. The ten samples all underwent both ICP-MS and ICP-AES analyses.

3.2.2.3. Scanning Electron Microscope (SEM)

The scanning electron microscope (SEM) and the Electron microprobe analyzer are devices that use a focused beam of high energy electrons to produce a variety of signals at the surface of the solid specimens (Weilie Zhou et al 2007). The signals derived from electron-sample interaction reveal information about the sample including external morphology (texture), chemical composition, and crystal structure and orientation of the materials making up the sample.

About 8 samples are selected and analyzed for this purpose. The samples were crushed and pulverized to 60 microns and sent to ASTU laboratory.

3.3. Phase of the Methods Conducted

Those methods can be done at three different stages. Those are preliminary activities (desk work), the field-work activities and the post-field activities.

a) Preliminary (desk work)

In desk work the following activities were conducted:

- ✓ Collection and revision of previous data that related to the proposed project. These data include published, unpublished articles, reports, journals from Advisors, senior students and institutions like Ethiopian Geological Institute, and ETNO Mining companies.
- ✓ Analytical methods and instruments, accessibility and security were determined.
- ✓ Topographic map preparation

b) Field Work

The following major activities conducted during the field work for two weeks were:

- ➢ Geological observations on mineralization style
- ➢ Proper sampling of rock, labeling and sectioning rock samples for petrographic & geochemical analysis
- ➢ Collection of 26 core and pit samples for mineralogy and geochemical characterization

c) Post Filed Work

The main activities that performed after accomplishing the field work are the following:

i) Analyzing Mineralogical data including petrographic data:

The selected and collected representative core samples from the selected bore holes was sent to laboratory for the preparation of 12 polished thin section in Geological Institute of Ethiopia and 6 samples for XRD analysis in Adama Science and Technology University (ASTU). In addition, 8 samples were sent for Scanning Electron Microscope to ASTU.

- The prepared polished sections were analyzed using reflected petrographic microscope
- Texture of the ores was described from polished section and SEM
- Gangue minerals is identified and their association with gold
- Determination of the composition of gold ore is conducted by analyzing data from XRD and ore petrography

ii) Geochemical data analysis

✓ About 12 representative samples from both the host rock and mineralized samples of bore hole samples was sent to ALS for geochemical analysis means that whole rock analysis in addition to gold analysis by ICP-AES.

iii) Documentation, Interpretation and presentation:

- Compiling and processing of the data’s obtained from field work
- Interpreting the result obtained and concluding the research
- Final thesis document written
- Preparing for presentation of the thesis

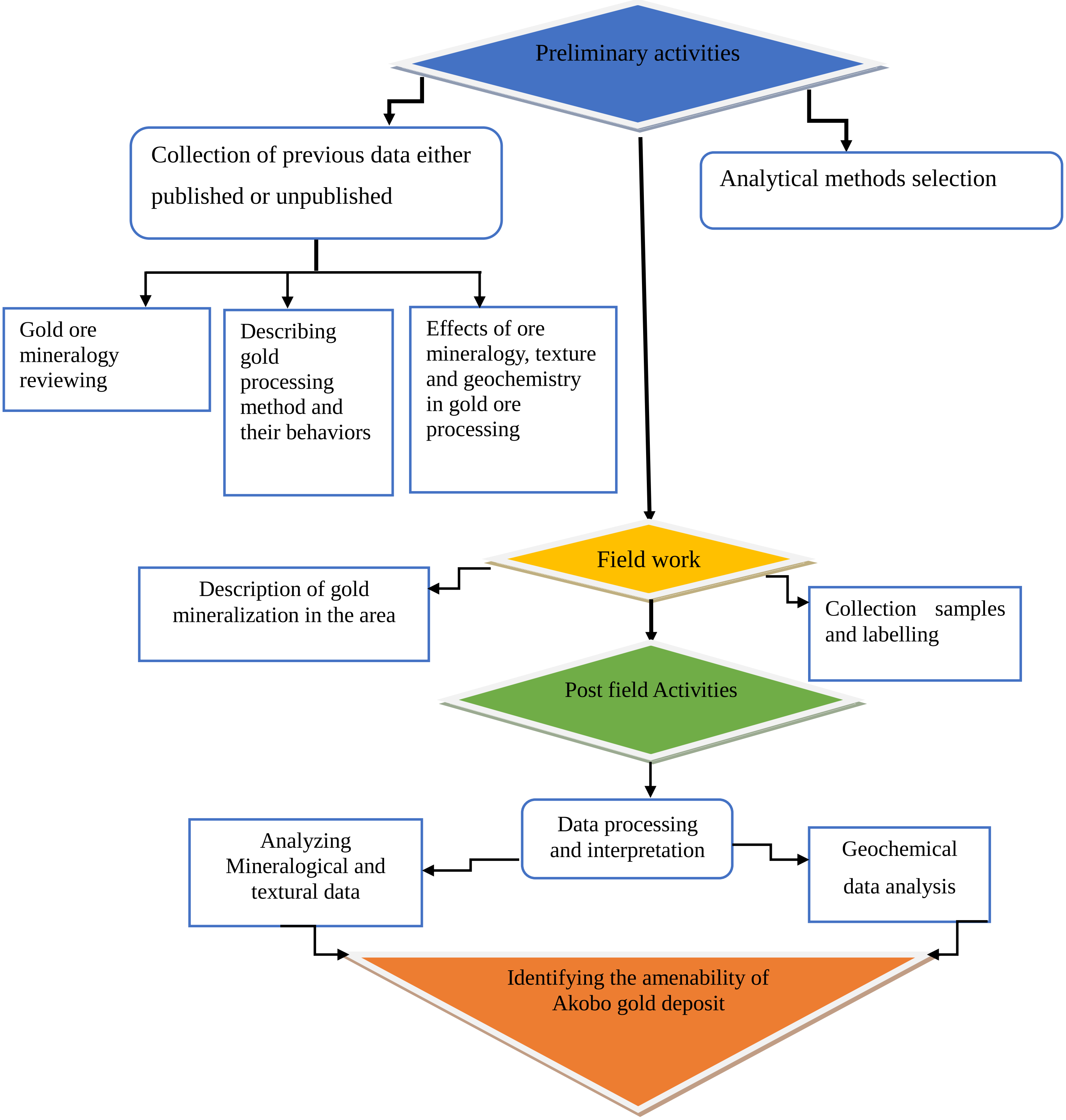


Figure 3.1: Flow chart to show the generalized methodology

CHAPTER FOUR

RESULT

4.1. Mineralization

a) Host rock

The Akobo deposit is characterized by a range of metavolcanics host rocks and alteration processes. These features contribute to the complexity of the rock sequences and mineralized zones. The host rocks are the following:

- **Metagabbro**: The Akobo gold deposit is hosted by metagabbro, a metamorphic rock composed mainly of gabbro minerals, such as plagioclase feldspar, pyroxene, and amphibole. Metagabbro serves as the primary host rock for the gold mineralization within the deposit.
- **Chloritic Schist with Coarse Magnetite Crystals**: The deposit also contains a chloritic schist unit that exhibits coarse grain magnetite crystals. Schist is a foliated metamorphic rock characterized by the presence of minerals aligned in thin layers. The chlorite and coarse magnetite crystals within the schist indicate hydrothermal alteration processes. The occurrence of magnetite suggests the involvement of iron-rich fluids in the mineralization process.

- **Fine-Grained, Magnetite-Bearing Carbonate-Talc Unit with Minor Mafic and Felsic Dykes**: Another unit observed in the deposit is a fine-grained, magnetite-bearing carbonate-talc unit that also contains minor mafic and felsic dyke.

b) Alteration Processes in Akobo gold deposit:

Talc Alteration: Talc alteration is a prevalent process observed in the Akobo gold deposit. Talc, a hydrated magnesium silicate mineral, forms through the alteration of other minerals.

Carbonatization: Carbonatization refers to the introduction and replacement of minerals with carbonates. This alteration is associated with the gold-bearing, altered zone. Additionally, it may result from the interaction of hydrothermal fluids with the host rocks. Carbonate minerals provide sites for gold precipitation and can serve as indicators of potential mineralization.

Silicification/Minor Quartz Veinlets: Silicification involves the introduction of silica (SiO_2) into rocks, which can result in the formation of quartz veinlets or the replacement of existing minerals with silica. In the Akobo deposit, minor quartz veinlets are observed, indicating the presence of silica-rich fluids during the mineralization process. Silica can act as a trapping mechanism for gold, contributing to the formation of gold-bearing quartz veins.

These processes are predominantly associated with the gold-bearing, altered zone and are interpreted as ore proximal alteration. Gold mineralization is primarily associated with the carbonate-talc-magnetite zone, suggesting that this specific lithological unit provides favorable conditions for gold deposition.

Structurally, the area has experienced multistage ductile-brittle deformation episodes. The multistage nature of the deformation further complicates the rock sequences and mineralized zones, creating a complex structural framework for the distribution of mineralization.

The section log of the Borehole 113 indicates the gold mineralization. Gold mineralization is around 30-50 meters in the borehole whereas in pits it starts from 8m in pit one and round 13m in the second pit **(Fig. 4.2).**

Figure 4.1: Visible gold (Au) in meta-gabbro (a) and talc-carbonate-schist

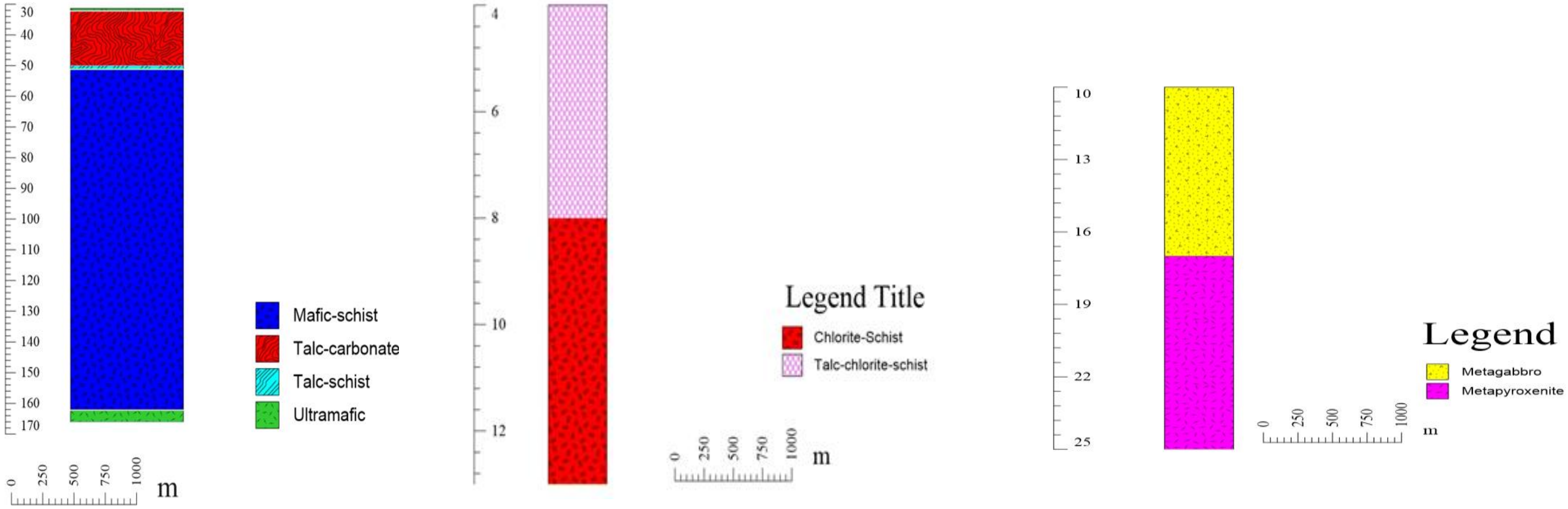


Figure 4.2: log section of borehole 113 (a), pit one (b) and pit two (c) with gold mineralization zone

4.2. Ore petrography

About 11 polished sections were prepared and observed in Addis Ababa University department of earth sciences economic geology laboratory. From the polished section analysis, it is possible to observe fine grain gold mineral which in some case disseminated in gangue mineral may be silicate like actinolite, tremolite, chlorite and quartz **(Fig. 4.3).** The mineral identified under the microscopes are gold, magnetite, arsenopyrite and pyrite. The gold grain is identified under the magnification of 200X and it is difficult to observe the optical properties of gold as it is very fine; it is identified by its very high reflectance as in **Fig. 4.3** & **4.4.**

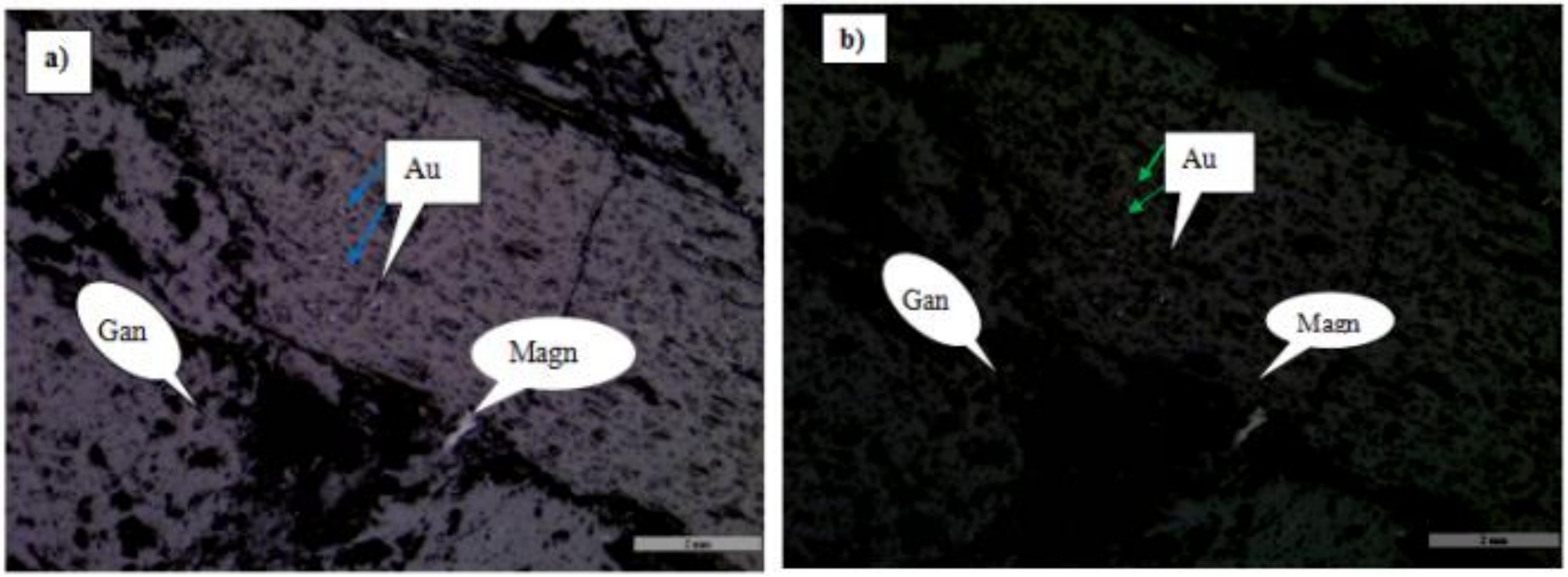


Figure 4.3: Photomicrograph showing ore minerals (gold-Au which is somewhat bright and magnetite-Magn elongated light grey) and gangue (black and grey) in PPL (a) and XPL (b) respectively in AKPO-03 sample.

Very fine grain gold distributed in the gangue mineral with no clear optical properties of gold are also identified by their higher brightness with the grain of magnetite on the other view of the same sample (AKPO-03) in Fig 4.3 & 4.4).

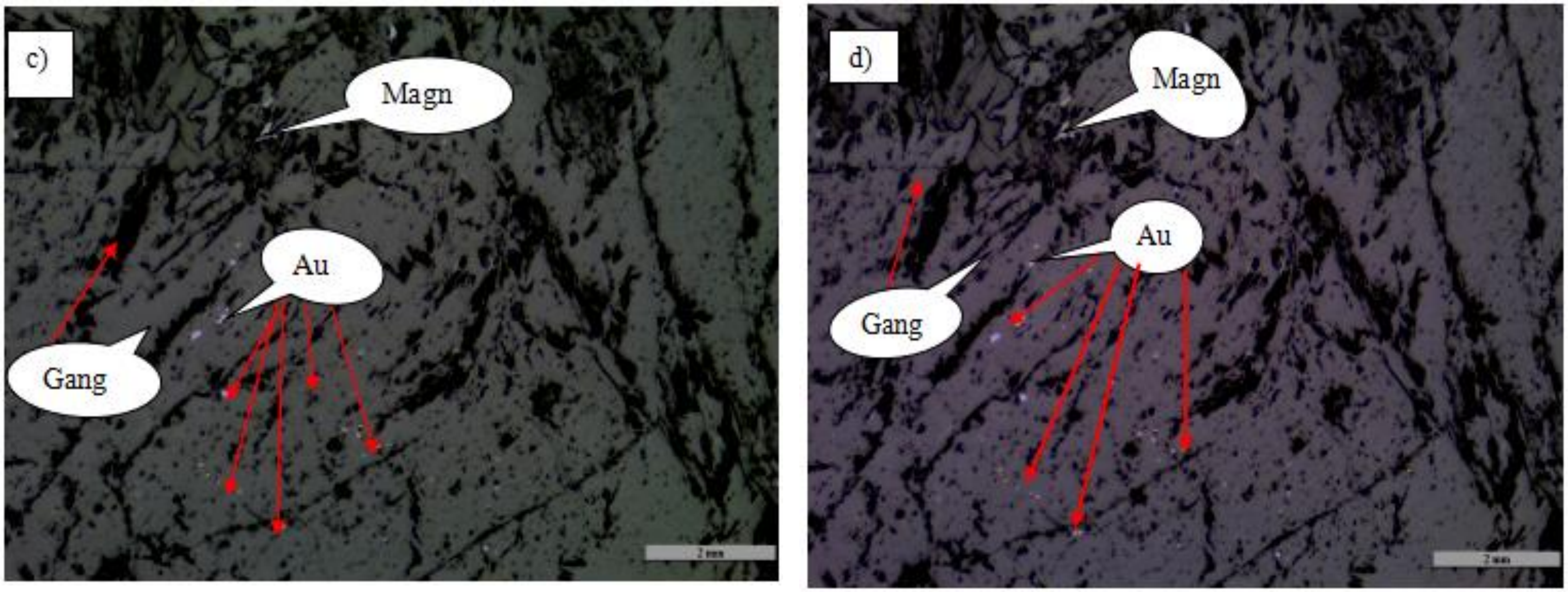


Figure 4.4: Photomicrographs showing disseminated gold grain in gangues and grains of magnetite with low reflectance on the upper parts of the picture in PPL (c) and XPL (d) respectively. (Where Au- is gold, Magn- is magnetite, Gang- is gangue).

Akobo gold deposit is also associated with arsenopyrite brighter one in which some inclusion present found inside and pyrite in addition to magnetite (**Fig.4.5 & 4.6)**

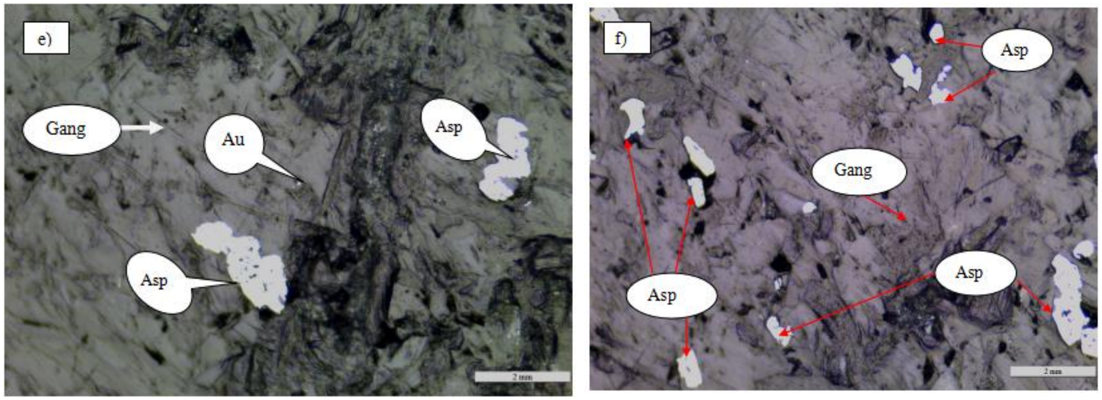


Figure 4.5: Photomicrographs showing bright gold grain in the gangue mineral with anhedral arsenopyrite with gangue inside it under XPL (e) and subhedral to euhedral arsenopyrite grain with moderate to high reflectance in the sample AKPN-05 under PPL (f). The sample is AKPN-04. (Where Asp-Arsenopyrite, Gang-gangue, Au-gold).

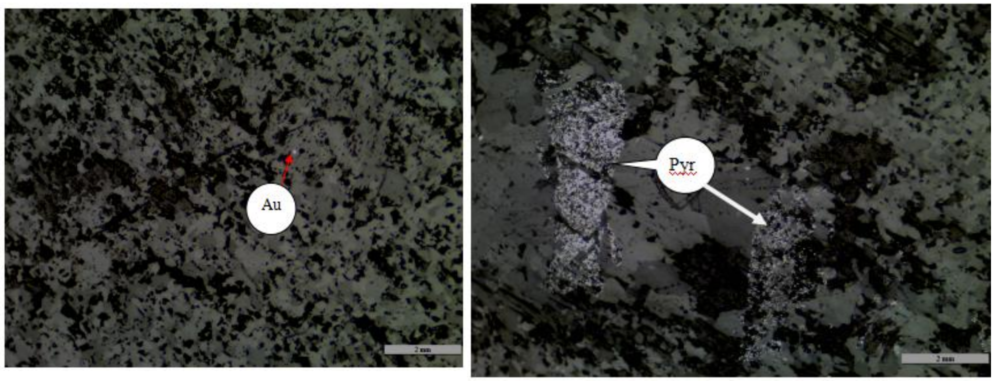


Figure 4.6: Photomicrographs showing pyrite (white) replacing gangues in XPL (where Pyr- is pyrite).

4.3. X-Ray Diffraction Results

About six selected samples are analyzed for ore mineralogy in Adama Science and Technology University (ASTU) XRD laboratory.

The XRD of the gold ore showed a lot of diffraction peaks with numerous background noise. This could be due to presence of numerous associated minerals in the gold ore. The result of XRD diffraction indicates that there is magnetite, quartz, actinolite, chlorite, arsenopyrite, siderite, chalcopyrite, pyrite, cubanite, covellite, berthierite and stibnite associated gangue minerals whereas gold ore mineralogy like buckhornite krennerite, aurstobite, montbrayite and calaverite as major gold mineralogy and associated minerals.

In the sample AKD-13, the dominant minerals associated with gold are cubanite ($CuFe_2S_3$), quartz, pyrite and magnetite (**Fig.4.7**).

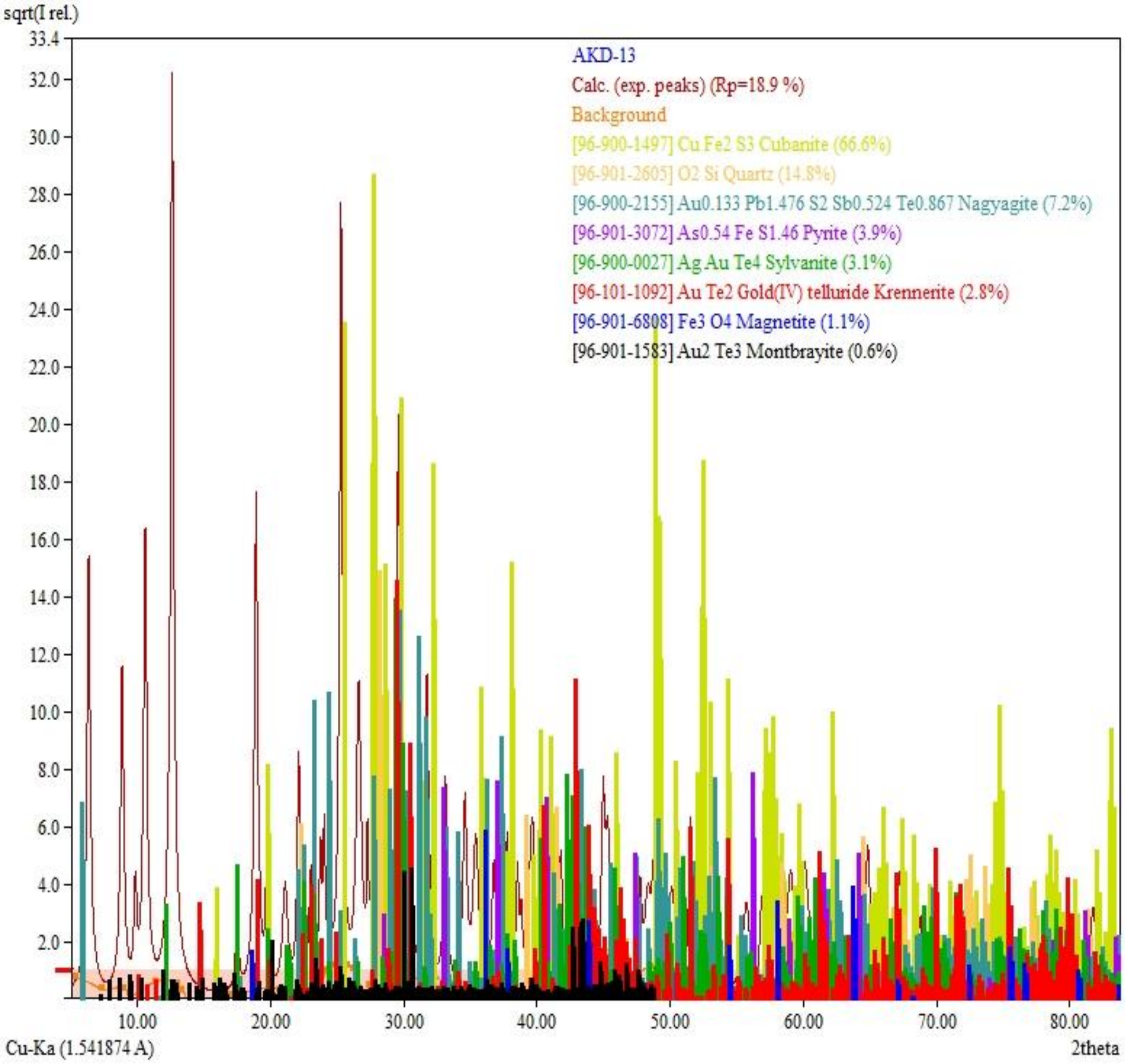


Figure 4.7: X-ray diffractogram showing major minerals in sample AKD-13 with gold ore mineralogy

In sample AKD-03, there are quartz, siderite, and arsenopyrite gangue mineral with gold ore mineralogy. The detected gold ore mineralogy is montbrayite, buckhornite, austobite and krennerite (**Fig.4.8**).

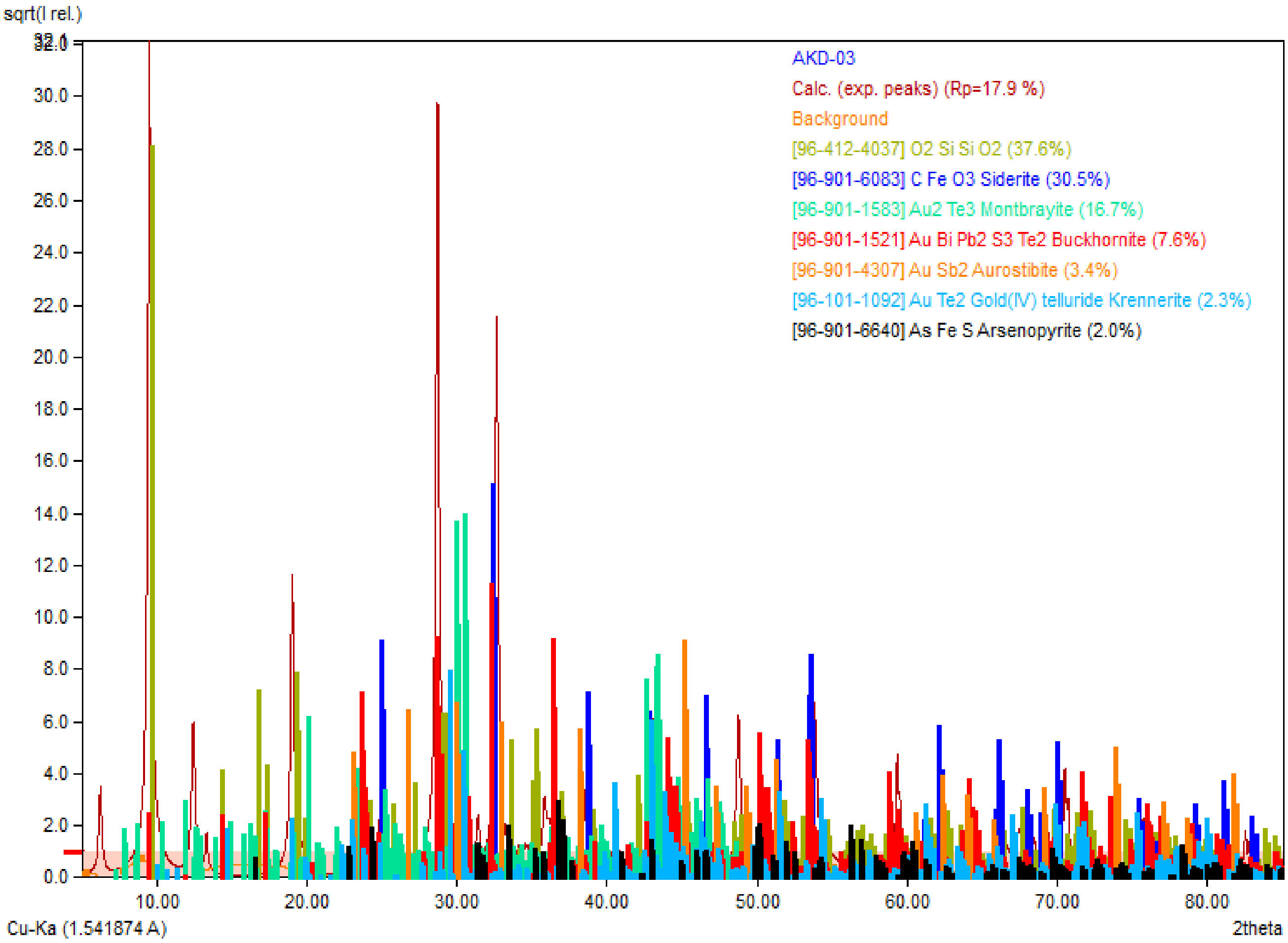


Figure 4.8: X-ray diffractogram illustrating gold ore mineralogy and associated minerals diffraction of the sample (AKD-03).

Iron carbonate (siderite, $FeCO_3$) is the major mineral phase identified in the sample AKD-03 with silica and arsenopyrite. Montbrayite, Buckhornite, Aurostibite and krennerite are gold ore mineralogy phase in this samples **(Fig.4.8).**

Stibnite and covellite as well as chalcopyrite are the gangue mineral present in addition to magnetite in another sample (AKPO-01 and AKPO-03) **Fig. 4.9 and 4.10**).

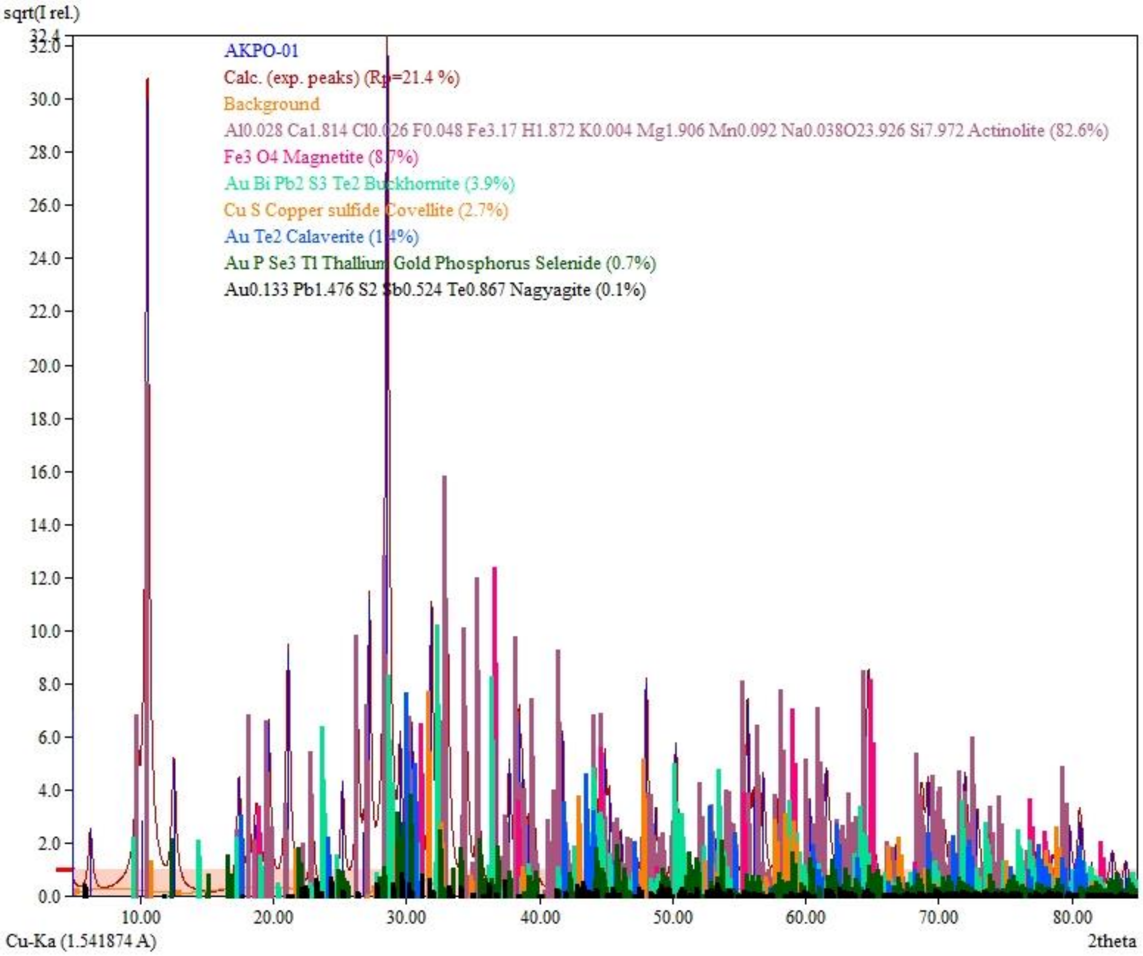


Figure 4.9: X-ray diffractogram illustrating gold ore mineralogy and associated minerals diffraction of the sample (AKPO-01).

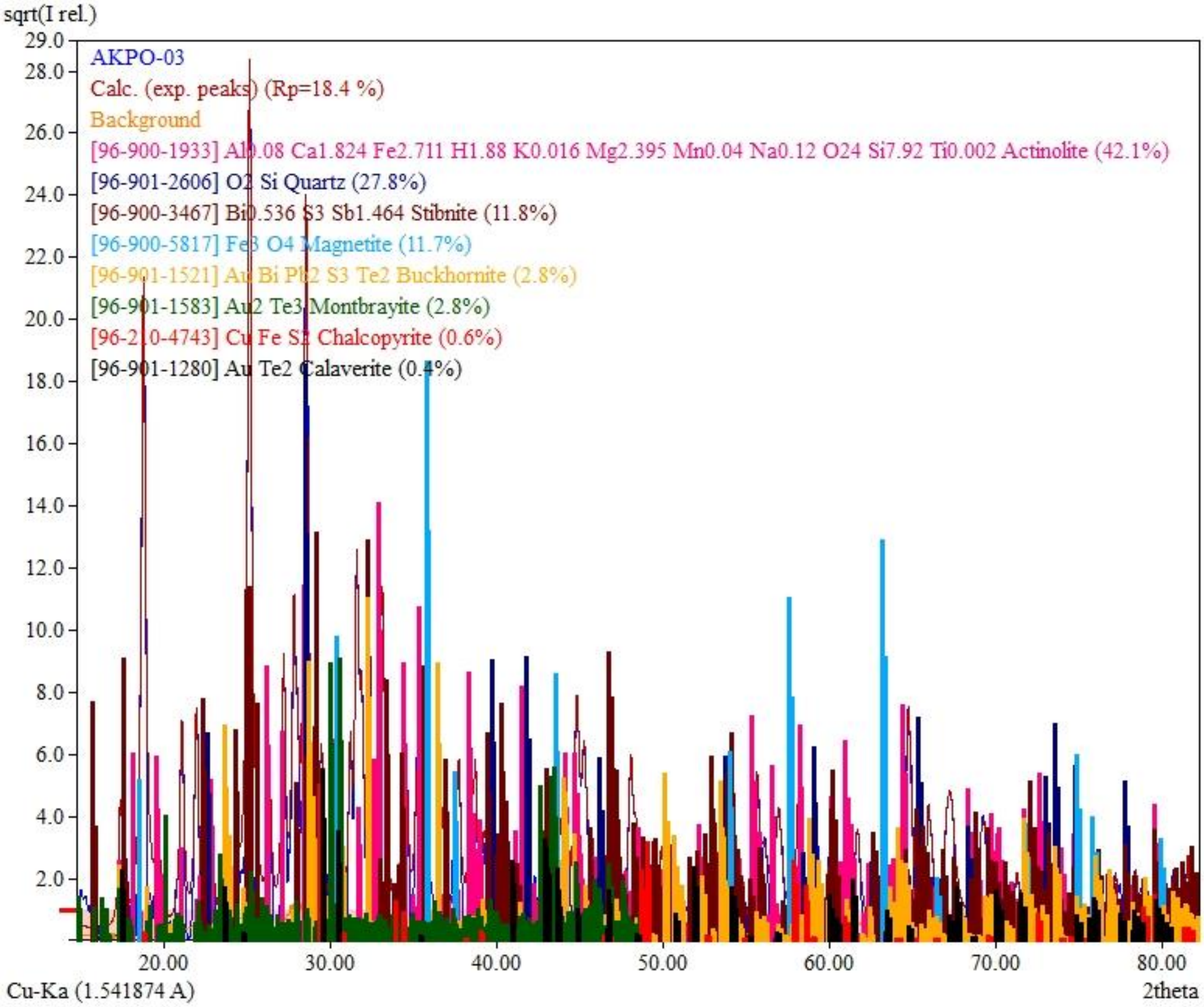


Figure 4.10: X-ray diffractogram illustrating gold ore mineralogy and associated minerals diffraction of the sample (AKPO-03).

Chlorite and magnetite are the phase found in the sample AKMtR-01; these two phases comparatively higher in this samples. Krennerite, thallium gold phosphorous selenide, montbrayite and nagyagite are gold ore mineralogical phase identified (**Fig.4.11**).

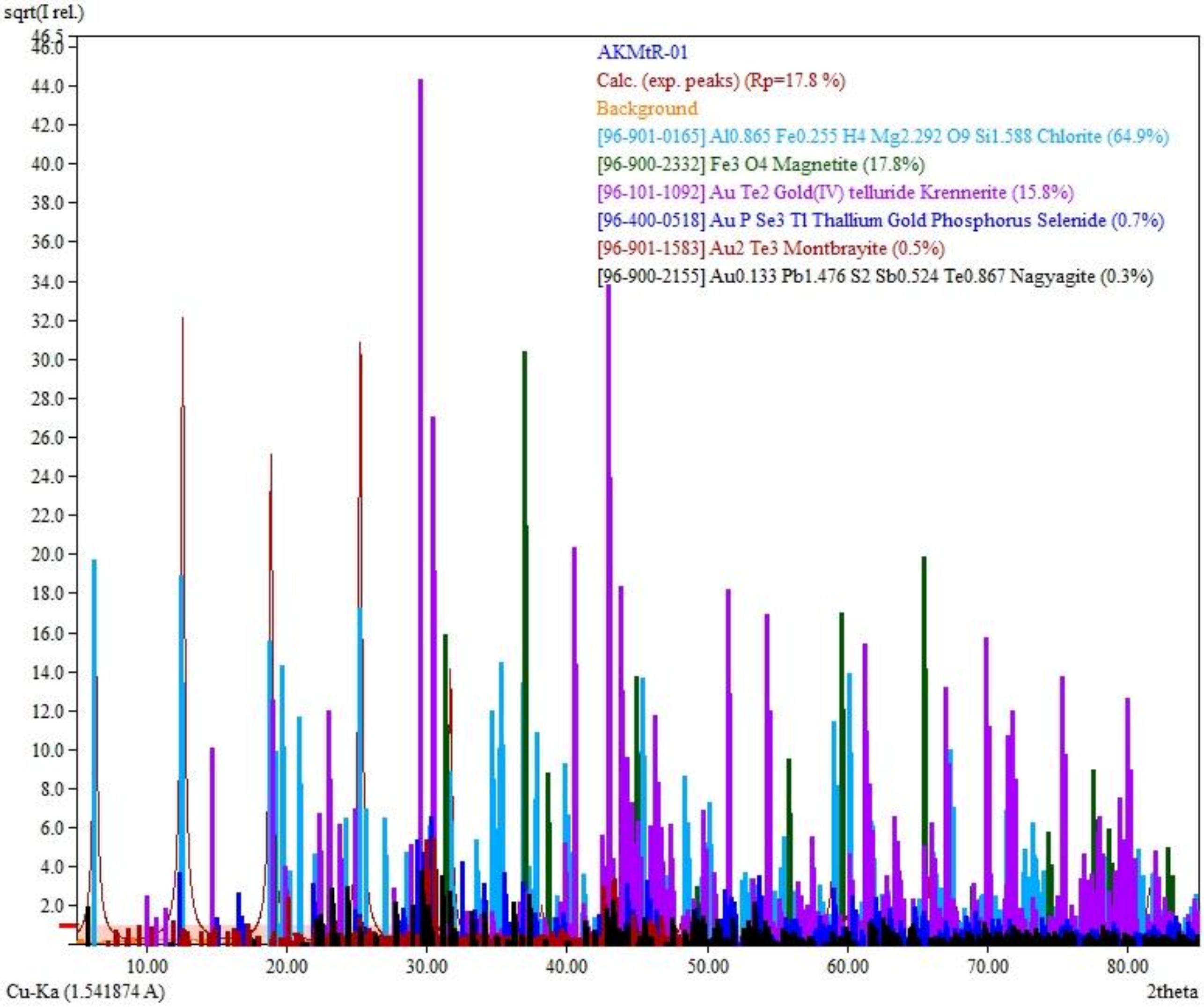


Figure 4.11: The diffraction of gold ore mineralogy (krennerite, thallium gold phosphorous selenide, montbrayite and nagyagite) and its associated minerals (chlorite, quartz, and magnetite) in sample AKMtR-01

In the as indicated in **Fig. 4.12** berthierite (FeS_4Sb_2) is the dominant gangue mineral associated. Additionally, there is chlorite and magnetite. The only major gold ore mineralogy detected is montbrayite.

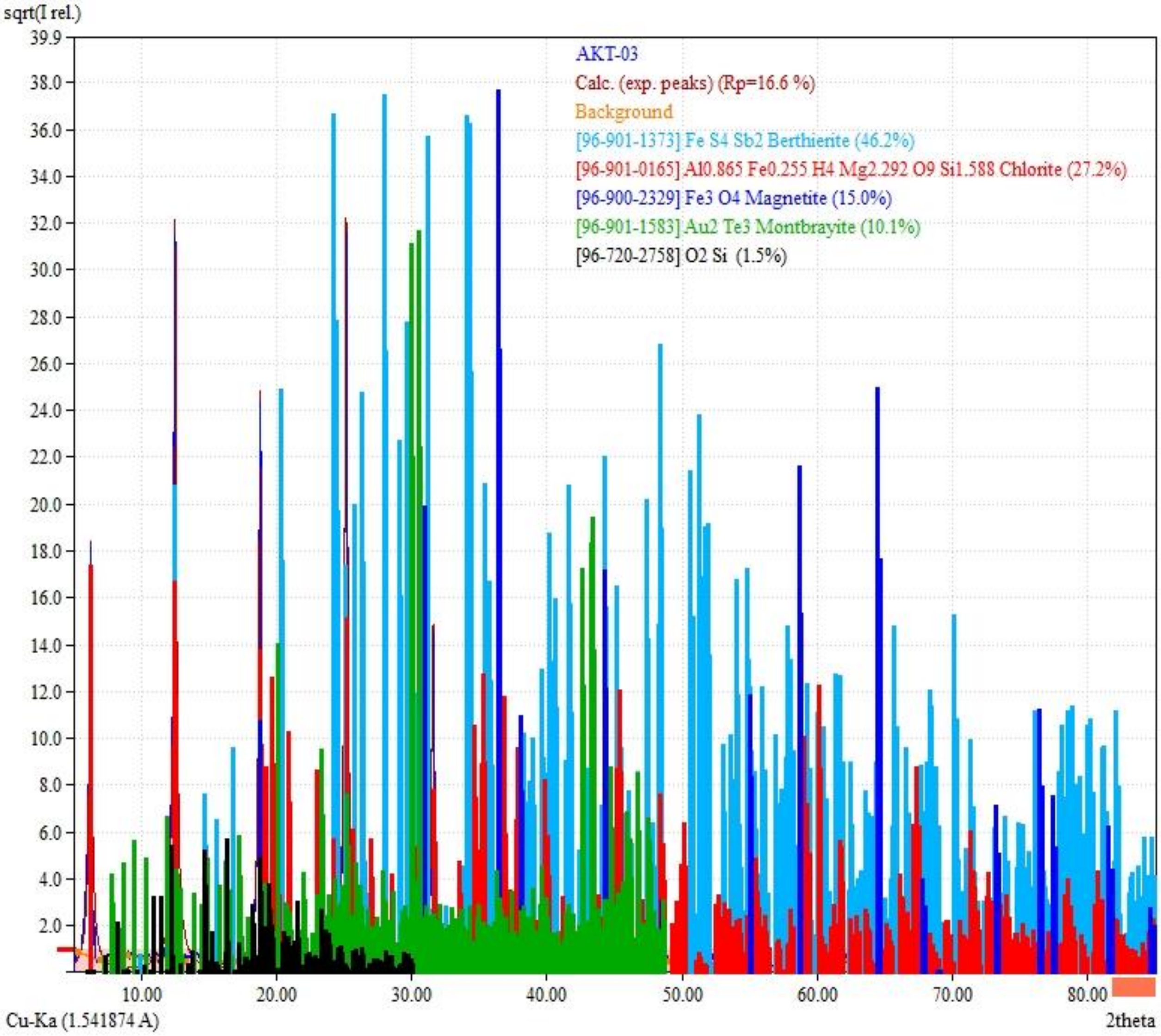
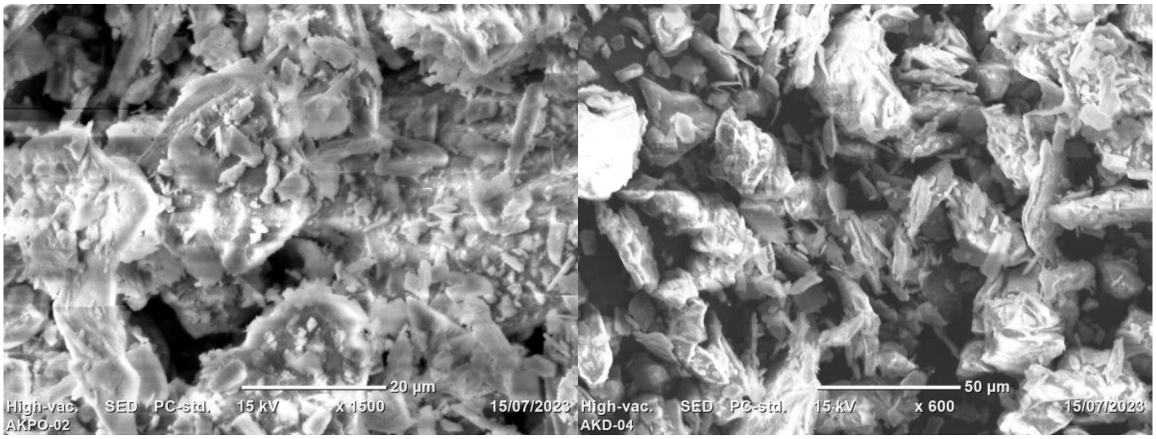


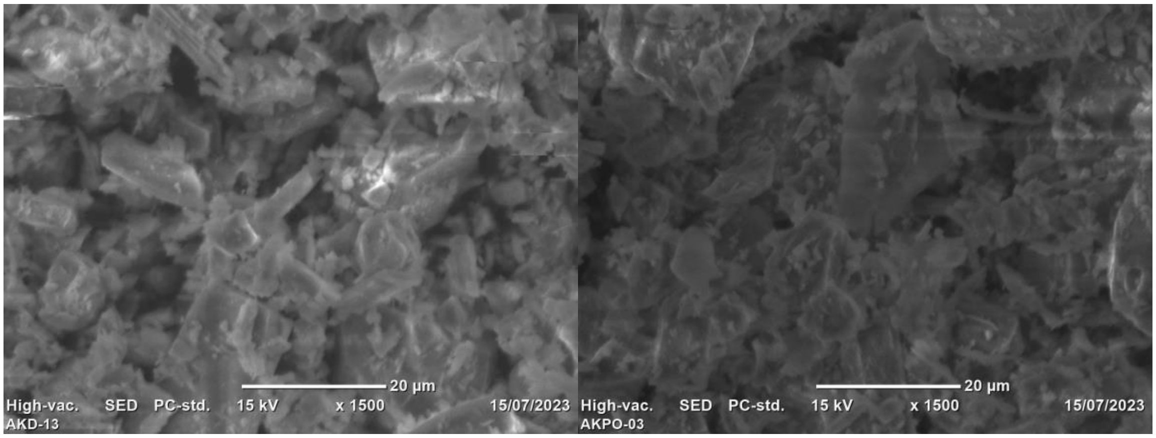
Figure 4.12: X-ray diffractogram illustrating gold ore mineralogy and associated minerals diffraction of the sample (AKT-03).

4.4. Scanning Electron Microscope

The results revealed that the majority of the grains in the deposit fell within the size range of 20 µm to 50 µm (**Fig 4.13**). This finding suggests that the gold particles in the deposit are predominantly fine-grained, with sizes ranging from 20 µm to 50 µm.

Additionally, the analysis of the samples revealed the presence of a replacement texture within the deposit. This texture indicates that certain minerals, such as pyrite, have replaced the original gangue minerals. Replacement textures are commonly observed in mineral deposits and occur when one mineral replaces another due to chemical reactions or alterations in the surrounding environment. In this case, pyrite has replaced some of the gangue minerals present in the Akobo gold deposit.





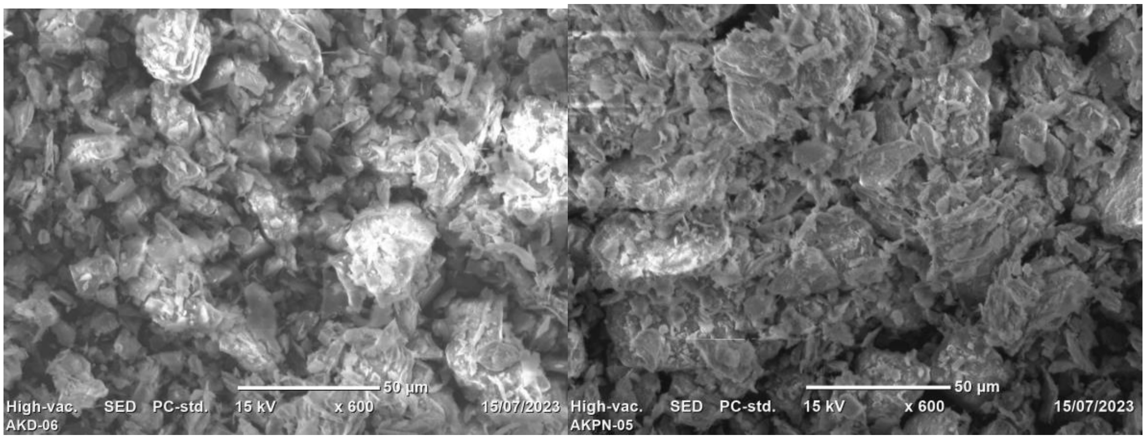


Figure 4.13: SEM image for gold ore and associated gangue minerals

4.5. Geochemistry of Akobo Gold Deposit

For the purpose of geochemical analysis, a total of 12 representative samples were systematically collected from various sources such as drill core, pit, and trenches. These samples were carefully chosen to ensure they provide a comprehensive overview of the geological composition in the area of interest. The samples were then sent to the ALS laboratory in Ireland for geochemical analysis.

The analysis aimed to determine the concentration of gold (Au) in the samples, and for this purpose, six samples were specifically selected for analysis using ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectroscopy). In addition to gold, the concentrations of other selected base metals such as copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn), as well as rare earth and trace elements, were investigated using ICP-MS/AES (Inductively Coupled Plasma-Mass Spectrometry/Atomic Emission Spectroscopy) in all twelve collected samples.

The results of the analysis provided valuable information regarding the concentrations of gold and various metals. According to the results depicted in **Fig. 4.14**, the sample AKPO-01 exhibited the highest gold grade with a concentration of 9.76 parts per million (ppm), while the lowest gold concentration was found in sample AKD-09, measuring only 0.001 ppm.

The concentrations of nickel (Ni) in the analyzed samples varied significantly, ranging from 66 to 1630 ppm in samples AKPN-01 and AKD-05, respectively. Similarly, the concentration of zinc (Zn) displayed a range of 16 to 103 ppm. Notably, both nickel and zinc exhibited higher concentrations compared to copper (Cu) in the samples. The maximum copper concentration recorded was 15 ppm, observed in the sample with the highest gold grade (AKPO-01).

Furthermore, the maximum concentration of zinc was found to be 103 ppm, while the minimum concentration was 16 ppm. On average, the concentration of zinc across all samples was calculated to be 58.83 ppm. The concentration of tin (Sn) in the analyzed samples revealed significant variations. The highest concentration of tin, measuring 2.9 ppm, was observed in sample AKPN-01. Additionally, samples AKD-12 and AKT-02 exhibited tin concentrations of 1.2 ppm and 0.5 ppm, respectively. Among the analyzed samples, only AKPO-01 exhibited a detectable concentration of cadmium (Cd) above the detection limit, measuring 0.5 ppm.

In general, the geochemical analysis findings indicate that the Akobo gold deposits have notable concentrations of cobalt (Co), nickel (Ni), and zinc (Zn), as highlighted in table 8**.** These results provide valuable insights into the elemental composition of the Akobo gold deposits, particularly emphasizing the presence of cobalt, nickel, and zinc in significant amounts.

Table 6: Results of Gold Ore Geochemistry using ICP-AES/MS method

	Major Oxide (wt. %)														
Sample Id	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**Cr_2O_3**	**TiO_2**	**MnO**	**P_2O_5**	**SrO**	**BaO**	**LOI**	**Total**
AKD-05	26.7	0.85	6.89	0.76	35	<0.01	0.01	0.592	0.01	0.24	0.01	<0.01	<0.01	28.1	99.16
AKD-08	38.1	22.4	4.84	12.2	8.44	3.71	0.15	0.038	0.11	0.09	<0.01	0.03	0.01	11.25	101.37
AKD-09	43	18.25	3.79	12.25	7.62	4.26	0.06	0.076	0.19	0.07	<0.01	0.03	<0.01	11.65	101.25
AKPN-01	34.9	25.1	12.6	6.82	10.9	1.07	0.99	0.038	1.56	0.3	<0.01	0.08	0.37	6.63	101.36
AKPO-01	51.2	2.42	10.2	15.85	16	0.19	0.05	0.11	0.24	0.2	0.01	<0.01	<0.01	3.89	100.36
AKPO-02	47	2.78	8.48	17.65	14.6	0.22	0.05	0.187	0.32	0.18	0.01	<0.01	<0.01	6.76	98.24
AKD-10	39.2	22.8	4.69	10.4	7.74	3.66	0.92	0.094	0.21	0.07	<0.01	0.04	0.02	11	100.84
AKD-11	49.3	14.75	9.02	9.28	4.89	3.3	0.95	0.011	0.96	0.13	0.22	0.02	0.09	5.82	98.74
AKD-12	42.5	15.25	13.05	10.15	9.16	2.13	0.49	0.039	1.64	0.2	0.16	0.03	0.05	4.65	99.5
AKT-01	58	0.32	4.51	0.02	28.1	0.03	0.01	0.148	0.01	0.02	0.01	<0.01	<0.01	4.6	95.78
AKT-02	47.1	14	10	10.3	13.3	2.28	0.09	0.077	0.71	0.21	0.05	0.01	<0.01	2.95	101.08
AKT-04	26.2	19.1	19.3	0.24	23	0.01	<0.01	0.065	2.47	0.51	0.16	<0.01	<0.01	10.15	101.21
Average	**41.93**	**13.17**	**8.95**	**8.83**	**14.89**	**1.90**	**-**	**0.12**	**0.70**	**0.19**	**-**	**-**	**-**	**8.95**	
Minimum	**26.2**	**0.32**	**3.79**	**0.02**	**4.89**	**0.01**	**<0.01**	**0.011**	**0.01**	**0.02**	**< 0.01**	**< 0.01**	**< 0.01**	**2.95**	
Maximum	**58**	**25.1**	**19.3**	**17.65**	**35**	**4.26**	**0.99**	**0.592**	**2.47**	**0.51**	**0.22**	**0.08**	**0.37**	**28.1**	

Table 7: Trace and REE in Akobo gold deposits

	Sample Id	**AKD-05**	**AKD-08**	**AKD-09**	**AKPN-01**	**AKPO-01**	**AKPO-02**	**AKD-10**	**AKD-11**	**AKD-12**	**AKT-01**	**AKT-02**	**AKT-04**
Trace Elements (ICP-MS) (ppm)	Li	<10	30	10	50	<10	<10	-	-	-	-	-	-
	Ba	< 0.5	55.6	28.5	3340	10.6	5	216	880	447	<0.5	27.8	0.5
	Ce	1.1	0.6	1.3	25.4	11.6	12	-	-	-	-	-	-
	Cr	4620	287	564	297	798	1535	2.2	31.4	17.2	0.1	9.1	20.6
	Cs	<0.01	0.02	0.01	0.11	0.03	0.01	0.07	0.47	0.2	<0.01	0.05	0.01
	Dy	0.16	0.62	0.73	7.28	3.72	4.53	0.82	3.63	4.08	<0.05	2.82	4.09
	Er	0.1	0.23	0.42	4.24	2.19	2.27	0.42	1.94	1.8	<0.03	1.77	2.48
	Eu	0.06	0.4	0.31	6.46	0.37	0.58	0.45	1.5	1.23	<0.02	0.77	0.46
	Ga	2.1	12.5	12.1	21.2	4.3	4.8	14.7	16.4	19.4	1.6	12.8	21.3
	Gd	0.16	0.36	0.63	6.16	3.17	3.73	0.6	3.99	3.94	<0.05	2.59	3.9
	Hf	0.06	0.17	0.28	3.86	0.78	0.89	0.27	1.36	2.72	<0.05	1.34	4.53
	Ho	0.02	0.11	0.18	1.42	0.8	0.77	0.16	0.73	0.7	0.01	0.58	0.76
	La	0.7	0.3	0.6	11	3.9	3.8	1	16	6.7	<0.1	4.7	12.4
	Lu	0.03	0.04	0.04	0.61	0.33	0.33	0.06	0.31	0.32	<0.01	0.22	0.31
	Nb	<0.05	<0.05	<0.05	4.29	1.24	2.3	0.06	6.86	5.88	0.99	2.33	11.25
	Nd	0.6	0.6	1.2	16.1	9	9.9	1.2	16.7	11.2	0.1	6.4	15.1
	Pr	0.16	0.09	0.2	3.27	1.96	1.77	0.26	3.92	2.47	<0.02	1.34	3.61
	Rb	<0.2	1.5	0.7	9.4	0.7	0.3	9.1	11.8	5.7	<0.2	1.1	0.4
	Sm	0.15	0.3	0.39	4.97	2.9	2.87	0.57	4.14	3.61	<0.03	2.24	3.74
	Sn	<0.5	<0.5	<0.5	2.9	<0.5	<0.5	<0.5	<0.5	1.2	<0.5	0.5	<0.5
	Sr	16.7	355	317	775	24.2	41.1	397	274	301	0.6	176.5	2.9
	Ta	0.1	0.1	0.1	0.4	0.1	0.2	0.1	0.4	0.3	0.1	0.2	0.7

Trace Elements (ICP-MS) (ppm)	Tb	0.01	0.09	0.16	1.12	0.57	0.65	0.13	0.63	0.68	0.01	0.46	0.7
	Th	0.09	<0.05	<0.05	1.81	0.44	0.5	0.1	0.46	0.4	0.12	0.41	0.69
	Tm	<0.01	<0.01	0.03	0.62	0.31	0.35	0.01	0.28	0.23	<0.01	0.24	0.31
	U	<0.05	<0.05	<0.05	0.26	0.2	0.15	<0.05	0.19	0.18	<0.05	0.13	0.31
	V	19	25	76	281	219	300	94	220	247	46	181	272
	W	0.5	1.8	2.2	2.5	1.5	1	3.3	0.9	1.1	6.7	6.6	0.5
	Y	0.9	2.4	3.9	39.6	20.8	21.9	4	19.6	19.2	0.2	16	19.8
	Yb	0.18	0.31	0.35	3.86	2.13	1.96	0.32	1.72	1.67	<0.03	1.62	2
	Zr	4	4	6	144	27	21	7	47	107	<1	50	165

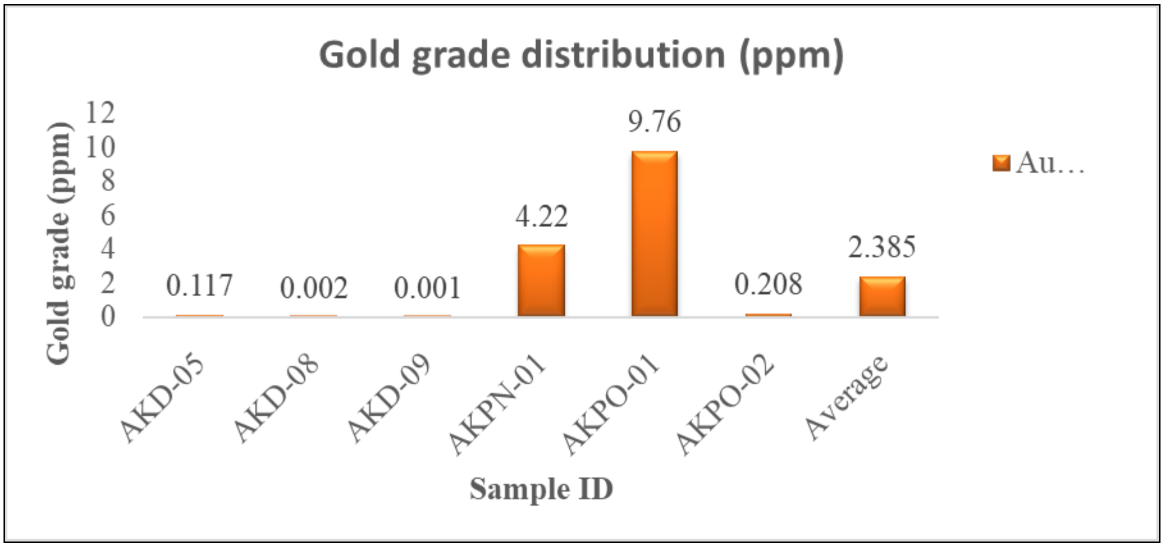


Figure 4.14: Akobo gold grade concentration in (ppm) with average grade.

Table 8: The concentration of element associated with gold

Elements	Average grade (ppm)
Au	0.001- 9.76
As	<5-728
Co	27-89
Ni	66-1630
Zn	16-103
Sn	<0.5-29
Cr	287-4620
W	0.5-2.5

4.5.1. Major Oxide Results

From the table the maximum and minimum silica ($SiO_{2)}$ are 58% (AKT-03) and 26.2% (AKD-05) respectively with an average of 41.93% **(**Table 6**).** The concentration of iron oxide (Fe_2O_3) ranges from 3.79% to 19.3%. The chromium oxide concentration is range from 0.011% to 0.592%. The gold deposit has higher calcium and magnesium oxide concentration than sodium and potassium oxide. Titanium oxide (Ti_2O) concentration is somewhat higher than potassium oxide; the highest Ti_2O is 2.47 (%) in the sample AKT-04. Loss of ignition ranges from 2.95-28.1; but the average is 8.95. Highest loss of ignition suggests that presence of hydrous minerals like chlorite, actinolite and carbonate like siderite

Fe_2O_3, SiO_2, CaO and MgO have strong positive correlation to weak correlation (in order of their lists) with gold whereas Cr_2O_3 has negative correlation (Table 9).

Table 9: Correlation between some major oxides with gold grade

Au (%) Pearson Correlation N- 6	Fe_2O_3 (%)	SiO_2 (%)	CaO (%)	MgO (%)	Cr_2O_3 (%)
	0.663	0.487	0.327	0.251	-0.270

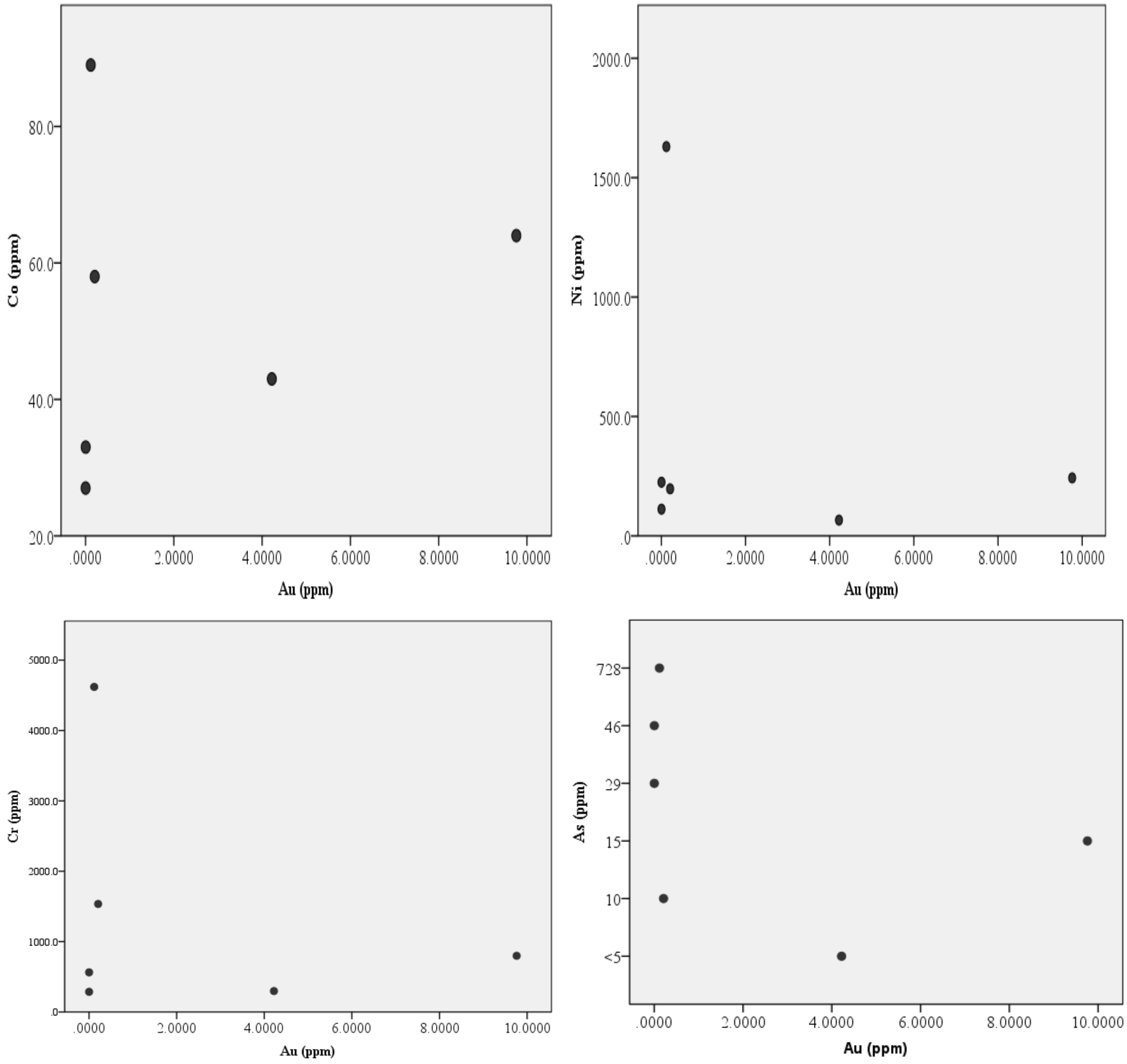
There is positive (strong) correlation coefficient (with level of significance 0.015) between gold and Fe_2O_3 (%) and moderate to weak positive correlation of SiO_2 (%) and CaO (%) with gold. This means that as the concentration of Fe_2O_3, SiO_2 and CaO increases (in order of the correlation), the gold concentration tends to increase as well and vice versa. It is also known that iron oxide (magnetite) to be associated with gold mineralization in some geological settings like in IOCG deposit even though the genesis of Akobo gold deposit is not well known and it needs further scientific recognition. The association between gold and quartz can be explained by the geological processes involved in the formation of gold deposits. During hydrothermal or magmatic activities, gold-bearing fluids can migrate through fractures and faults in the Earth's crust. As these fluids interact with the surrounding rocks, they can deposit gold within the quartz-rich formations

The gold and chromium oxide have a weak negative correlation coefficient (-0.27). This means that as the concentration of chromium increases, the gold concentration tends to decrease slightly and vice versa.

4.5.2. Association of Element with Gold in Akobo Gold Deposits

The association between various elements, including cobalt, nickel, chromium, arsenic, zinc, and tungsten, with gold is depicted in Fig. 4.15. The figure and accompanying table reveal the correlations between these elements and gold concentration.

From the figure and table, it is evident that there is a positive correlation between gold and cobalt, gold and zinc, and gold and tungsten. The Pearson correlation coefficients for these relationships are 0.176, 0.241, and 0.189, respectively. This implies that as the concentrations of cobalt, zinc, and tungsten increase, the concentration of gold also tends to increase, and vice versa. These positive correlations suggest a potential association or co-occurrence of these elements with gold in the studied samples.



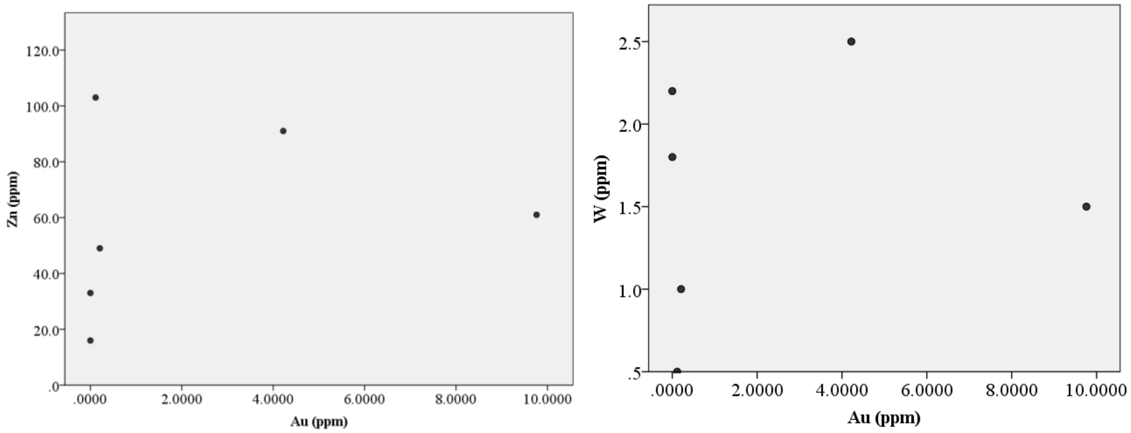


Figure 4.15: The scatter plot of Gold vs Co, Ni, Cr, As, Zn and W

Table 10: The correlation between gold and element like Cobalt, Nickel, Chromium, Zinc and Tungsten.

Au (%) Pearson Correlation	**Co**	**Ni**	**Cr**	**Zn**	**W**
	0.176	-0.253	-0.284	0.241	0.189

4.5.3. Association of REE with Gold

Significant concentrations of Ba, Co, U, W, Cr, Sr, and Zr up to 3340 ppm, 89 ppm, 0.31 ppm, 6.67 ppm, 2.5 ppm, 4620 ppm, 775 ppm, and 165 ppm, respectively. In the Akobo gold deposits, there is a noticeable high concentration of REE consisting of scandium, yttrium, and lanthanides **(**Table 11**)**.

The scatter plot shows a slightly positive correlation between Y (Yttrium), Ce (Cerium) and Sc (Scandium) concentration and gold concentration **Fig. 4.16**. However, strontium and gold have negative correlation coefficient (table 9). As Y, Ce and Sc concentration increases, gold concentration tends to increase as well, although the relationship is not very strong.

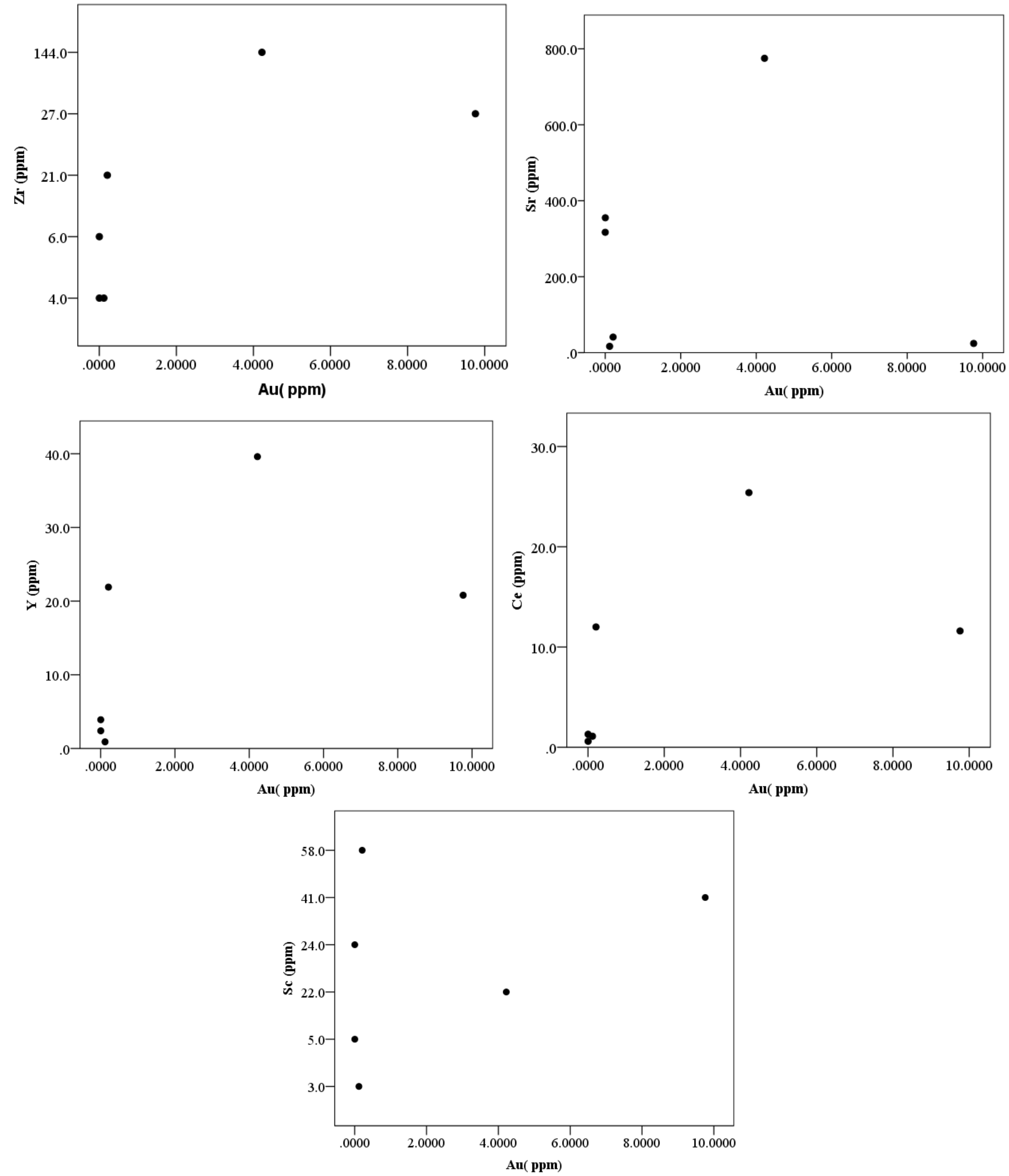


Figure 4.16: The scatter plot of REE (Zr, Sr, Cs, Y, Sc) vs gold grade.

Table 11: The correlation between REE and gold grade in ppm

Au (ppm) Pearson Correlation N-6	Zr (ppm)	Sr (ppm)	Y (ppm)	Ce (ppm)	Sc (ppm)
	0.355	-0.022	0.531	0.510	0.334

CHAPTER FIVE

DISCUSSION

5.1. Akobo Gold Ore Mineralogy

The Akobo deposit is known for its diverse mineralogy of gold ore, consisting of telluride minerals and sulphide/selenide (table 12). The telluride gold mineralogy in Akobo gold includes:

- **Krennerite**: Krennerite is a gold telluride mineral with the chemical formula $AuTe_2$.
- **Montbrayite**: Montbrayite is a gold telluride mineral with the chemical formula Au_2Te_3.
- **Buckhornite**: Buckhornite is a gold telluride mineral with the chemical formula $AuPb_2BiTe_2S_3$. It contains gold along with lead, bismuth, and tellurium.
- **Austobite**: Austobite is a gold telluride mineral with the chemical formula $AuTe_2$. It is another gold-bearing mineral that contributes to the overall gold content in the Akobo deposit.
- **Calaverite**: Calaverite is a gold telluride mineral with the chemical formula $AuTe_2$. It is a major source of gold in many gold deposits worldwide, including the Akobo deposit.
- **Nagyagite**: Nagyagite is a complex gold telluride mineral with the chemical formula $Pb5Au(Te, Sb, Bi)_4S_{5\text{-}8}$. It contains gold along with other elements like lead, antimony, bismuth, tellurium, and sulfur, and plays a role in gold mineralization at the Akobo deposit.
- **Thallium Gold Phosphorous Selenide**: This mineral refers to a gold-bearing mineral containing thallium, phosphorous, and selenium.

Additionally, the Akobo deposit also contains minor gold ore mineralogy, including:

- *Uytenbogaardite*: is a silver-gold sulfide mineral with the chemical formula Ag_3AuS_2. Although it is a minor component, it contributes to the overall gold mineralization in the deposit.

- *Fischesserite*: is a silver-gold selenide mineral with the chemical formula Ag_3AuSe_2. Similar to Uytenbogaardite, it is a minor gold-bearing mineral present in the Akobo deposit.

These various gold ore minerals, both major and minor, contribute to the overall gold content and mineralization of the Akobo deposit.

5.2. Textural characteristics of the deposit

5.2.1. Gold grain size and its Interlocking

In the Akobo gold deposit, the majority of the gold is found enclosed within the gangue minerals. The gangue minerals commonly associated with the gold deposit are quartz, actinolite, and chlorite, which are silicate minerals. These minerals act as the host or matrix within which the gold is contained. The presence of gold grains encapsulated within the gangue minerals indicates that the gold mineralization in the Akobo deposit is disseminated throughout the rock.

The grain size distribution of the gold in the Akobo deposit ranges from submicroscopic to microscopic. The most common size range of the gold grains in the Akobo deposit is between 50µm (micrometers) and 100µm (about 41%) **(**Fig. 4.3 and Fig. 4.17); However, it is worth noting that there are also visible gold grains that can be observed in hand specimens. These visible gold grains are larger and can be seen without the aid of magnification.

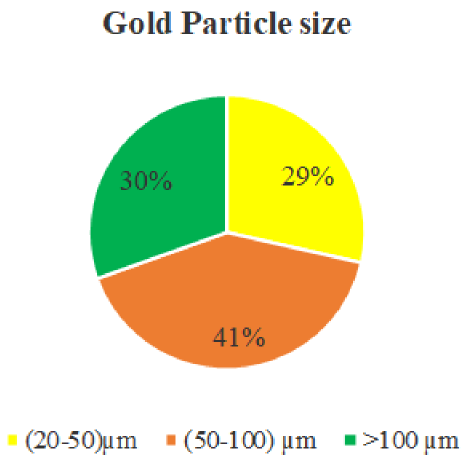


Figure 4.17: Pie chart showing rough particle size distribution of Akobo gold deposit

5.2.2. Associated Minerals and Gangue

The mineral assemblage associated with the Akobo gold deposits has been characterized using a combination of ore microscopy and X-ray diffraction (XRD) techniques. Through these analyses, several minerals have been identified, providing insights into the composition of the deposit. The identified minerals include magnetite, arsenopyrite, pyrite (identified through both polished sections and XRD), chalcopyrite, quartz, actinolite, chlorite, siderite, cubanite, covellite, stibnite, and bertherite **(**Table 13**).** These minerals are commonly associated with the gold ore found in the deposit may be silicate minerals, which encompass the gold ore, and sulfide minerals with indistinct boundaries with gold, are prevalent associations within the deposit.

In addition, iron oxide minerals, particularly magnetite, are frequently present. These minerals contribute to the overall mineralogy and geochemical characteristics of the Akobo gold deposits.

Table 12: Modal proportion of associated mineral and Gold Mineralogy in Akobo Gold Deposit

Gold mineralogy and Associated mineral	***Modal proportion (in percent***)					
	AKPO-01	AKPO-03	AKD-03	AKD-13	AKT-03	AKMtR-01
Gold telluride (Buckhornite, Krennerite, Montbrayite, Calaverite, Austobite) and selenide	6.1	6	30	13.7	10	17.3
Actinolite	82.6	42.1	-	-	-	-
Quartz	-	27.8	37.6	14.8	1.5	-
Magnetite	8.7	11.7	-	1.1	15	17.8
Chlorite	-	-	-	-	27.2	64.9
Cubanite	-	-	-	66.6	-	-
Bertheirite	-		-		46.2	
Siderite	-	-	30.5	-	-	-
Stibnite	-	11.8	-	-	-	-
Covellite	2.7		-	-	-	-
Arsenopyrite	-	-	2	-	-	-
Chalcopyrite	-	0.6	-	-	-	-
Pyrite	-	-	-	3.9	-	
Total	***100.1***	***100***	***100.1***	***100.1***	***100.1***	***100***

5.3. Effect of Gold Ore Mineralogy

The extractive metallurgy of gold ores is largely driven by mineralogical factors due to the fact that gold often occurs in at least two forms in an ore (Zhou, 2016). As stated, before the Akobo gold ore mineralogy is telluride mostly even though some sulfide and selenide also existed. This makes them refractory ore. Processing of telluride ore is somewhat difficult as gold telluride are not dissolved rapidly in conventional leaching solutions using cyanide (Youlton et al., 2021).

In order to obtain higher gold recovery from refractory ores, it is necessary to adopt the pretreatment process before leaching to break the structure of the gold tellurides and release free gold (Zhang et al., 2010). Various pretreatment methods have been used, such as roasting, pressure oxidation and bio-oxidation (Guo et al., 2019). However, these pretreatment processes have the followed disadvantages, for example, the discharge of SO_2 and As_2O_3 in the roasting process, high investment cost for high pressure operation, and bacterial growth was inhibited by arsenic during bioleaching (Li et al., 2017)

Additionally, the presence of a high content of Cu-rich minerals must be taken into account, because Cu forms complexes with cyanide and, then, more cyanide must be added in the solution (Medina & Anderson, 2020)

5.4. Effect of Geochemical Element

Geochemical studies have shown that gold migrates easily and is concentrated, along with characteristic elements such as arsenic and antimony, during the endogenous mineralization of gold deposits (Yang, 2017). Additionally, due to its siderophile properties, gold is frequently bonded with silver, copper and other metals (Gökelma et al., 2016). However, the coexistence of those elements increases the difficulty of extracting gold from refractory gold ores.

Moreover, it should be noted that the presence of arsenic, copper (excluding chalcopyrite), and the majority of base metal minerals containing iron, arsenic, antimony, zinc, nickel, and cobalt is associated with a tendency to consume cyanides and oxygen.

This particular type of ore is commonly referred to as reactive ore (Aylmore & Muir, 2001; Karimi et al., 2010).

The presence of arsenic in mineral concentrates creates two unique problems (De Michelis et al., 2013). Firstly, arsenic causes metallurgical challenges by limiting metal extraction and preventing the production of a high-purity final product (Nan et al., 2014). Second, arsenic is recognized as a highly hazardous pollutant with the potential to create environmental difficulties through the discharge of arsenic-bearing ores and concentrates into the atmosphere and the pollution of water sources during the processing of arsenic-bearing ores and concentrates (De Michelis et al., 2013).

The presence of copper minerals in gold ores often has the tendency of decreasing the gold recovery during cyanidation due to copper dissolution and formation of copper cyanide complexes which creates a deficiency of free cyanide in the solution for reaction with gold particles (Larrabure & Rodríguez-Reyes, 2021). These effects mainly interfere with the gold cyanide reaction and the carbon adsorption. Most of the copper minerals react rapidly with cyanide, forming multiple cyanide complexes. The copper that form cyanide complexes during the gold cyanidation can cause issues during the activated carbon adsorption, for example, by competing with the gold to be adsorbed, therefore requiring a higher free cyanide concentration (Medina & Anderson, 2020). The presence of copper in the ore at above 0.3% concentration may make direct cyanidation uneconomic without re-treating the $Cu\ (CN)_2$ formed in leaching according to Zhou & Cabri (2004).

5.5. Effects of Gangue Minerals and Textures

The presence of gangue minerals in gold ores greatly influences the selection of an effective gold recovery process, as (Mlaki et al., 2013) emphasize. This is mostly due to the fact that gangue minerals can either directly or indirectly interfere with gold recovery. Gangue minerals, in particular cubanite, covellite, arsenopyrite, and stibnite, have the ability to consume cyanide during the leaching process, reducing its effectiveness in dissolving gold and potentially affecting overall gold recovery (Jiang et al., 2001; Karimi et al., 2010; Medina & Anderson, 2020).

In Akobo gold deposit, there are different sulfides and oxide minerals of iron, copper, arsenic and antimony elements are commonly associated with the gold ore. These are magnetite, quartz, arsenopyrite, actinolite, chlorite, stibnite, cubanite and pyrite (table 12). The associated minerals have some effects on gold recovery by leaching. As stated before arsenopyrite (FeAsS), realgar (AsS) and orpiment (As2S3) and stibnite (Sb2S3) are known as cyanide, oxygen or lime consumed minerals in addition to copper minerals; the latter two being the most reactive ores (Vaughan, 2004). During the direct cyanide leaching process, the dissolution of stibnite (Sb2S3) not only increases the consumption of OH−, CN−, and O2, but also forms precipitates that coat the surfaces of the gold particles, which leads to low leaching recoveries (Yang, 2017).

The presence of siderite, an iron-rich carbonate mineral, within the Akobo gold deposits makes them resistant to ordinary cyanide solutions. Applying a pretreatment step prior to cyanidation is critical for achieving increased gold recovery (Marsden & House, 2006)

Akobo gold deposit as it has been observed that the majority of the gold is enclosed within the gangue minerals. Among the gangue minerals commonly associated with this gold deposit are quartz, actinolite, and chlorite, which belong to the silicate mineral group. While quartz does not directly impact gold recovery, its presence can have indirect effects, as highlighted by Mlaki et al (2013). Quartz is known for its hardness and abrasiveness, which can lead to increased wear and tear on processing equipment. Additionally, its presence can create physical barriers that hinder the access of leaching solutions to gold particles.

One of the most effective methods employed for treating gold ores that are encapsulated in sulphides involves the implementation of an ultrafine grinding process (Dyer et al., 2017; Ellis, 2003; González-Anaya et al., 2011). This process aims to maximize mineral liberation and enhance the interaction between the mineral surface and the cyanide solution, while also activating the surface mechanically, resulting in an increased leaching rate.

However, when gold is encapsulated within gangue minerals, particularly quartz or silicate minerals, exposing the gold effectively during oxidative roasting becomes challenging (Li et al., 2017). On the contrary, after oxidative roasting, the silicate minerals tend to form a more compact structure, leading to a secondary encapsulation of gold by silicates in the case of gold encapsulated in quartz. To overcome this, a preliminary treatment involving the use of hydrofluoric acid (HF) to dissolve quartz has been proposed (González-Anaya et al., 2011), along with an alkali washing pretreatment (Li et al., 2017).

Finally, as Akobo gold deposit is also physical locked (some are sub-microscopic) the but based on current grain size distribution, no need of ultra-fine grinding (if the size is >11µm) (Ellis, 2003), even though full grain size distribution of the deposit is still not identified.

5.6. Correlation between Akobo Gold Deposit and other Gold in the World

The Akobo gold deposit, characterized by its specific gold ore mineralogy and associated gangue minerals, can be correlated with various well-known gold deposits around the world. While it is challenging to find an exact match, I can identify similarities in mineralogy and processing methods with certain gold deposits.

a) **Carlin-type gold deposits**: Carlin-type gold deposits in Nevada, USA, are known for their complex composition and refractory character. They contain a mixture of gold-bearing minerals such as montbrayite, buckhornite, krennerite, calaverite, and thallium gold phosphorus selenide. Quartz, actinolite, chlorite, pyrite, and arsenopyrite are all gangue minerals found in the Akobo gold deposit (Berger et al., 2014; Cline et al., 2005). Pressure oxidation, bio-oxidation, and carbonaceous ore processing are common pretreatment processing methods for Carlin-type deposits.

b) **Golden Sunlight deposit**: The Golden Sunlight deposit in Montana, USA, is well-known for its precious metal mineralogy, particularly for gold and silver telluride minerals. Native gold, calaverite ($AuTe_2$), krennerite ($(Au, Ag)Te_2$), sylvanite ($(Au,Ag)_2Te_4$), petzite, buckhornite, and hessite are all common gold ore minerals; the two most prevalent gold minerals, however, are native gold and calaverite (Spry & Thieben, 2000). According to Spry & Thieben (2000), it is processed by crushing and grinding, gravity separation (uses density differences to separate heavier precious metal minerals from gangue minerals), flotation (is used to separate precious minerals by causing them to float while leaving undesirable minerals behind), cyanidation and carbon-in-pulp and carbon-in-leach methods (use activated carbon to adsorb dissolved valuable metals, which are then recovered via desorption and refining) as revealed from **.**

c) **Witwatersrand gold deposits**: The Witwatersrand Basin is the world's largest goldfield, producing about 52,000 tonnes of gold in total, accounting for more than one-third of all gold ever produced on Earth (Tucker et al., 2016). Additionally, it is renowned for unique mineralogy. While the specific gold ore minerals mentioned in the Akobo deposit may not be present, the presence of gangue minerals like quartz and pyrite is common in both deposits. The Witwatersrand deposits are typically processed using a combination of crushing, grinding, gravity concentration, and cyanide leaching (Nwaila et al., 2013).

Processing methods for the Akobo gold deposit might differ depending on characteristics such as mineralogy, particle size, and economic feasibility. Here are some processing methods to consider:

- ✓ **Gravity Concentration**: Gravity concentration methods such as centrifugal concentrators or shaking tables can be useful for separating gold from gangue minerals such as quartz and magnetite. This approach takes advantage of the density differential between gold and the surrounding minerals.
- ✓ **Flotation:** Flotation can be used to extract gold-bearing minerals from sulfide minerals such as pyrite, chalcopyrite, and arsenopyrite. The differences in surface characteristics and hydrophobicity are used to selectively float the precious minerals in this process.
- ✓ **Cyanide Leaching:** Cyanide leaching is a common gold extraction process. It involves removing gold from ore with a cyanide solution. However, the presence of refractory minerals in the Akobo deposit, such as arsenopyrite, cubanite, and covellite, may necessitate additional pre-treatment operations, such as roasting, pressure oxidation, or bioleaching, to improve gold recovery before cyanidation.

- ✓ **Bio-oxidation**: is a biological technique that uses microorganisms to oxidize sulfide rocks and release the encapsulated gold. This approach may be useful for gold resources that contain refractory minerals such as arsenopyrite, cubanite, and covellite.
- ✓ **Roasting/Pressure Oxidation**: Roasting and pressure oxidation are pre-treatment procedures that can be used to break down or change refractory minerals, making gold more accessible for extraction. These methods entail heating the ore to high temperatures in order to oxidize sulfide minerals and improve gold recovery

To ensure efficient processing of the Akobo gold deposit, it is crucial to consider detailed mineralogical and metallurgical studies, along with economic factors. A thorough evaluation of the ore's characteristics and comprehensive testing should be conducted to identify the most suitable processing route that maximizes gold recovery.

5.6.1. Carlin-Type Gold Deposits found in Nevada, USA

The gold ore mineralogy, gangue minerals, and related elements in Carlin-type gold deposits in Nevada, USA, have different properties (Berger et al., 2014; Cline et al., 2005):

a) **Gold Ore Mineralogy:** Carlin deposits are primarily gold deposits. Gold can be found in a variety of forms, including microscopic particles, submicroscopic gold, and gold contained within sulfide minerals. Arsenian Pyrite (FeAsS): Arsenian pyrite is a mineral that is abundant in Carlin-type deposits. It consists of different levels of gold and arsenic and frequently contains the majority of the gold in the deposit. Realgar (As_4S_4) and orpiment (As_2S_3) are two arsenic sulfide minerals found in Carlin-type deposits. They are frequently found in conjunction with gold and arsenopyrite.

b) ***Gangue Minerals:***

Quartz (SiO2), carbonaceous material, siderite ($FeCO_3$), and other minerals such as calcite, dolomite, adularia, and clay minerals are among the gangue minerals found in the Carlin gold deposit Quartz is a common gangue mineral in Carlin-type deposits. It forms the main gangue matrix along with other minerals and often hosts the disseminated gold particles. The presence of carbonaceous materials such as organic matter and graphite makes the Carlin gold deposit refractory and poses problems during the recovery of gold.

*c) **Associated Elements**:*

Mineralization in Carlin-type deposits is defined by geochemical indicators such as gold (Au), arsenic (As), mercury (Hg) (rare occurrence), and antimony (Sb). Arsenic is usually found in arsenopyrite and can also be found in realgar and orpiment, whereas antimony is found in stibnite. Silver (Ag), tellurium (Te), bismuth (Bi), and thallium (Tl) are additional trace elements linked with gold mineralization in Carlin-type deposits. The quantity and abundance of these components vary depending on the deposit (Cline et al., 2005).

5.6.2. IOCG and Akobo Gold Comparisons

The mineralogy, host rock, and gangue minerals of the Akobo gold deposit distinguish it from other well-known IOCG (iron oxide copper gold) deposits. The presence of iron oxide minerals, copper, and gold-bearing minerals in a certain geological environment characterizes IOCG deposits. The Akobo gold deposit, on the other hand, has a peculiar mineralogy and gangue mineral assemblage that distinguishes it from normal IOCG deposits. Here is a comparison of the Akobo gold deposit to the IOCG deposits:

Mineralogy: The Akobo gold deposit has unique gold ore mineralogy, with minerals such as montbrayite, buckhornite, krennerite, calaverite, and thallium gold phosphorus selenide. Magnetite, quartz, actinolite, chlorite, cubanite, covellite, arsenopyrite, pyrite, chalcopyrite, siderite, berthierite, and stibnite are some of the gangue minerals associated with the deposit.

In contrast, IOCG deposits are distinguished by the occurrence of iron oxide minerals, particularly magnetite and hematite, as well as copper and gold-bearing minerals. Chalcopyrite, bornite, covellite, pyrite, and magnetite are all common minerals found in IOCG deposits. Gold in IOCG deposits can occur in a variety of forms, including native gold, electrum, and gold-bearing sulfide minerals.

Host Rock:

IOCG deposits are found in complicated geological settings and are frequently linked with iron-rich rocks such as banded iron formations (BIFs), ironstones, and iron-rich sedimentary rocks. These deposits can also form near intrusions and fault systems.

In contrast, the Akobo gold deposit is connected with greenstone belts and metavolcanic and metasedimentary rocks. These rock types are typically associated with gold deposits globally and serve as common host rocks for gold mineralization.

Processing

Iron Oxide Copper Gold (IOCG) Deposits: Processing IOCG deposits involves a range of techniques, such as crushing, grinding, gravity concentration, magnetic separation (to recover magnetite), flotation (to separate copper and other sulfide minerals), and cyanide leaching (for gold extraction). The choice of processing methods depends on factors like the deposit's mineralogy, grade, and metallurgical characteristics (Spry & Thieben, 2000)

Akobo Gold Deposit: The processing methods for the Akobo gold deposit would depend on factors such as the specific mineralogy, particle size, and economic considerations. Potential processing methods could include gravity concentration, flotation, cyanide leaching, and advanced extraction techniques like roasting, pressure oxidation, or bio-oxidation.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1. Conclusion

The gold ore mineralogy of the Akobo deposit in Ethiopia is characterized by several primary gold-bearing minerals, including montbrayite, buckhornite, krennerite, calaverite, and thallium gold phosphorus selenide. These minerals are the main sources of gold within the deposit. Additionally, there are several gangue minerals associated with the ore, which are non-valuable minerals found alongside the gold-bearing minerals. The gangue minerals in the Akobo deposit include magnetite, quartz, actinolite, chlorite, cubanite, covellite, arsenopyrite, pyrite, chalcopyrite, siderite, berthierite, and stibnite.

The gold deposit in Akobo is encapsulated within these gangue minerals, which can be silicate minerals such as quartz, actinolite, or chlorite. The grain size of the deposit ranges from sub-microscopic to microscopic, with most sizes ranging from 50µm to 100µm. Due to the small grain size, the optical properties of the gold are not clearly observed, but reflectance is one of the major criteria used for identification.

The gold grade in the Akobo deposit varies from 0.001 to 9.76 parts per million (ppm). The ore is associated with magnetite, chlorite, and serpentinite alteration, with actinolite playing a significant role. The deposit is hosted within mafic to intermediate rocks, with silica content ranging from 26.1% to 58%. Geochemically, the deposit shows a clear association with cobalt, copper, zinc, and tungsten.

Based on the described gold ore mineralogy, it can be concluded that the Akobo gold deposit exhibits characteristics of refractory ore. Refractory ore refers to ores that pose challenges to conventional leaching methods, resulting in lower gold recovery rates, typically below 80%. The presence of certain reactive gangue minerals such as stibnite, berthierite, cubanite, arsenopyrite, and covellite contributes to the refractory nature of the ore.

Refractory ores are challenging to process because the gold particles are often encapsulated or occluded within these refractory minerals, making them less accessible for extraction. As a result, additional pre-treatment processes are required to enhance gold recovery before employing conventional methods like cyanidation, which is a widely used technique for gold extraction. Several pre-treatment methods can be considered, depending on the specific mineralogy and characteristics of the Akobo gold deposit. These methods may include roasting, pressure oxidation, bioleaching, or even a combination of these techniques.

6.2. Recommendations

The statement highlights the importance of understanding the direct gold mineralogy in ore processing. However, due to the difficulties and costs associated with comprehensive mineralogical analysis, it is often neglected until processing issues arise. This means that potential processing problems may go unnoticed until they impact the efficiency or effectiveness of the recovery process. As a result, it is recommended that thorough mineralogical characterization be carried out before selecting the processing methods.

In the case of the Akobo gold deposit, the factors affecting gold recoveries have been proposed based on the mineralogy of the ore. To gain a better understanding of these factors and their impact on gold recovery, it is recommended to conduct metallurgical test work. Metallurgical test work involves conducting laboratory-scale experiments to assess the behavior of the ore under various processing conditions. By evaluating the ore's response to different variables, such as grind size, reagent dosage, and leaching conditions, the extent to which each factor affects the recovery process can be determined.

In recent years, advanced techniques have emerged and played a crucial role in gold mineralogical studies. One such technique is the use of QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy), which allows for automated mineralogical analysis of samples and provides detailed information about the distribution and composition of minerals within the ore, including the presence of visible gold and gold grain chemistry by microprobe. So, in addition to metallurgical test, it is highly recommended to characterizing gold mineralogy by this sophisticated method for getting valuable insights that inform processing selection, optimization, troubleshooting, and ultimately lead to improved gold recovery and operational efficiency.

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