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CENTER FOR ETHIO-MINES DEVELOPMENT

MINERALOGICAL CHARACTERIZATION OF OKOTE GOLD ORE DEPOSIT, OROMIA REGION, SOUTHERN ETHIOPIA: IMPLICATION TO GOLD PROCESSING

A Project Submitted to Center for the Ethio-Mines Development, Collage of Technology and Built Environment, Addis Ababa University, Addis Ababa, Ethiopia, in Partial Fulfillment of the Requirements for the Degree of Master of Engineering(M.Eng.) in Mineral Engineering

Prepared by: Ebisa Dugasa

Advisor: Prof. Worash Getaneh

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Mineralogical Characterization of Okote Gold Ore Deposit, Oromia Region, Southern Ethiopia: Implication to Gold Processing

By
Ebisa Dugasa Kitata

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Declaration

I hereby declare that this graduate project work entitled "**Mineralogical Characterization of Okote Gold Ore Deposit, Oromia Region, Southern Ethiopia: Implication to Gold Processing**" is the result of my original project work conducted under the guidance and supervision of my project work advisor Prof. Worash Getaneh. I affirm that this project work has not been submitted previously for any degree or diploma and that all sources of information used in this study have been duly acknowledged and cited. I further declare that all laboratory data and experiments in this project work are authentic and have been conducted in accordance with ethical standards and guidelines. I take full responsibility for any errors or omissions contained in this project work and hereby grant permission for it to be made available for public access and use.

Ebisa Dugasa	_____	_____
Student Name	Signature	Date

GRADUATE PROJECT WORK APPROVAL SHEET

The following graduate faculty members certify that this student has successfully presented the necessary written final graduate project work and oral presentation for partial fulfillment of the thesis requirement for the Degree of Master of Engineering in Mineral Engineering.

Approved by the Committee of Examiners

Dr. Zinnabu Tassew		18/06/2026
Internal Examiner	signature	date
_____	_____	_____
Internal Examiner	signature	date
Dr. Shumet Sender		18/06/2026
External Examiner	signature	date
Worash Getaneh (Prof)		18/06/2026
Advisor	signature	date
Dr. Artineh Mariliyn		June 18, 2026
Chair Person	signature	date

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Acronyms and Symbols

AAS	Atomic Absorption Spectroscopy
BGRIMM	Beijing Genral Research Institute of Mining and Metallurgy
BIOX	Bio-oxidation
CIL	Carbon In Leach
CIP	Carbon In Pulp
CN	Cyanide/chemical species made of carbon (C) and nitrogen (N) atoms
Eh	Electrode potential/oxidation-reduction (Redox potential
EMC	Ethiopian Mineral Corporation
EPMA	Electron Prob Micro Analysis
FA-AA	Fire assay atomic absorption
g/cm^3	Gram per cubic centimeter
GIE	Geological Institute of Ethiopia
GPS	Global positioning system
ID	Identification
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
Kpa	Kilo Pascal
LIMS	Laser ion mass spectrometry
LOI	Loss on Ignition
mamsl	Meter above mean sea level
MoM	Ministry of Mines
Mt	Million ton
NaCN	Sodium cyanide
NMiC	National Mining Corporation
OM	Optical Microscopy
PGE	Platinum group elements
PH	Acidity/Alkalinity
POX	Pressure Oxidation
Ppm	parts per million
PPL	Plane Polarized Light
QEMSCAN	Quantitative Evaluation of Materials by Scanning Electron Microscopy
SART	Sulfidation, acidification, recycling & thickening
SCN^-	Sulfur cyanide with a negative charge
SEM	Scanning Electron Microscopy
t	Ton
µm	Micro meter
UTM	Universal Traverse Mercator
XRD	X-Ray Diffraction
XRF	X-ray fluorescence
WAI	Wardell Armstrong International

Abstract

Gold, the yellow metal possesses unique physical and chemical properties, attractive in color and brightness, durability, resistant to corrosion and oxidation, made it valued mainly for jewelry and other adornments. Gold has been known and valued for a long period since ancient time and its demand and price has been increasing from time to time. Processing of gold that involve liberation through comminution, concentration using flotation, gravity and cyanidation or combination of these require mineralogical understanding of the gold ore deposit for acceptable gold recovery. The current study, mineralogical characterization of Okote gold ore deposit, aim at identification of gold ore and associated minerals, grain size distribution, and understand their impacts on gold processing; that help for selection of gold processing methods for appropriate gold recovery in the feasibility study and plant design of Okote gold deposit. The study approach involved chemical analysis for major, minor and trace elements using AAS, ICP-OES and ICP-MS and mineralogical analysis using optical microscopy, XRD and electron microprobe analyzer (EMPA). The ore minerals identified is exclusively native gold, with trace amounts of electrum, and telluride mineral-petzite. Associated minerals: pyrite (dominant), pyrrhotie, chalcopyrite, covellite sphalerite, rutile, tannantite, goethite, limonite, hematite, and magnetite. Gangue minerals are dominated by quartz (49.34%) and calcite (19.4%), followed by mica + illite (9.3%), chlorite (8.0%), amphibole-hornblende (3.86%), dolomite (2.28%), and others such as feldspars and tourmaline (7.82%). Grain size distribution of gold is as follows: 15.59% >74 µm, 40.07% between 74 µm and 37 µm, 28.01% between 37 µm and 10 µm, 10.39% between 10 µm and 5 µm, and 5.59% below 5 µm. Chemical analysis revealed low concentrations of Ag, Cu, Zn, Pb, As, Sb, and Te, alongside moderate levels of sulfur and organic carbon (CORG). These characteristics indicate moderate cyanide and oxygen consumption due to iron sulfides, as well as medium preg-robbing effects from organic carbon in cyanide solution. The presence of significant clay, mica, and chlorite in the gangue may cause viscosity issues during downstream processing, requiring proper management. Approximately 84% of gold grains are finer than 74 µm, implying that liberation will require fine to ultrafine grinding, provided slime-related challenges are addressed and economic viability is confirmed. The Okote deposit is largely composed of free-milling ores with a minor refractory component. While flotation, gravity separation, and cyanidation, or their combinations, are technically feasible, the complex chemistry of flotation demands specialized training, reagent management, and precise operational control. Given the wide gold grain size distribution, a combination of gravity separation followed by cyanidation is recommended as the more appropriate processing route for the Okote gold deposit.

KeyWords: Gold, mineralogy, Okote gold deposit, gold processing

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1. INTRODUCTION

1.1. General Background

Gold (Au) is a yellow noble metal and a transition element in the periodic table, with atomic number 79 and atomic mass of approximately 197. It possesses unique chemical and physical properties: when pure, gold has a high specific gravity of 19.3, a melting point of 1063°C, a brilliant luster, and is extremely malleable and ductile. It is also a good conductor of heat and electricity, ranking after silver and copper. Gold is resistant to corrosion. Naturally occurring gold is never completely pure; the purest form, known as 24 karats or a fineness of 1000, is a refined standard (Macdonald, 2007).

Gold is known to have been mined in substantial amounts for at least 6000 years. Over the centuries, it has been the principal medium of international monetary exchange, and its physical properties and common occurrence as native metal made it prized for jewelry and other adornments. Gold is still the backbone of global finance and one commodity whose value has appreciated steadily and steeply since 1971 (MihirDeb and SanjibChandraSarkar, 2017).

Gold used in jewelry is alloyed with variable amounts of silver and copper, which allows for a wide variation in the color of the finished artifact, from white to yellow to pink. Nickel and zinc are used in smaller amounts for increased hardness and durability, and for color variations.

Gold exhibits superior electrical and thermal conductivity, reflects both infrared radiation and most of the visible spectrum, readily forms alloys with other metals, and is highly resistant to corrosion and tarnishing. These characteristics make gold valuable in high-technology products such as computers, communications equipment, and spacecraft.

Nowadays, gold is also used in various industries, including electronics, architectural glass, and dental applications, among others. Looking to the future, Nano-sized gold particles are expected to play an increasingly important role as catalysts in chemical production, pollution control, and medical applications (Walter, 2011).

Globally, the demands for, supply of, and price of gold have fluctuated significantly over time. For example, the price of gold was $160 per ounce in 1975, rose to $600 per ounce in 1980, dropped to $260 in 2001, and then surged to a peak of $1,900 per ounce in 2011. It subsequently fell to $1,100 in 2015, $1,200 in 2018, $1,792 in 2022, and reached $3,270 per ounce in April 2025 (https:/www.investing.com and https://www.gold.org).

Estimated global gold consumption as of 2022 was as follows: jewelry, 47%; physical bars, 17%; central banks and other institutions, 20%; official coins, medals, and imitation coins, 9%; electrical and electronics, 6%; and other uses, 1%. The top 10 gold-producing countries in 2023 were: China (370 t), Australia (310 t), Russia (310 t), Canada (200 t), USA (170 t), Kazakhstan (130 t), Mexico (120 t), Indonesia (110 t), South Africa (100 t), and Ghana (90 t). The top five

gold-producing African countries in 2023 were: South Africa (100 t), Ghana (90 t), Tanzania (60 t), Mali (60 t), and Burkina Faso (60 t) (USGS, 2024)

Since gold is inert at room temperatures and pressures, only very few occur in compound form. The main ore minerals of gold include: native gold, electrum, and tellurides. Gold tellurides are the most common gold minerals after native gold and electrum. Other gold ore minerals include amalgam (Au_2Hg_3), maldonite (Au_2Bi), auricupride ($AuCu_3$), tetra-auricupride (AuCu), PGE gold alloys. Some minerals are typically associated with gold and are also gold host/carrier ore minerals which include sulfides and sulfosalts such as pyrite (FeS_2), arsenopyrite (FeAsS), pyrrhotite ($Fe_{(1-x)}S$), marcasite (FeS_2), chalcopyrite ($CuFeS_2$), galena (PbS), sphalerite (ZnS), stibnite (Sb_2S_3), realgar, acanthite (Ag_2S), loellingite ($FeAs_2$), enargite ($CuAsS_4$), tennantite ($Cu_6[Cu_4(Fe,Zn)_2As_4S_{13}]$ and others like various selenium minerals and magnetite (Fe_3O_4).

Mineralogical characterization of gold involves the determination of mineralogy (ore and associated minerals), grain size distribution, textures, and modal mineralogy that can influence the metal recovery.

Gold ore/minerals can be categorized into two broad types, which are based on their mode of occurrence and the difficulties they pose in the processing.

Based on their mode of occurrence, gold can be classified into three types: microscopic, sub-microscopic (including solid solution and colloidal forms), and surface-bound gold (Zhou et al., 2004). Microscopic gold consists of particles visible under an optical or electron microscope and includes gold alloys, as well as gold-bearing tellurides, sulfides, and selenides. Sub-microscopic gold refers to gold particles smaller than 0.1 μm in diameter, which cannot be observed under either an optical or an electron microscope; it typically occurs as discrete particles within sulfide minerals such as pyrite and arsenopyrite (Hausen, 1981; Wang et al., 1992, 1994). Surface-bound gold is detectable only by laser-induced mass spectrometry (LIMS) and is found adsorbed onto mineral surfaces, including carbonaceous matter, stained quartz, clay minerals, and iron oxides.

Based on processing difficulties, gold ores can be categorized into three types: free-milling ore, which is readily extractable with over 90% recovery using standard cyanidation; complex ores (cyanide-consuming, oxygen-consuming, and preg-robbing), from which high gold recoveries are possible under modified or intensive leaching; and refractory gold ores, where gold is physically and chemically locked, often as very fine particles within sulfides, making it inaccessible to lixiviants, so that acceptable recovery cannot be achieved under normal standard cyanidation procedures.

Particle size of gold, associated minerals, availability of oxygen and preg-robbing minerals/materials, presence of physically and chemically locked refractory sub-microscopic gold and etc. are the mineralogical factors that determine the extractive metallurgy of gold. Gold mineralogical characterization handles all problems connected with gold ore processing and it is

widely used for feasibility studies and during the development as well as operational stages of process (Zhou & Cabri, 2004).

Mineralogical characterization is gaining more attention to address the various problems encountered during the processing of gold ores, as many complex and refractory gold ores are being discovered while free-milling ores are depleting (J.Y. Zhou et al., 2004). The gradual increase in gold demand and price is driving the application of gold mineralogical characterization to enhance gold production.

The techniques and methods commonly used in gold mineralogical characterization studies include optical microscopy (OM), X-ray diffraction (XRD), electron microprobe analysis (EMPA), scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), automated mineralogy methods such as mineral liberation analysis (MLA) and QEMSCAN, as well as assay methods (XRF, FA-AA/AAS, ICP-MS/ICP-OES) combined with mineralogical analysis.

Gold concentration typically involves gravity separation, flotation, and cyanide leaching. The choice among these processes depends on the mineralogical characterization and gold content of the ore (Alim Gül et al., 2010).

An effective gold processing route is directly linked to the inherent mineralogical features of the gold ore being processed. The performance of the chemical and physical processes involved in gold extraction is determined by the mineral assemblages present in the deposit (Chryssoulis and Cabri, 1990; Chryssoulis and McMullen, 2005).

Gold deposits and occurrences in Ethiopia are widely distributed across the greenstone belts in the southern, western, and northern peripheral parts of the country. The majority of Ethiopia’s gold is produced through artisanal and small-scale mining. The only large-scale, mechanized mining and processing operations are the Lega Dembi-Sakaro mine and the recently operational Akobo Gold Mine, both located in the southern greenstone belt. Other gold deposits at advanced exploration and development stages include Okote, Kurmuk, Tulu Kapi, and Metekel.

The project work area, known as the Okote gold ore deposit, is one of Ethiopia's potential gold deposit zones. It is situated in the southern greenstone belt, south of the Lega Dembi Gold Mine, within the Megado metavolcanosedimentary assemblage of the late Proterozoic Adola granite-greenstone terrain.

The area was studied over an extended period by the Geological Survey Institute of Ethiopia and the Mineral Resources Development Corporation (prior to 1995) to assess its gold potential. Subsequently, from 1996 to the near present, the National Mining Corporation has conducted explorations and identified that the Okote gold deposit is characterized by shear-hosted vein-type gold mineralization as well as metagranodiorite-hosted gold mineralization. The Okote gold

deposit is currently owned by Godu General Trading Share Company, and exploration is at an advanced stage

Different research works have been carried out in the area regarding the geochemistry, alteration, and genesis of gold mineralization, as well as the structural and lithological controls of the ore deposit. The lithology of the Okote gold deposit comprises chlorite-amphibole schist, epidote-chlorite-amphibole schist, amphibole schist, chlorite schist, chlorite-carbonate schist, meta-gabbro, meta-granodiorite, and talc-tremolite-actinolite schist (Alamrew, 2013). The host rocks for gold mineralization include chlorite-carbonate schist, epidote-chlorite-amphibole schist, chlorite schist, amphibole-carbonate-chlorite schist, sheared meta-gabbro, and meta-granodiorite (Deksissa and Kober, 2004; Wube, 2013; Geda, 2015). According to Deksissa and Kober (2004), concordant N-S to N20°E striking, sub-vertical west-dipping auriferous quartz-carbonate-tourmaline veins (qv2) and wall rock mineralization are associated with pyrite, chalcopyrite, pyrrhotite, gold, and accessory chalcocite, covellite, galena, and melonite ($NiTe_2$). Gold mineralization in the Okote area is related to quartz veins, veinlets, and wall rock alteration (Wube, 2005). Apart from the research works mentioned above, no detailed mineralogical study, nor its impact on gold processing research or graduate project work, has yet been conducted. Therefore, characterizing the mineralogy of the Okote gold ore is important for a better understanding of the process routes.

The purpose of the present study is to characterize the mineralogy of the Okote gold ore in order to understand the nature and properties of the gold ore and its associated minerals, to categorize the ore deposit mineralogy, and to discuss the implications for the efficiency of gold processing methods. The Okote gold ore deposit is currently at an advanced stage of exploration, approaching the development phase, and a detailed mineralogical characterization of the area will support the definitive feasibility study. Therefore, this project is important, as it contributes to a deeper understanding of the gold ore, its associated minerals, and their impact on the processing of the Okote gold ore deposit..

1.2. Location of the Study area

Okote is located in Hallo kebele, Melka Soda woreda, West Guji zone of Oromia National Regional State in southern Ethiopia (Figure.1). The area can be accessed along the Addis Ababa-Moyale asphalt road up to Fincha-Woha with a distance of 560km. Fincha-Woha to Okote is about 90km along the Fincha-Woha-Shakiso dry weather road. It is bounded by geographical coordinates of 474200-477100mE and 564000-567200mN.

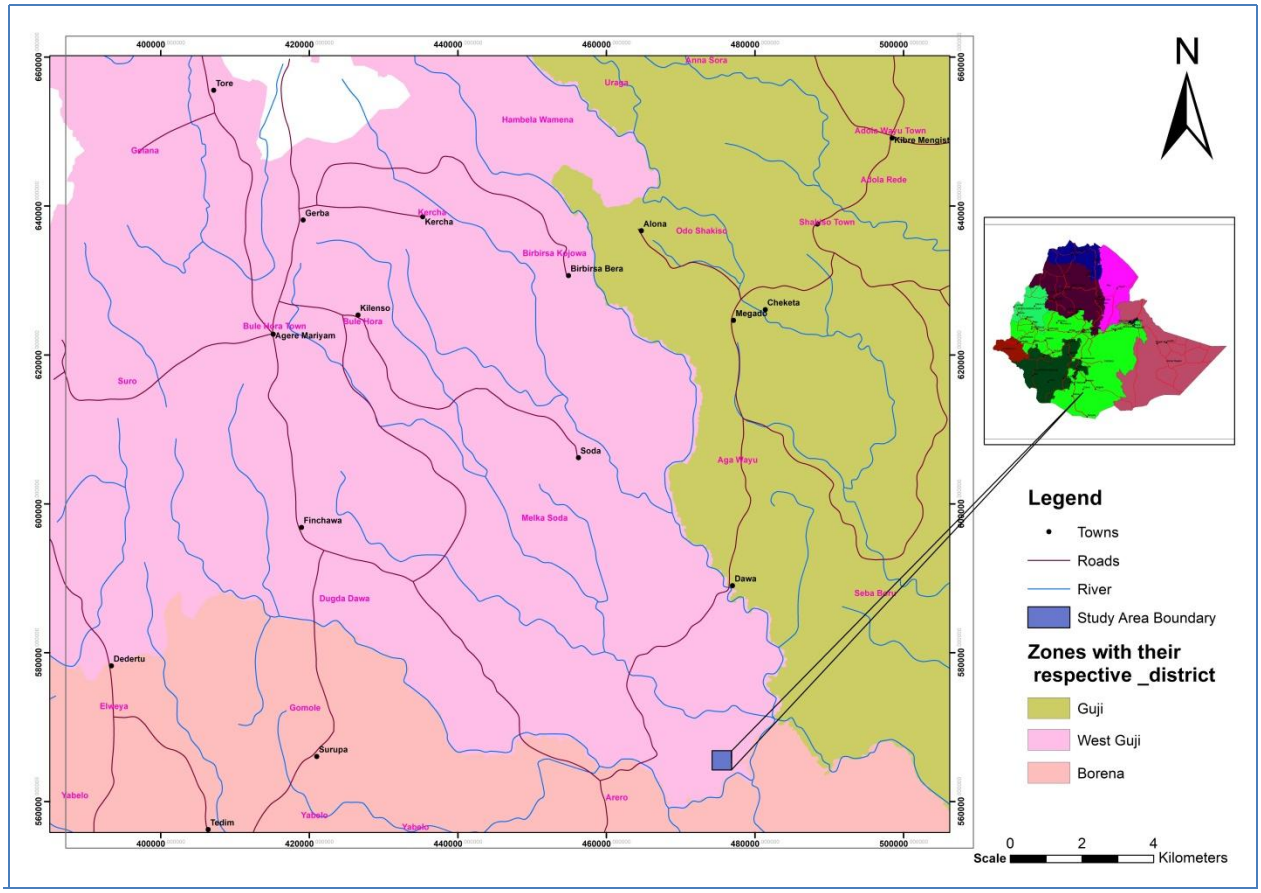


Figure 1 Location map of project area

1.3. Physiography

The Okote gold deposit project area, situated in southern Ethiopia within the Adola Greenstone Belt, is characterized by a rugged and highly dissected topographic landscape. Elevations across the project area range from 892 meters to 1,393 meters above mean sea level. The landscape is highly rugged, characterized by numerous steep ridges and deeply incised valleys. Perennial rivers flow along the valley floors, sustaining water throughout the year.

Even though climate of the region is tropical, its high altitude ensures that most areas experience mild conditions. The average annual temperature stands at 19°C, with monthly extremes ranging from a minimum of 5.5°C to a maximum of 30°C. The area is semi-arid, receiving low rainfall year-round. Monthly precipitation drops to around 15 mm during the dry seasons and peaks at approximately 200 mm in May, though typical monthly totals range between 40 mm and 70 mm (NMiC, 2011).

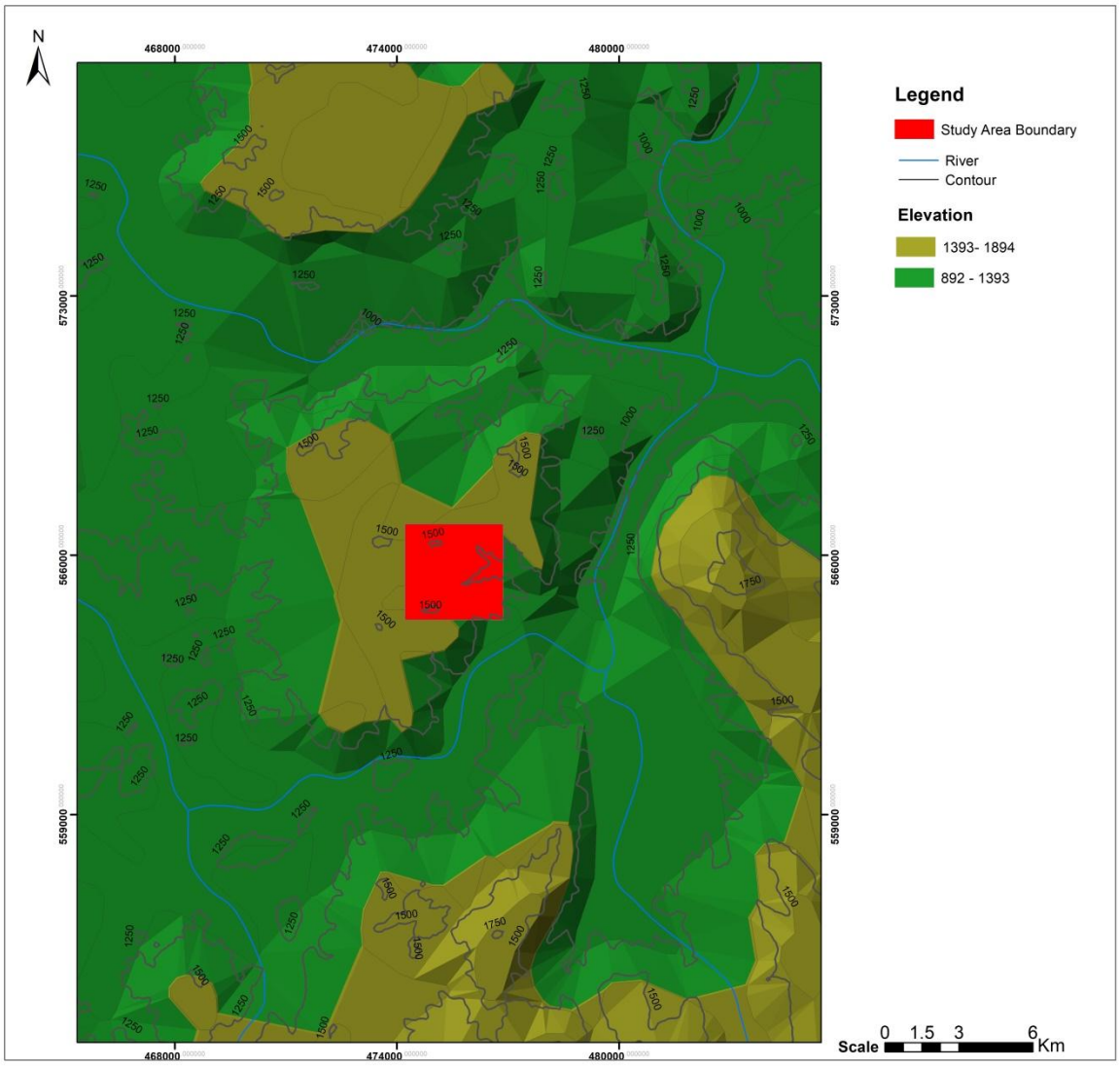


Figure 2 Physiographic map of project area

1.4. Statements of the Problem

The global demand and price of gold have been steadily increasing over time. Gold serves as a foundation for a country's economic development and is Ethiopia's primary source of foreign currency earnings. Although Ethiopia has high gold resource potential, its annual production remains only a few tons compared to other countries. Among known deposits, the Okote gold deposit is the largest in Ethiopia. Exploration in the area began in 1995 under the then Geological Survey of Ethiopia and the Mineral Resource Development Corporation, involving geological mapping, aeromagnetic surveys, and radioactive measurements. Following indications of potential gold occurrences, NMiC launched a gold exploration project in Dawa Digati in 1996, which included drilling, trenching, and sampling, with a focus on the Okote gold project.

Through intensive exploration, NMiC identified substantial resources in the area. Currently, the project is at an advanced stage of exploration and is approaching development.

Different research works have been carried out on the area regarding geochemistry, alteration, and genesis of gold mineralization, as well as structural and lithological control of the ore deposit. Alamrew (2013) identified that the geology of Okote gold deposit comprises lithologic units such as chlorite- amphibole schist, epidote-chlorite-amphibole schist, amphibole schist, chlorite schist, chlorite-carbonate schist, Meta-gabbro, Meta-granodiorite and talc-tremolite-actinolite schist. According to Deksissa and Kober (2004), Wube (2013), Geda (2015); the host rocks for gold mineralization are chlorite-carbonate schist, epidote-chlorite-amphibole schist, chlorite schist, amphibole-carbonate-chlorite schist, sheared Meta-gabbro, and Meta-granodiorite. Deksissa and Koeber (2004) further reported that concordant N–S to N20°E striking, sub-vertical west-dipping auriferous quartz-carbonate-tourmaline veins (qv2) and wall-rock mineralization are associated with pyrite, chalcopyrite, pyrrhotite, gold, and accessory chalcocite, covellite, galena, and melonite. Wube (2005) indicated that gold mineralization in the Okote area is also linked to quartz veins, veinlets, and wall-rock alteration. However, beyond the studies mentioned above, no research or project work has yet been conducted on the mineralogical characterization of the deposit and its implications for gold processing.

To support a definitive feasibility study and efficient gold production, the area requires intensive research. A key component that informs the selection of an appropriate ore processing route is the mineralogical characterization of the deposit. As no such study has ever been conducted in this area, characterizing the gold ore deposit mineralogy is essential for both the feasibility study and the determination of the processing route.

The texture and mineralogy of the gold ore dictate the required fineness of grinding for adequate gold liberation and the economically optimum extraction recovery.

Feasibility study of an ore deposits as well as quality control in the process enhancement requires mineralogical investigations (M.D. Adams, 2005). Mineralogical information must be considered in conjunction with the metallurgical test work program results to ensure that appropriate processing methods are evaluated and that the optimum processing technology and flowsheet methods are selected and incorporated into the final plant design.

The inherent mineralogical feature of gold ore has an effect on the efficiency of gold extraction process routes. The chemical and physical process techniques in gold extraction are determined by mineralogical assemblage of the ore deposit (Chryssoulis and Cabri, 1990; Marsden and House, 1992; Chryssoulis and McMullen, 2005). It is therefore important to accurately characterize the mineralogical nature of the ore to be processed which involve gold distribution focusing on its size, shape, ore mineral, association and gangue minerals.

Overall, the research works so far done on the area is related to structural and lithological role in gold mineralization, geochemistry and genesis of gold mineralization and open pit planning and

design. Research regarding mineralogical characterization and its implication on gold processing has never been done in the current study area.

Therefore, conducting research/graduate project work on detail mineralogical characterization of Okote gold ore deposit is mandatory and important aspect of proper metallurgical tests, process selection and plant design in the feasibility study.

1.5. Objectives of the study

1.5.1. General Objective

The primary objective of this project is to characterize the mineralogy of the Okote gold ore deposit, located in Hallo Kebele, Melka Soda Woreda, West Guji Zone, Oromia National Regional State; in order to suggest suitable processing methods for the deposit.

1.5.2. Specific Objectives

Current specific Objectives:

- Mineralogical composition analysis and characterization
- Textural (grain size distribution, grain shape and interlocking) characterization
- Categorization of gold ores based on process difficulties
- Propose possible ore processing methods

1.6. Scope of the Study

The scope of this study includes identifying gold ore minerals and their types, along with associated ore and gangue mineralogy, as well as the distribution of gold grain sizes. This is achieved through chemical analysis of major, minor, and trace elements, and mineralogical analysis using optical microscopy, XRD, and EMPA. The analytical results are interpreted, integrated, and categorized according to their implications for gold processing challenges. Based on these findings and interpretations, input data and information are provided, from a mineralogical perspective of the ore deposit, to guide appropriate metallurgical tests and process design during the feasibility study.

1.7. Expected Outcomes and Project Significance

This project work identifies gold minerals, associated gangue minerals, size distribution, and deleterious substances that pose challenges for gold processing. The primary significance of this research is that it provides essential data and information on the ore deposit, supporting the feasibility study and design of a gold processing plant to be undertaken by Godu General Trade S.C. Additional benefits of the research include: (1) establishing a foundation for further work or research on metallurgical testing; (2) assisting in the development of an appropriate plant flowsheet; and (3) serving as a reference for other researchers and students in their studies.

2. LITERATURE REVIEW

2.1. Physical and Chemical Properties of Gold

2.1.1. Physical Properties

Gold is a soft yellow metal, with the highest ductility and malleability of any metal (Yannopoulos, 1991). It can be cold drawn to give wires of less than 10μm diameter, and beaten into gold foil with a thickness of 0.2μm. Because of its softness, gold can be highly polished into different ornaments (Eoin H. Macdonald, 2007).

Gold has high thermal and electrical conductivities. Pure gold and many gold alloys are nonmagnetic.

Gold as it occurs in nature usually does not have a very crystalline appearance (Habashi, 2013). It exhibits threadlike, leaf-shaped, and spherical forms, on which cubic, octahedral, and dodecahedral surfaces can sometimes be seen.

Gold forms alloys with a number of metals (Bi, Cd, Co, Ni, Cr, Fe, Pb, Zn…). The carat gold, used mainly in jewelry, is alloys of gold, silver, and copper except for white gold (Au-Ag). The carat is used to express the proportion of gold contained: 24 carats are pure gold (100% Au); 18 carats are 75% gold and so on (Hansen and Anderko, 1958). The main physical properties of metallic gold are listed in Table 1.

Gold occurs mainly in its native state, often alloyed with silver, copper, bismuth, mercury and platinum-group elements, and in tellurides and selenides [Habashi, F. (2013]. Native gold is distinguished from other minerals having similar yellowish coloration, often referred to as “fools gold) (e.g. pyrite, chalcopyrite and millerite), by its strong metallic luster and characteristic tint as well as by its lower hardness and yellowish streak.

Table 1: The main properties of gold

Chemical symbol	Au
Atomic number	79
Atomic weight	197
Crystal form	Cubic
Color	Golden yellow to silver white rarely orange red
Melting point	1063 ºC
Boiling point	2600ºC
Diaphaneity	Opaque
Hardness	2.5 to 3.0
Density (g/cm^3) at 20ºC	19.3 when pure
Magnetic susceptibility	Low
Resistivity	$2.2*10^{-8}$
Ductility	High
Luster	Metallic
Tensile strength	138 mega Pascal when annealed
Crustal abundance	0.005ppm
Volatility	Commences well below melting point

Note. Au=chemical symbol for gold

2.1.2. Chemical Properties

Gold does not react with water, dry or humid air, oxygen (even at high temperature), ozone (O_3), nitrogen (N), hydrogen(H), fluorine (F), iodine (I), sulfur (S), and hydrogen sulfide(HS) under normal conditions (Habashi. F., 1997).

Sulfuric acid (HSO_4), hydrochloric acid (HCl), hydrofluoric acid (HF), phosphoric acid (HPO_4), halide-free nitric acid (HNO_3)-except in very high concentrations, and all organic acids have no effect on gold, either in concentrated or dilute solutions and at temperatures up to the boiling point [Habashi.F. (2013]. Gold will dissolve in aquaregia (a mixture of hydrochloric acid and nitric acid), and also a combination of oxidizing agent, nitric acid with a halogen , hydrogen peroxide (H_2O_2), or chromic acid ($HCrO_4$). Gold can also be dissolved in a combination of water and a halogen (the Plattner process) and in selenic acid.

Aqueous solutions of alkali metal hydroxides, alkali metal salts of the mineral acids, and alkali metal sulfides do not attack gold. However, gold dissolves in solutions of alkali metal cyanides in the presence of oxygen or other oxidizing agents, like cyanogen bromide (the Diehl process), 4-nitrobenzoic acid and 3-nitrobenzenesulfonic acid, provided they do not rapidly destroy the cyanide. Gold is also 'attacked by sodium thiosulfate solutions in the presence of oxygen, and by alkali metal polysulfide solutions.

Gold reacts readily with dry chlorine. The maximum reactivity occurs at 250°C, and the minimum at 475 °C. Above 475°C the reactivity increases with increasing temperature up to and beyond the melting point (Habashi, 1997).

2.2. Geology/Types of gold Deposits

Gold occurs in a wide variety of geological settings, and understanding the types of gold ore deposit is a critical for determining process techniques.

Gold deposits are quite common, in numbers, geographical spread and genetic diversity. Clearly, relatively common crustal fluids are able to mobilize, transport and concentrate gold. Metamorphic and magmatic fluid systems are prolific producers of primary gold deposits.

2.2.1. Major types of gold ore Deposits

2.2.1.1. Orogenic gold deposits (also kwon as mesothermal or lode gold)

Orogenic gold deposits are hydrothermal (metamorphic fluids, meteoric water, sea water, connate water…) origin deposit in the crust in which associated magmatic intrusions are considered as a source of heat for fluid circulations (Nguimtsia et al., 2017).

Host rocks: quartz veins and vein stockworks in schists, greenstones, and sediments.

Ore and gangue mineralogy: the main ore is native gold associated with arsenopyrite, pyrite, and pyrrhotite. There may be also magnetite, sphalerite, and chalcopyrite.

Gold form: free gold, often associated with pyrite, arsenopyrite. Process techniques often involve gravity + cyanidation-CIL/CIP.

2.2.1.2. Carlin-Type (sedimentary-hosted) gold deposits

The Carlin-type gold deposits, named after discovery in Nevada, America in 1960s make up the biggest hydrothermal gold deposits in the globe (Nguimatsia, et al., 2017).

Host rocks: carbonate rich sedimentary rocks. Intrusive rocks mainly felsic porphyritic dykes are also present.

Ore and gangue mineralogy: ore minerals include very fine grained native gold, pyrite, realgar, and orpiment. There may be also arsenopyrite, cinnabar, fluorite, barite and stibnite.

Gold from as submicroscopic, refractory gold in pyrite and arsenopyrite and processing involve roasting, POX or BIOX followed by cyanidation

2.2.1.3. Volcanogenic Massive Sulfide (VMS)

VMS deposits are stratiform ore bodies formed from hydrothermal fluids in the seafloor associated with volcanic rocks (Nguimtsia et al., 2017). Such deposits form in a range of tectonic environments and occur in volcanic and volcano-sedimentary sequences from Archean to present.

They are primarily mined for copper, zinc and lead but some of them contain significant amounts of gold or silver.

Host rocks: They may occur in any rock type, but the predominant hosts are volcanic rocks and fine grained, clay rich sediments and turbiditic to hemipelagic graywacke interbedded with or intruded by basalt.

Ore and gangue minerals: iron sulphides (pyrite, pyrrthotite) with chalcopyrite, sphalerite, and galena as the principal economic minerals and barite and cherty silica are common gangue accessory minerals.

Gold form associated with Cu-Zn-Pb sulfide ores and processing of the deposit involves flotation for base metal concentrates, gold as byproduct.

2.2.1.4. Epithermal gold deposits

The epithermal deposits are magmatic-hydrothermal origin gold deposit related to volcano-plutonic arcs along subduction zones tectonic settings.

Host rocks: Host rocks range from volcanic andesitic to dacitic belonging to the calcalkaline series as well as rhyolite, and tuffs.

Ore and gangue minerals: Gold and silver are the main economic minerals with lesser Hg, The common gangue minerals are quartz, chalcedony, calcite, rhodochrosite, adularia, barite and illite in low sulfidation and quartz, kaolinite, alunite and barite in high sulfidation.

Gold form: free-gold or associated with sulfides, tellurides, or native silver

Processing: cyanidation; refractory ores may require oxidation

2.2.1.5. Porphyry Deposits

Porphyry deposits are magmatic-hydrothermal deposits connected with felsic to intermediate magma intrusions, making up the largest gold reservoirs deposit. The main metals occurrences in this type of deposit are copper, molybdenum and gold.

Host rocks: Gold occurs in porphyritic, fine-grained diorite and tonalite as well as grnodiorite, and quartz monazite

Ore and gangue mineralogy: Native gold and electrum, in a quartz stockwork. Magnetite is commonly present (Rytuba and Dannis, 1991).

Gold form as disseminated gold with Cu-Mo-Au sulfides and processing of the deposit include flotation for copper/gold concentrates.

2.2.1.6. Skarn Deposit

Skarns deposits formed at contact zone between intrusive and carbonates by hydrothermal fluids interaction from silicate magma.

Host rocks: Gold skarns are hosted by sedimentary carbonates, calcareous clastics, volcaniclastics or (rarely) volcanic flows.

Ore and gangue mineralogy: Native gold ± pyrrhotite ± chalcopyrite ± pyrite ± magnetite ± galena ± tetrahedrite for Magnesian subtype and Native gold ± chalcopyrite ± pyrite ± arsenopyrite ± sphalerite ± magnetite ± hematite ± pyrrhotite ± galena ± tellurides ± bismuthinite for calcic subtype.

Gold form associated with base metals (Cu, Zn, Pb) and processing involves flotation and/or cyanidation depending on mineralogy

2.2.1.7. Iron-Oxide-Copper-Gold (IOCG)/ Deposit

IOCG deposits are of magmatic-hydrothermal origin and are distinguished by high concentration of iron oxides, phosphorus, fluorine, barium and rare earths, and their low titanium content. These deposits, which date from the Archean to the Mesozoic era, are primarily mined for their copper and gold (Nguimatsia et al., 2017).

Host rocks: host rocks include plutonic granitoids, andesitic (meta) volcanic rocks, and (meta) siliclastic-metabasic rock, hematite-rich breccias.

Ore and gangue mineralogy: In IOCG deposits, the ore and gangue mineralogy is characterized by copper-iron sulfide chalcopyrite as the primary ore mineral, along with pyrite as gangue, together constituting 10–15% of the rock volume. Additional copper-bearing phases include malachite, cuprite, native copper, and minor digenite and chalcocite (Skirrow, 2022). The gangue assemblage consists of hematite, actinolite, pyroxene, tourmaline, epidote, and chlorite (Skirrow, 2022).

Gold is commonly associated with copper sulfides and iron oxides, and the processing of such deposits typically involves flotation to produce copper-gold concentrates (Sillitoe, 2010; Bulatovic, 2007).

2.2.1.8. Intrusive related gold system

Intrusive related systems deposits are associated with granitic intrusion in orogenic belts that are orthomagmatic origin (Andersen et al. 1998).

Host rocks: intrusive rocks, often with sheeted veins or breccias Gold form often free gold with arsenopyrite, Bi minerals and processing involve cyanidation; sometimes requires oxidation

2.2.1.9. Lateritic and supergene gold deposit

Lateritic and supergene gold deposits are related to weathered zones in tropical climates.

Host rocks: regolith overlying primary gold deposits. Gold forms as free gold in clay or iron oxide-rich laterite and processing of the deposit may be gravity + simple cyanidation.

2.2.1.10. Placer gold deposit

Placer deposits are formed when gold-bearing lode ores are exposed to chemical and physical weathering and subsequent erosion, resulting in transportation and deposition to form sedimentary deposits. They are often deposited at river beds, alluvial plains and beach sands.

Host medium: unconsolidated sediment (particulate rock that is not cemented together). The host sediment can range from gravels to sand in fluvial systems, as well as to various types of tills in glacial or beach sands.

Ore and gangue mineralogy: gold occur as native metal, usually associated with varying amounts of silver as alloys such as electrum. It also occurs in chemical combination with tellurium and mercury. Gold is usually accompanied by "black sand," consisting of magnetite, ilmenite, hematite, garnet, zircon and other heavy minerals.

Gold form coarse, free-milling gold nuggets and flakes and processing involve gravity concentration (sluicing, panning, jigs etc).

2.3. Mineralogy of Gold

2.3.1. Gold Minerals and Alloys

Gold being the most inert metal, only few minerals naturally occur as gold compounds and it mainly occurs as native metal frequently alloyed with silver (Boyle, 1979). Gold alloy with greater than 20% silver content is called electrum. Copper is found association with native gold similar to silver and may occur concentrated in its lattice in minor and larger amounts like in cuproauride, tetraauricupride and auricupride. Tellurides are the most abundant gold-bearing minerals after native gold and electrum, with aurostibite ($AuSb_2$) being less common. The predominant tellurides are calaverite ($AuTe_2$) and sylvanite [$(Au,Ag)Te_2$].

Native gold: Gold content of native gold mostly vary between 85% and 95%, where silver is the main impurity. Native gold may occur as free milling (coarse grained), or refractory (as inclusions in sulphide and sulphosalt minerals). Silver content of native gold may range from 2–20% (Morrison et al. 1991), 0.1–0.5% copper and iron, and trace amounts of bismuth, mercury, lead, tin, zinc and platinum group metals. Gold can be found alloyed with PGE metals though relatively rare (Cabral et al. 2002).

Electrum: Gold usually occurs alloyed with some silver and called electrum when the silver content is between 20% and 55%. Electrum has a pale-yellow color and lower density.

Amalgam: Mercury has strong affinity for gold and many occur in nature as amalgam (Au_2Hg_3) and naturally occurring amalgam is much more widely distributed in gold-mining (Yannopoulos, 1991).

Tellurides: Gold tellurides occur widely in both epithermal and Archean greenstone belt type deposit. The most common gold-bearing varieties are sylvanite ($(Au,Ag)_2Te_4$), calaverite ($AuTe_2$), and petzite (Ag_3AuTe_2), with krennerite ($AuTe_2$), montbrayite (Au_2Te_3), and kostovite ($CuAuTe_4$) less common (Yannopoulos, 1991). The densities of gold tellurides are lower than native gold, and the colors are less distinctive shades of white, gray, and black.

Other gold minerals: Gold occasionally occurs with bismuth in the mineral maldonite (Au_2Bi). Maldonite has lower density and Mohs hardness (1.5 to 2.0) than gold and dissolve slowly in cyanide solutions (Marsden and House, 2006). Gold and copper form the extremely rare intermetallic compounds and the copper content imparts a deep red color.

Table 2: Major gold minerals

Group	Mineral	Chemical formula	Impurity content	Gold (Au) content (%)	Density (g/cm^3)
Native gold and alloys	Native gold	Au	0-20%Ag	>75	16.4-19.3
	Electrum	Au/Ag	20-50%Ag	45-75	13.2-16.4
	Cuproauride	Au/Cu	5-10%Cu	65.8-92.7	11.5
	Auricupride	$Au\ Cu_3$	40%Cu	50.8	11.5
	Amalgama	Au/Hg		10-34	15.5
	Bismuthauride	Au/Bi	2-4%Bi	64.5-65	15.5
Tellurides	Calaverite	$AuTe_2$		39.2-42.8	9.2
	Sylvanite	$(Au, Ag)Te_2$		24.2-29.9	8.2
	Petzite	Ag_3AuTe_2		9.0-25	9.1
	Nagyagite	$Au(Pb,Sb,Fe)(S,Te_{11})$	unstable	7.4–10.2	7.5
	Montbrayite	Au_2Te_3		38.6-44.3	9.9
	Krennerite	$AuTe_2$		30.7-43.9	8.6
	Kostovite	$CuAuTe_4$		25.2	
Antimony	Aurostibnite	$AuSb_2$		43.5–50.9	9.9
Bismuth	Maldonite	Au_2Bi		64.5–65.1	15.7
Gold associated with PGE	Platinum gold	AuPt	Up to 10%Pt		19.3-21.45
	Rhodite	AuRh	30-40%Rh		
	Rhodian gold	AuRh	5-11%Rh		
	Aurosmiride	Au,Ir,Os	5%Os+5-7%Ir		

(Source: Kuch and Plimer (2001), Palache et al (1994)

2.3.2. Classification of gold ores and Minerals

Gold ores are generally divided into two main types: free-milling and refractory. Free-milling ores are characterized by the ability to recover more than 90% of their gold content using

standard cyanide leaching. In contrast, refractory ores either yield poor gold recoveries or achieve acceptable recoveries only through notably higher reagent usage or more elaborate pretreatment methods (La Brooy et al., 1994; Zhou et al., 2004; Marsden and House, 2006).

Gold mineralogical types: Based on their mode of occurrence or deportment, gold in an ore can be categorized into three mineralogical types such as microscopic, submicroscopic, and surface-bound gold (J. Zhou et al., 2016).

Gold minerals are those that contain gold as a primary component, such as native gold and electrum. In contrast, gold carriers include not only these gold minerals but also other minerals-like pyrite and arsenopyrite-in which gold occurs only in trace amounts (Zhou et al., 2004).

I. Microscopic Gold

Microscopic gold, also known as visible gold, includes alloys of gold, gold-(tellurides, sulfides, selenides, sulfotellurides, and sulfoselenides), among others (Zhou, 2004). In primary ores, microscopic gold occurs as pristine grains of various sizes and shapes, found within fractures and microfractures, or attached to /and enclosed within other minerals.

II Submicroscopic Gold

Submicroscopic gold cannot be detected using an optical microscope or a scanning electron microscope (Zhou, 2004). It represents the primary form of gold found in refractory gold ores, including: Carlin-type gold deposits, certain epithermal gold deposits and volcanogenic massive sulfide (VMS) deposits.

In these ores, gold is typically present as distinct particles smaller than 0.1 μm in diameter, enclosed within sulfide minerals-primarily pyrite and arsenopyrite (Hausen, 1981; Radtke, 1985; Hausen et al., 1986; Wang et al., 1992, 1994). The gold content in pyrite and arsenopyrite varies from less than one part per million (ppm) to several hundred ppm. Other minerals hosting invisible gold include chalcopyrite (Cook et al., 1990), loellingite (Neumayr et al., 1993), marcasite (FeS), iron oxides, realgar, and clay minerals (Chao et al., 1987; Wang et al., 1994). The term "submicroscopic" refers to both solid-solution and colloidal forms of gold.

Solid solution gold- Solid-solution gold is gold that is chemically locked/atomically distributed in the crystal structure of sulfide minerals like pyrite and arsenopyrite. Solid-solution gold is typically strongly enriched in the finer-grained sulfides (<20 μm) and it is hard to liberate from arsenopyrite (Cook and Chryssoulis, 1990; Novgodorava, 1993). Other minerals that may contain significant concentrations of solid solution gold are loellingite, enargite and tennantite.

Colloidal gold: refers to gold that occurs as discrete submicron inclusions within sulfide minerals. These inclusions are not visible under optical microscopes or conventional scanning electron microscopy (SEM), but they can be detected using secondary ion mass spectrometry (SIMS) (Chryssoulis et al., 1987).

Colloidal gold can be also imaged and analyzed by high-resolution transmission electron microscopy (HR-TEM) (Bakken et al., 1989) and vary from 5 to 500nm (Thiele, 1950). The preferential host of colloidal gold is pyrite and, to a lesser extent, arsenopyrite. Unlike solid-solution gold, there is no requirement for pyrite to be arsenian (arsenic-bearing typically with more than 0.5% As by mass).

III. Surface Gold: Surface gold refers to gold that is adsorbed onto the surfaces of mineral particles-primarily carbonaceous particles. It is not visible under either an optical or an electron microscope. This type of gold can only be detected using LIMS, and the main carriers of surface gold in the ore include iron oxides (FeOx), stained quartz, carbonaceous matter, clay minerals, and wood chips (Zhou et al., 2004).

Table 3: Classification of gold by form and carriers

Form	Microscopic Gold	Submicroscopic Gold	Surface Gold
Nature	Visible under a microscope	Invisible under a microscope	Invisible under a microscope
Carrier	Found in all gold-bearing minerals, most commonly native gold and electrum, and less frequently in calaverite, aurostibite, and maldonite.	Hosted in arsenopyrite, pyrite, marcasite, chalcopyrite, enargite, realgar, loellingite, acanthite, iron oxides, and clay minerals.	Associated with carbonaceous matter, iron oxides, stained quartz, activated carbon, clay minerals, wood chips, pyrite, and arsenopyrite.

(Source: J. Zhou, et al., 2004)

2.3.3. Mineralogical Characterization

Mineralogical characterization involves determination of mineralogy (gold ore minerals, gangue, and host minerals/carriers), ore mineral associations, grain size distribution, modal mineralogy, textural and liberation test via X-ray diffraction (XRD), X-ray fluorescence (XRF), petrography and optical microscopy (thin sections and polished sections), EMPA, QEMSCAN, SEM, LAM-CP-MS, MLA, D-SIMS, TOF-SIMS, and other analytical techniques.

I. Gold ore types classification (based on difficulty in processing and recovery)

Classification system of gold ores may vary from author to author with almost the same concept. The following three distinct gold type's description is strongly based on Vaughan (2004).

These include (1) free milling (oxides and sulfides), (2) complex ores (cyanide consuming, oxygen consuming and preg-robbing ores), and (3) refractory (in order of increasing processing difficulty).

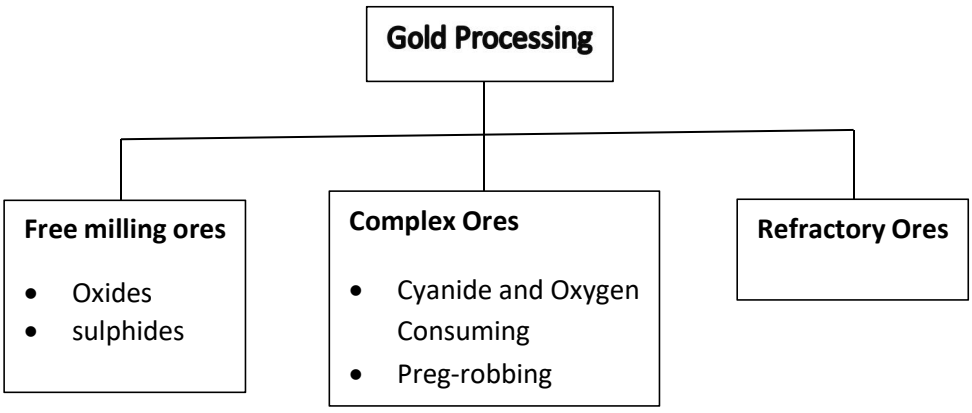


Figure 3 Gold ore characterization chart

a. **Free milling ores**

Free milling ores are defined as those from which cyanidation can extract about 95% of the gold when the ore is ground to a size of 80% passing below 75μm, as commonly applied in industrial practice, without incurring prohibitively high reagent consumptions. Frequently, some of the gold is recovered by gravity concentration and gangue mineral composition does not significantly affect the processing requirements (Marsden and House, 2000).

b. **Complex ores**

Complex ores are ores from which high recovery of gold is possible only under modified or more intense leaching conditions. Complex ores can be subdivided into two classes: preg-robbing and reactive (cyanide and oxygen consumers).

i. **Preg-robbing ores**

Preg-robbing ores host constituents that can adsorb gold-cyanide complexes during the leaching process-such as carbonaceous material (particularly elemental and organic carbon)-though clays exhibit only a limited preg-robbing ability (Goodall, 2005; Miller, 2005; Vaughan, 2004).

Carbonaceous preg-robbing: The most famous carbonaceous ores are those containing gold, such as the deposits found in Nevada's Carlin region. These ores are challenging to process because the finely divided carbonaceous matter within them absorbs gold from the leaching solution, which is why they are referred to as "preg-robbing" ores.

The preg-robbing parts of the ore are carbonaceous materials such as wood chips, organic carbon, and native carbon (Rees and van Deventer, 2000). Gold can also coated by carbonaceous matter that can prevent cyanide solution from dissolution of gold (D. Miller et al., 2009).

The carbonaceous material originates from metamorphic alteration of organic matter that was initially associated with the rock. This process, known as graphitization, is influenced by temperature, pressure, and the nature of the carbon precursor (Beyssac et al., 2002).

ii. Reactive ores

Reactive ore are any ore that contains material that reacts with reagents required for successful gold leaching. These reactive materials tend to be cyanicides (i.e. they react with and reduce the available concentration of cyanide) or oxygen consumers. Cyanicide minerals include; pyrrhotite, copper minerals (such as chalcocite, malachite, azurite, and cuprite), as well as most base metal minerals that contain iron, arsenic, antimony, zinc, nickel, and cobalt (Aylmore and Muir, 2001; Karimi et al., 2010).

Cyanide consuming ores: includes ores associated with base-metals (Cu, Zn, Pb), particularly copper ore minerals that can consume cyanide and lowering gold recoveries.

The most difficult copper-gold ores to treat are near-surface oxide and supergene ores, which frequently contain copper oxides, carbonates, metallic copper, and the secondary copper sulfides (such as chalcocite). These minerals are much more cyanide-soluble then chalcopyrite, which is the most common sulfide in primary (hypogene) ores.

Oxygen consuming: Ore minerals that dissolve by oxygen (like pyrrhotite). Pyrrhotite is common in many gold ores and is easily oxidized, thereby consuming oxygen from the leach solution. Observations indicate that certain pyrrhotites undergo oxidation faster than others, likely due to differences in their iron-deficiency levels (expressed as $Fe_{1-x}S$). Consequently, some gold ores containing pyrrhotite pose greater processing challenges than others.

In addition to the copper minerals and pyrrhotite, other minerals that consume cyanide, oxygen, or lime, to a greater or lesser extent, include arsenopyrite (FeAsS), realgar (AsS), orpiment (As_2S_3), and stibnite (Sb_2S_3), the latter two being the most reactive. The presence of stibnite and aurostibite in antimonial gold ores may cause considerable processing problems.

c. Refractory ores

Refractory ores are ore deposits from which acceptable gold recoveries cannot be achieved using standard procedures. These ores fall into two categories based on how the gold is locked: physically or chemically, both of which prevent lixiviants such as cyanide from accessing the gold. Physically locked gold occurs as extremely fine inclusions, typically within sulfide minerals. Chemically locked gold, on the other hand, is found either as discrete gold minerals, such as gold tellurides, aurostibite, aurocupride, and maldonite (Harris, 1990; Vaughan, 2004); or as a solid solution within certain minerals, where gold atoms are incorporated into the crystal lattice (Chryssoulis, Cabri, and Salter, 1987; Vaughan and Kyin, 2004). Arsenopyrite, and to a

lesser extent pyrite, are known to host this type of solid-solution gold (Barker et al., 2009; Vaughan, 2004).

Pyrite is the primary sulfide mineral that hosts gold. Within pyrite, gold is predominantly found as native gold or electrum, occurring in a wide range of grain sizes and diverse forms that vary according to the ore's grade and overall textural characteristics. The refractory nature of such ores stems from the gold remaining locked within the pyrite matrix, even after the finest possible grinding; typically limited to particle sizes of around 10 to 15 μm by conventional mills, which prevents complete liberation of the finer gold.

Arsenopyrite is a fairly known gold host mineral, likely ranking next to pyrite. The associations between gold and arsenopyrite closely resemble those between gold and pyrite, involving gold distributed along fractures and voids, as well as fully enclosed particles of various sizes.

Gold ores containing pyrite, pyrrhotite, arsenopyrite, and/or stibnite are refractory. Besides consuming high amounts of cyanide, arsenic and antimony minerals can also contain microcrystalline gold trapped within their crystal lattices.

II. Categorization of Gold Ores by Mineralogical Features and Processing Methods

Based on their mineralogical characteristics and the mineral processing techniques they demand, gold ores can be grouped into the following types: placer gold, quartz vein-lode ores, oxidized ores, silver-rich ores, copper sulfide ores, iron oxide copper-gold ores, iron sulfide ores, arsenic sulfide ores, antimony sulfide ores, bismuth sulfide ores, telluride ores, and carbonaceous-sulfidic/carbonaceous ores (Zhou et al., 2004; Zhou and Y. Gu, 2016).

Generally, ores such as placer gold, quartz vein-lode, oxidized, silver-rich, copper sulfide, and iron oxide copper-gold tend to be more free-milling. In contrast, arsenic sulfide, antimony sulfide, bismuth sulfide, telluride, and carbonaceous-sulfidic or carbonaceous ore types are more complex and refractory.

Placers: In placer deposits, gold is either readily liberated or already freed prior to processing. Grain sizes typically range from 50 to 100 μm. These ores are free-milling, allowing gold recovery via gravity separation and/or direct cyanide leaching (Zhou and Y. Gu, 2008).

Quartz vein-lode ores: In quartz vein-lode deposits, gold is primarily found as native metal within quartz veins, lodes, or stockwork zones, with lesser amounts occurring as tellurides, and occasionally as aurostibite or maldonite. While much of the gold exists as free particles, some may be finely disseminated within the ore. These ores are considered free-milling, allowing gold recovery through gravity separation and/or direct cyanide leaching (Zhou and Y. Gu, 2008).

Oxidized ores: In oxidized ores, gold is typically found either in a free state or within the alteration products derived from sulfide minerals. Such ores are free-milling, allowing gold to be recovered through gravity separation and/or direct cyanide leaching. While the oxidized zones of

some epithermal deposits may also be free-milling, they more often contain substantial amounts of sulfides. In these cases, gold is present as fine inclusions or at a submicroscopic scale, making the ore refractory.

Silver-rich ores: In these ores, gold is typically found as electrum, though kustelite may occur in certain deposits, and native silver can also be available. These ores are often free-milling, but when the silver grade exceeds 10ppm and/or the gold is in the form of electrum, adjustments to the processing method may be required. Due to silver's higher reactivity, it can affect the behavior of gold during flotation, leaching, and other recovery processes. Electrum with a high silver content can result in poor gold extraction by flotation, as the silver tends to tarnish (Fleming, 1998).

Copper sulfide ores: In these ores, gold can occur either as coarse, liberated particles or as fine particles enclosed within copper sulfides. These ores are classified as either free-milling or complex (Zhou et al., 2004).

Iron sulfide ores: In these ores, gold is present as free particles, attached to sulfide minerals, or included within them-most often in pyrite, and less frequently in marcasite and pyrrhotite as well as in submicroscopic form within sulfides. These ores contain varying ratios of non-refractory and refractory gold. Gold in non-refractory sulfide ores can be extracted through whole-ore cyanidation or a combination of flotation and cyanidation (Zhou et al., 2004).

Arsenic sulfide ores: In arsenic sulfide ores, gold is present both as free particles and inclusions, along with submicroscopic gold locked within arsenopyrite and its oxidation products. These ores contain varying ratios of non-refractory and refractory gold. To achieve satisfactory gold recovery through cyanide leaching, it requires a pre-oxidation step beforehand (Zhou et al., 2004).

Antimony sulfide ores: In antimony sulfide ores, gold is predominantly found as native gold, either exposed or encapsulated, along with small to moderate quantities of aurostibite within the sulfides. Aurostibite, a type of antimony sulfide gold ore, exhibits slow dissolution during cyanide leaching and is classified as a refractory gold mineral.

Bismuth sulfide ores: In bismuth sulfide ores, gold is predominantly found in its native form, accompanied by small to moderate quantities of maldonite. Maldonite, bismuth sulfide gold mineral, dissolves slowly during cyanide leaching and is classified as a refractory gold ore.

Telluride ores: In telluride ores, gold can be found either as free particles or enclosed within sulfides, occurring as native gold and gold tellurides. Additionally, submicroscopic gold may also be present. Ores containing telluride gold-such as gold tellurides, are often moderately refractory due to their slow dissolution rate during cyanide leaching.

Carbonaceous-sulfidic ores/Carbonaceous ores: In carbonaceous and carbonaceous-sulfidic ores, gold is primarily found as submicroscopic particles within sulfide minerals, as well as gold adsorbed on the surfaces of carbonaceous material and iron oxides (FeOx). The gold is finely disseminated and mostly associated with sulfides such as pyrite or arsenopyrite present in these ores. Typically, the recovery process entails pre-oxidation to liberate gold from sulfide matrices, after which cyanidation is applied, occasionally preceded by flotation concentration (Marsden & House, 2006).

Some gold also occurs as colloidal-grains size less than 0.1 µm within carbonates or microcrystalline quartz (Fleming, 1998). Because carbonaceous matter adsorbs gold from cyanide solutions; a process known as "preg-robbing" recovering gold from carbonaceous sulfidic ores is more challenging (Wan, 2001).

2.3.4. Mineralogical factors affecting gold processing

The mineralogical factors that influence gold processing include particle size; the way gold associates with other minerals; the presence of coatings and rimmings; cyanicides and oxygen consumers, and preg-robbers; refractory gold minerals; and the encapsulation of sub-microscopic gold within sulfide and sulfarsenide mineral structures, among others. Among the factors listed in Table 4, liberation, grain size and association are regarded as the top three factors that are seen in all gold ores (Zhou et al., 2016).

Presence of refractory gold minerals such as calaverite ($AuTe_2$) and sylvanite [$(Au,Au)Te_2$], aurostibite ($AuSb_2$), and maldonite (Au_2Bi) often cause lower gold recoveries due to their slow leaching kinetics. Submicroscopic gold and carbonaceous matter are the main trouble-makers in carbonaceous sulfide ore processing, where gold is not only locked in sulfide minerals but also absorbed onto carbonaceous matter during leaching (preg-robbing) (Zhou et al., 2004; Zhou, 2013).

The key mineralogical factors influencing gold extraction metallurgy include:

Gold Grain Size plays a key role in determining the effectiveness of recovery methods. Coarse gold may not fully leach or may fail to attach to bubbles during flotation. Conversely, ultrafine gold is poorly recovered using gravity or flotation techniques. When the gold is extremely fine (less than 10 µm) and hosted in sulfide minerals, cyanidation can also yield poor results (Marsden et al., 1992). Additionally, visible gold that is encapsulated within sulfide or silicate minerals often leads to significant gold losses.

Particulate gold that is very fine (typically less than 10 µm) and encapsulated in sulfide or other gangue minerals may remain unexposed to cyanide solutions when grinding to a "normal" particle size of 80% passing 75 µm. To liberate such gold, finer or even ultra-fine grinding is often needed-for instance, 80% passing 20 µm or 80% passing 10 µm (Vaughan, 2004; Coetzee et al, 2011).

Submicroscopic gold: Submicroscopic gold is defined as gold occurring in solid solution within extremely fine-grained sulfide minerals. Because this form of gold is poorly liberated even after ultrafine grinding, it represents a major source of gold losses in many cyanidation operations (Vaughan, 2004 and Coetzee et al., 2011).

Gold that is present in "solid solution" or as sub-microscopic particles embedded within the crystal lattices of sulfides-such as pyrite, arsenian-pyrite, stibnite, and arsenopyrite (Reich et al., 2005); can lead to extremely low recovery rates when directly subjected to cyanidation.

Coatings and rimmings: Coatings and rimmings can impact gold extraction, particularly affecting flotation and cyanidation processes. Iron oxides or hydroxides such as limonite and goethite can create coatings or rimmings (Zhou et al., 2004). Another type of coating results from the reaction of sulfide ions with gold, producing insoluble aurous sulfide (Fink et al., 1950). Furthermore, the presence of thioarsenite and thioantimonite ions can also induce gold passivation (Heldey et al., 1958).

Silver in gold minerals: In gold ores, silver primarily occurs within electrum and, less commonly, in kustelite. Silver-rich electrum and kustelite tarnish rapidly upon exposure to air, forming a silver sulfide layer in the presence of sulfide ions. This layer can hinder the penetration of cyanide solution. Subsequent oxidation of the silver sulfide coating into silver sulfate imparts some hydrophilic properties, which may adversely affect recovery through flotation (Jilin Institute of Metallurgy, 1978).

Gold tellurides, aurostibite and maldonite are generally classified as refractory ores as they dissolve only slowly in cyanide solution.

Presence of cyanide and oxygen consumers/Complex ores: Many gold ores are classified as complex due to the presence of minerals that react with cyanide solutions, depleting both oxygen and cyanide, which in turn hinders the efficiency or completeness of gold leaching. The most prevalent problematic minerals include sulfides of iron, arsenic, antimony, copper, zinc, and tellurium (Fleming, 1998).

The presence of cyanide-consuming species, often at levels as low as <100 ppm-such as secondary copper minerals (e.g., chalcocite, covellite, malachite, azurite), can lead to extremely large cyanide usage and results in poor gold recovery, since cyanide preferentially reacts with the more abundant copper phases before it can dissolve gold. Additionally, the formation of insoluble cyanide precipitates containing both copper and gold may further contribute to reduced gold recoveries.

Oxygen is one of the reagents consumed during cyanidation, and a shortage of dissolved oxygen in the leach solution will slow down the cyanidation reaction. Oxygen consumers, such as pyrrhotite and marcasite, can have a detrimental effect on cyanidation. Compounds that consume

oxygen, including pyrrhotite and marcasite, can therefore have a harmful impact on gold leaching.

Gangue Mineralogy: The behavior of gangue minerals varies in several ways:

Quartz and most silicates are generally unreactive. However, under strongly acidic conditions, they can partially dissolve, producing a gelatinous silicate residue (e.g., during bio-oxidation) that may coat exposed gold surfaces and hinder filtration. Chlorite is soluble in sulfuric acid and generates byproducts that also cause filtration difficulties.

Carbonates readily react with sulfuric acid, forming sulfates such as gypsum and magnesium sulfate, which consume large amounts of acid. For instance, 1% limestone in an ore requires 10 kg of H_2SO_4 per tonne of ore. The decomposition products of carbonates can also create downstream issues, including increased slurry viscosity, coating of exposed gold surfaces, and scale buildup in pipes and reactors (Marsden et al., 1992).

Carbonaceous matter and other materials can reduce gold recovery during cyanide leaching by adsorbing dissolved gold from the solution. In Witwatersrand ores (South Africa), pyrophyllite and shale have been identified as gold-adsorbing preg-robbing materials (Corrans et al., 1985).

The presence of preg-robbers, such as organic carbon, can also have a detrimental effect on gold recoveries. Clay minerals, some micas, sulphides and occasionally ironoxyhydroxides may act as preg-borrowers (Venter et al., 2004).

Solid-solution gold analysis should not be limited exclusively to sulfides, because gold can also become finely locked within limonite as a solid-solution during the partial replacement of pyrite by limonite. Given that limonite is hydrophilic, employing flotation for gold concentration may lead to poor recovery (Cyanamid, 1989).

Other deleterious minerals: pyrophyllite and talc are natural floating minerals (Chryssoulis, 2001)**.** Gold ore recover by flotation containing substantial amount of these minerals result in gold grade dilution in the flotation concentrate. The presence of substantial quantities of clay minerals, such as montmorillonite-causes challenges in solid–liquid separation.

Table 4: Common mineralogical issues affecting gold extraction

S/N	Mineralogical Issue	Affected Processes
1	Liberation/locking	Gravity, flotation, and leaching
2	Grain size	Gravity, flotation, and leaching
3	Association	Gravity, flotation, and leaching
4	Surface chemistry	Gravity, flotation, and leaching
5	Coating and rimming	Gravity, flotation, and leaching
6	Dissolution kinetics	Leaching
7	Cyanides and oxygen consumers (secondary copper minerals, pyrrhotite)	Leaching
8	Refractoriness (sub-microscopic gold)	Gravity, leaching
9	Preg-robbing (C-matter, iron oxide, etc.)	Leaching
10	Deleterious minerals/toxic elements (As, Hg, Se, Sb, Te, etc.	Flotation, leaching solution purification, and tails disposal
11	Gangue mineralogy (clays, acid-forming and acid-consuming minerals)	Flotation, leaching and tail disposal

(Source: Zhou, 2016)

2.3.5. Techniques used for gold process mineralogical study

Gold process mineralogical studies typically rely on a combination of conventional and advanced instrumental techniques (Zhou & Cabri, 2004).

a. Conventional techniques

Fire assaying-the traditional approach to gold analysis, is an essential component across various parts of a typical gold process mineralogical study. It offers bulk gold balance information that supports and complements the mineralogical findings from other techniques.

Gravity concentration techniques: Gravity concentration methods are employed to prepare samples for mineralogical studies of gold. The most commonly used techniques include heavy liquid separation, super panning, Mozley table, and hydroseparation. When processing larger sample volumes, Wilfley tables and Knelson concentrators are also utilized (https://www.911metallurgist.c). Among these methods, super panning and hydroseparation prove to be the most effective. With a superpanner, a small tip (i.e., pan concentrate, typically ranging from 100 to 500 mg) is obtained for gold examination, allowing all liberated gold particles to be concentrated in the tip, while a clean sulfide fraction and a silicate fraction are separately recovered for gold assays. Hydroseparation is especially valuable in process mineralogical studies of platinum-group elements, gold, and silver ores, handling sample sizes from 5 g up to 2,000 g.

Reflected light microscopy: Reflected light microscopy remains the most essential and commonly employed technique in gold process mineralogy. At 500x magnification, the resolution limit of optical microscopy is approximately 2 μm for free gold particles and -0.5 μm

for gold inclusions. Its key strength lies in the ability to recognize gold and other minerals based on properties such as reflectivity, color, hardness, cleavage, and other mineralogical features.

X-ray diffraction (XRD): XRD is an analytical technique for mineral identification and qualitative/semi-quantitative mineral analysis of bulk material.

b. Advanced Microbeam Techniques

Advanced analytical methods used in the mineralogical study of gold processing include scanning electron microscopy (SEM); SEM-based quantitative image analysis (encompassing MP-SEM-IPS, IA-KS400 [Zeiss Vision], quantitative evaluation of minerals by scanning electron microscope (QEMSCAN), and mineral liberation analysis (MIA)); electron probe microanalysis (EPMA); secondary ion mass spectrometry (SIMS); particle-induced X-ray emission (PIXE); laser ablation microprobe inductively coupled plasma mass spectroscopy (LAM-ICP-MS); and others.

SEM and image analysis are commonly applied for morphological examinations and the detection of fine-grained gold. Quantitative image analysis is also employed to measure the modal weight percentage of major minerals required for gold balancing.

EPMA is primarily utilized for the quantitative analysis of gold and its associated minerals.

SIMS, PIXE, and LAM-ICP-MS are employed to quantify submicroscopic gold present in sulfide and gangue minerals.

The TOF_LIMS technique is used to quantify gold adsorbed onto the surfaces of carbonaceous matter and other minerals, as well as to determine the inorganic composition of these surfaces.

Table 5: Techniques commonly used in gold processing mineralogy

S/N	Techniques	Detection limit	Application
1	Fire assay (FA)	0.1-50g/t Au	Quantifies total gold regardless of its form
2	Quadruple 1 t FA-AA assay (FA-AA)	0.001g/t Au	Quantifies total gold regardless of its form (enhanced sensitivity)
3	Cyanide leaching (CN)	-	Determines the proportion of gold recoverable via cyanidation
4	Gravity concentration (GC)	-	Enriches gold and gold-bearing minerals
5	Acid diagnostic leaching (ADL)	-	Identifies gold associated with carbonates, sulfides, and silicates
6	Optical microscopy (OM)	-0.05µm	Provides systematic search for gold particles; identifies minerals, alterations, and textural features
7	X-ray diffraction (XRD)	Semi- quantitative	Identifies minerals and performs qualitative/semi-quantitative analysis of bulk material
8	Automated digital imaging system (ADIS)	-	Scans and measures gold particles
9	Scanning electron microscope (SEM)	Semi-quantitative	Scans for gold, identifies minerals, and examines surface morphology
10	Quantitative evaluation of materials by scanning electron microscope (QEMSCAN)	1.5 to 3µm	Scans for gold; identifies minerals; assesses liberation, surface morphology, and modal composition
11	Electron probe microanalysis (EPMA)	0.1% EDX 0.02% WDX	Determines composition of gold and associated minerals
12	Dynamic secondary ion mass spectrometry (D-SIMS)	Sub-ppm	Quantifies and maps gold in sulfides and iron oxides (FeO_x)
13	Proton-induced x-ray emission (µ-PIXE)	ppm	Quantifies and maps gold in sulfides and silicates
14	Laser ablation microprobe plasma mass spectroscopy (LAM-ICP-MS)	Ppb	Quantifies gold in sulfides, silicates, and oxides
15	Time-of-flight laser ion mass spectrometry (TOF-LIMS)	ppm	Quantifies surface gold and analyzes surface chemistry

(Source: Y. Zhou and J. Cabri, 2004)

2.4. Gold Processing Methods/Techniques

The majority of modern gold extraction techniques are rooted in processes that have been recognized or developed for hundreds of years. Methods such as gravity concentration, flotation, amalgamation, cyanide leaching, roasting, zinc precipitation, and carbon or charcoal adsorption have each been in use for over a century, and their various combinations continue to form the foundation of most gold recovery flow sheets today.

Gold processing generally involves comminution, gravity concentration, flotation, leaching, pre-treatments [ultrafine grinding, oxidative (roasting, bacterial and pressure oxidation)], CIP/CIL, elution and electrowinning and smelting to produce gold "Dore" that finally refined to pure gold metal.

2.4.1. Comminution

Communition involve crushing and grinding to reduce ore size and liberate gold particles that is essential for increasing surface area and enabling effective gold recovery.

Comminution of gold ores and concentrates is primarily required to liberate gold, gold-bearing minerals, and other metals of economic value to make them amenable to subsequent gold extraction steps. The degree of comminution required depends on many factors, including the liberation size of gold, the size and nature of the host minerals, and the method(s) to be applied for gold recovery.

2.4.2. Gravity Concentration

Gravity concentration is a process to concentrate the mineral of interest based on difference in specific gravity/density. When two mineral particles of varying densities are placed in a fluid, their motion differs: the denser particle sinks quickly, while the lighter one either remains suspended or is swept away by the fluid's movement.

In current practice, the most commonly employed gravity concentration devices include sluice boxes, shaking tables, jigs, spirals, Moseley sizers, Knelson concentrators, Falcon Superbowl concentrators, and others.

According to Chryssoulis and McMullen (2005), the mineralogical factors that influence gravity-based processing methods include mineral density differential, particle size, degree of liberation, particle shape, composition, and hydrophobicity.

Gravity separation techniques are commonly employed to concentrate gold, owing to the substantial density contrast between the gold-bearing minerals, ranging from gold tellurides (8.2 g/cm³) to native gold (19.3 g/cm³), and the gangue minerals present in the ore, which have an average density of 2.7–3.5 g/cm³ (Kongolo and Mwema, 1998).

Generally, liberation of the constituent minerals from primary source is achieved by communition and grinding. Gravity separation efficiency significantly decreases with decreasing

particles size, although new technological improvements of gravity concentration devices have led to improved separation efficiency when treating fine-grained minerals. In practice, good liberated free coarse gold particles ranges from 2mm down to 40μm are suitable for gravity separation.

Even though gravity separation becomes considerably less effective as particle size decreases, recent advancements in gravity concentration equipment have enhanced its performance of processing fine-grained materials. In practice, well-liberated, free coarse gold particles in the size range of 2 mm down to 40 μm are well-suited for gravity separation. For gold originating from placer deposits, gravity concentration methods remain the primary recovery technique.

New developments of equipment for gravity processing (centrifugal concentrators like Falcon and Knelson) enabled the recovery of free gold down to about 20 μm in size, and occasionally down to 10 μm-with low efficiency (Laplante et al. 1990; .Nelson and Edwards 1990; Marsden et al. 1993).

Gravity concentration is especially advantageous when significant amounts of coarse gold are present (particles larger than 150 μm in diameter), as this type of gold is more challenging to recover efficiently using flotation.

The recovery efficiency of fine free gold particles too small for effective capture varies according to the equipment used: sluices are effective down to 500 μm, jigs to 200 μm, spirals to 50-100 μm, shaking tables to 50 μm, and centrifugal concentrators to 20-40 μm (Will, 1988).

Flaky gold particles are challenging to recover using a centrifugal concentrator because they tend to "surf the bowl," which increases the likelihood of gold being rejected (Knipe and Chryssoulis, 2004). Additionally, hydrophobicity imparted on gold surfaces due to the adsorption of hydrocarbons and elemental sulfur can keep flaky gold floating in shaking table concentrates, thereby leading to losses.

In the primary grinding circuit, a gravity separation process is employed to recover both coarse free gold and gold associated with complex sulfide minerals that interfere cyanidation.

Gravity concentration in gold processing plant often applied on cyclone underflow and sometimes ball mill discharge.

The resulting concentrates by gravity may be treated by direct cyanidation, smelting, amalgamation, intensive cyanide leaching, or occasionally, by flotation depending on their mineralogy.

The benefits of recovery by gravity separation are well-mentioned (Burt, 1984; Laplante and Gray, 2005; Wills, 2007). The application of gravity concentration prior to leaching can be beneficial to overall gold recovery, because coarse gold particles are recovered prior to leaching.

Coarse gold particles take the longest to leach during atmospheric cyanide leaching, and their removal can reduce the leaching retention time.

2.4.3. Flotation

The application of flotation on a reasonable scale within the gold-mining industry commenced in the early1930s following the introduction of water-soluble flotation collectors (specifically xanthates and dithiophosphate collectors) that allowed differential flotation of sulfide minerals (Dunne, R., 2005).

Flotation is a response to surface chemistry of the minerals and used commonly to concentrate sulfide-hosted gold for further processing. Naturally hydrophobic minerals can easily float. However, hydrophilic minerals can only float by the introduction of appropriate reagents (collectors, frothers, activators, depressants and modifiers). According to T. Smith (1980), a perfectly clean gold surface is hydrophilic, exhibiting a contact angle of zero. However, due to contamination by organic compounds, naturally occurring native gold surfaces are hydrophobic, as reported by Wang and Poling (1983).

The optimal processing method for gold ores containing sulfides, arsenides, or tellurides involves the production of a flotation concentrate (Anderson, 1980; Jones and Woodcock, 1984; King, 1982). This approach is nearly always adopted for refractory gold ores, particularly those associated with sulfide mineral species. Flotation reduces the volume of material requiring subsequent pretreatment and gold recovery, and when differential flotation is applied, it can also yield a separate concentrate of base metals that occur alongside gold. Given the fine particle size of gold within sulfides or other refractory matrices, concentration via flotation is necessary. The concentrate is then subjected to roasting/bacterial oxidation, or pressure oxidation to liberate the gold prior to cyanidation (Taggart, 1927; Chryssoulis and Cabri, 1990).

Gold flotation is influenced by several factors, including the Eh and pH of the pulp, the type of flotation gas and oxidation levels, particle size and morphology, flotation kinetics, the presence of slime coatings and floatable non-sulfide gangue, as well as natural metal and organic coatings on the gold surface.

Physical constraints such as the shape and size of liberated gold particles, along with froth stability, significantly influence the flotation recovery of free gold.

It is well established that liberated gold particles smaller than roughly 150 μm are readily floatable using common collectors such as xanthates and dithiophosphates. However, when free gold is floated in the presence of sulfide minerals, gold recovery declines because the sulfides accumulate on bubble surfaces, forming a physical barrier that impedes the attachment of free gold (Teague et al., 1999).

Generally different collectors, frothers, activators, depressants, and modifiers such as PH and Eh are used for flotation of placer and liberated gold; and gold carriers.

The optimal flotation reagent scheme must be chosen based heavily on the specific mineralogy of the gold ore being processed (Blaskett and Woodcock, 1953; Elvey and Woodcock, 1985; Woodcock, 1980).

Free gold slime grains smaller than 5 μm are typically lost to flotation tailings, as flotation efficiency declines sharply for particles below 5-7 μm (Chryssoulis et al., 2004). Floating large gold flakes demands higher collector dosages than those needed for smaller equidimensional grains (Chryssoulis et al., 2003a), and may require a gravity circuit depending on cost-benefit considerations. Gravity separation and flotation are complementary approaches for recovering gold particles across different size ranges.

Generally, gold associated with sulfides, tellurides, copper alloys, (sulfur, copper, silver on gold grains) and organic carbon coatings readily float and aid gold concentration by flotation.

2.4.4. Leaching

Since the late 1800s, cyanidation has been the dominant method for processing gold ores. Its widespread adoption stems from several advantages: relatively low cost, high effectiveness in dissolving gold and silver, selectivity for these precious metals over others, and straightforward recovery of metals from solution (M.D. Adams, 2016). Oxygen, typically supplied from air, is the most common oxidant in cyanide leaching, further enhancing the process's appeal.

Beginning in the mid-1970s, researchers began exploring alternative lixiviant systems for gold and silver extraction, driven by one or more of the following factors:

- Environmental concerns, and in some regions, legal restrictions that limit the use of cyanide;
- Faster leaching kinetics for gold and/or silver offered by some alternatives;
- Suitability of certain alternatives for acidic media, which can be advantageous when treating refractory ores;
- Greater selectivity than cyanide for gold and silver over base metals like copper and zinc.

Key reagent systems that have been studied (or reinvestigated) include chlorine-chloride, thiosulfate, thiocyanate, thiourea, ammonia, ammonia-cyanide, alkaline sulfide, and other halide combinations. Despite these potential benefits, every alternative system currently has drawbacks compared to cyanide. None are broadly applicable without major technological breakthroughs. Common issues include high cost, difficulties with recycling, poor stability, and limited process control. Nevertheless, thiosulfate has become the leading candidate for specific niche applications. Barrick Gold has successfully advanced and commercialized thiosulfate technology for treating carbonaceous "preg-robbing" material at its Goldstrike operation in Nevada. For this emerging technology, carbonaceous preg-robbing ores represent the primary potential application (Santiago & Ladeira, 2019).

2.4.4.1. Cyanidation/cyanide leching

Cyanidation technique is the most prevalent approach for extracting gold from ore, as it transforms the metal into water-soluble aurocyanide complex ions. Once dissolved, the gold is typically recovered using either the Carbon-in-Leach (CIL) or Carbon-in-Pulp (CIP) process (Marsden and House, 1992).

For over a century, large-scale operations have employed cyanide leaching to extract gold from ores and concentrates. The dissolution process is most commonly described by Elsner's equation: $4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_2 + 4NaOH$. A dilute sodium or potassium cyanide solution serves as the lixiviant for the precious metals. Lime or sodium hydroxide is added to maintain a pH between 10 and 11 (Kongolo and Mwema, 1998). Oxygen plays an essential role in gold dissolution. Before gold can form the soluble cyanide complex ion $Au(CN)_2^-$, it must first be oxidized to Au^+ (Adams, 2005).

Cyanidation has two key benefits: the ability of free cyanide to selectively dissolve gold, and the exceptional stability of the resulting cyanide complex.

Cyanide leaching can be applied using agitated tank systems (open or closed), heap or stockpile systems, or in vats. In situ leaching is generally unsuitable for the application of the cyanide reagent scheme because of its toxicity and environmental requirements (Adams, 2005).

Agitated Tank Leaching: This method is widely used for various ore types, typically carried out in steel vessels where solids are kept suspended using either mechanical stirrers or injected air. The ore is ground to a particle size that balances gold recovery with comminution expenses, generally ranging from 80% passing 150 µm to 80% passing 45 µm. In certain cases, the entire ore may need to be milled as fine as 80% below 20-25 µm for optimum performance, which may involve oxidative pretreatment and/or leaching. Agitation leaching is seldom applied to material coarser than roughly 150-180 µm, because suspending larger solids becomes increasingly difficult and equipment wear accelerates. The technique is also being explored for very finely ground materials. Thanks to advances in stirred milling, concentrates have been reduced to 80% passing 7-10 µm to liberate gold locked within refractory or semi-refractory sulfide mineral matrices, prior to agitation leaching and/or oxidative pretreatment.

Heap Leaching: This process involves stacking metal-bearing ore onto an impermeable liner to form a heap. Over an extended period, ranging from several weeks to months or even years, a chemical solution is sprayed onto the ore to dissolve the targeted metals. As the solution percolates through and drains from the base of the heap, it is recovered as a pregnant leach solution. According to Manning and Kappes (2016), heap leaching is typically chosen for purely economic reasons: it offers the best or least risky return on investment under the given conditions. As a low-cost technique, it is particularly well-suited for treating low-grade materials that would not justify the higher expenses associated with grinding and agitation leaching. The ore can be processed either at its run-of-mine (ROM) size or after crushing, with the optimal size

determined by balancing gold recovery against crushing costs. Gold extraction rates in heap leaching generally range from 0% to 80%. Cyanide consumption is typically lower than in agitated leaching systems, usually between 0.1 and 0.5 kg/t for non-refractory ores in crushed ore heaps and ROM stockpiles, though recovery rates are low.

Vat leaching is typically performed in large wooden or steel tanks, or occasionally through a valley-fill heap leaching configuration that allows the heap to be submerged (Marsden & House, 2006). However, this technique is seldom used today due to the high capital expenditure required for constructing the vats, combined with elevated operating costs, while offering only marginal (if any) improvements in recovery relative to conventional heap leaching.

Leachability of Gold Minerals

Cyanidation in Leach Tanks: Among gold-bearing minerals, only native gold, electrum, and auricupride are readily amenable to cyanidation in leach tanks. In contrast, minerals such as sylvanite ($AuAgTe_4$), calaverite ($AuTe_2$), and maldonite (Au_2Bi) are refractory under standard leaching conditions and require more aggressive, customized conditions to liberate part or all of their gold content (Spry et al., 2004). Aurostibite ($AuSb_2$) transforms into auroantimonate ($AuSbO_3$) in alkaline solutions, yielding no gold. Colloidal gold associated with iron oxyhydroxides in framboidal textures typically accumulates in leach plant tailings, indicating poor dissolution kinetics (Chryssoulis & McMullen, 2005). In plants processing sulfidic gold ores, lead nitrate ($PbNO_3$) is commonly added to improve gold leaching kinetics and recoveries (Sayiner, B., 2014).

Cyanicides are species that disrupt gold cyanidation through several mechanisms: (1) forming stronger cyanide complexes than gold (e.g., copper minerals); (2) generating new radicals such as thiocyanate (SCN^-); (3) adsorbing cyanide radicals (e.g., iron sulfides); and (4) consuming dissolved oxygen (e.g., pyrrhotite).

Early detection of these species is critical for implementing appropriate corrective measures, either as pretreatment steps or by adjusting leaching parameters to mitigate adverse effects.

Table 6: Response to direct cyanidation of the most common gold minerals and cyanicide minerals

Response to Direct Cyanidation of the Most Common Gold Minerals			**Cyanicides**		
			CN-Soluble Cu Minerals	Iron Sulfides	Fe/Sb/As Mineral
Gold minerals	Rate	Dissolution (%)	$Cu(CN)_x^{y-}$ formation	CN sorption	Dissolved O_2 consumption
Native gold (Au>0.8Ag<0.2)	Fastest	100	Malchite	pyrite	Pyrrhotite
Electrum (Au<0.8Ag>0.2)	Fast	100	Azurite		Marcasite
Aurocupride (AuCu)	Fast	100	Native Cu		Szomolnokite
Sylvanite ($AuAgTe_4$)	Slow	100	Cuprite		Stibnite
Calaverite ($AuTe_2$)	Slow	>80	Bornite		Gudumundite
Maldonite (Au_2Bi)	Slow	0-20	Covellite		Berthierite
Aurostibnite ($AuSb_2$)	0	0	Chalcocite		Realgar
Auroantimonate ($AuSbO_3$)	0	0	Tetrahedrite		Orpiment
			Elemental sulfur		Arsenopyrite
			SCN^- formation		Arsenian pyrite

(Source: S.L. Chryssoulis and J. McMullen, 2005)

2.4.4.2.Alternative Lixivants

Due to environmental concerns surrounding cyanide, alternative, more eco-friendly leaching agents are being researched and used.

Thiourea Leaching: An acidic leaching method that has been shown to be effective, often in combination with chlorination roasting

Thiosulfate Leaching: Often used in conjuction with carbon adsorption techniques or followed by reduction precipitation. It is most suitable for carbonaceous ores and silver rich ores.

2.4.5. Pretreatment for cyanide leaching

Pretreatments that include ultrafine grinding and oxidative (roasting, atmospheric, pressure and bio/bacterial oxidation) are required for complex and refractory ores.

Ultrafine grinding

This is physical method of gold liberation from sulfides, and silicate gangue minerals by reducing the particle size of ores significantly, often down to 10 microns.

The development of efficient fine-grinding technologies, such as the Xstrata IsaMill, Metso SMD Detritor, and Metprotech mill, has accelerated the use of ultrafine grinding to liberate gold from sulfide ores and concentrates. These advances enabled more energy-efficient comminution to finer particle sizes, typically 80% passing 10-15 μm or below, giving rise to the term "ultrafine" grinding. Additionally, the Metso Vertimill, initially proven in numerous tertiary grinding and regrinding applications, has since been adapted for ultrafine grinding, achieving product sizes of approximately 80% < 15 μm. The economic feasibility of grinding to such fine sizes created an alternative to costlier oxidative pretreatment methods, such as roasting, pressure oxidation, and biological oxidation, by directly liberating precious metals from refractory sulfides (M.D. Adams, 2005).

Oxidative Pretreatment

Oxidative pretreatments are applicable for sulfidic and carbonaceous refractory ore which are not effectively treated by simple cyanidation, flotation, or gravity concentration techniques. These include roasting, atmospheric oxidation, pressure oxidation, and biological oxidation (bacterial oxidation).

Oxidative pretreatment methods, such as roasting, atmospheric oxidation, pressure oxidation, and biological (bacterial) oxidation, are suitable for treating sulfidic and carbonaceous refractory ores that do not respond well to conventional cyanidation, flotation, or gravity concentration.

Roasting: Roasting is pyrometallurgical process that involves heating the ore in an oxygen-rich environment to decompose sulfide minerals and remove interfering elements like arsenic and sulfur; unlocking the gold from the sulfides.

During the 1980s, advances in roasting technology led to a renewed interest in low-cost roasting as a pretreatment method for refractory gold and silver ores and concentrates (Marsden and Sass 2014). The technique is especially advantageous for treating carbonaceous (preg-robbing) ores and sulfide minerals. Nevertheless, growing environmental concerns over sulfur dioxide (SO_2) emissions mean that new roasters are unlikely to be considered for many future projects.

Atmospheric Oxidation: Under ambient conditions, dissolved oxygen in solution can oxidize certain sulfide minerals. However, this atmospheric oxidation typically results in only partial surface oxidation of the sulfides and is generally ineffective for treating ores in which gold is finely disseminated within the sulfide matrix (Marsden & House, 2006).

Pressure oxidation is a process that oxidizes sulfide minerals, such as pyrite (FeS_2) and marcasite (FeS_2), under elevated temperature and pressure. This oxidation liberates encapsulated gold particles from the sulfides, rendering the oxidation residue more amenable to subsequent gold recovery via cyanidation. In the gold industry, two major developments in pressure hydrometallurgy include: (1) pressure oxidation of whole ores using either alkaline or acidic routes, or (2) acidic pressure oxidation of sulfide concentrates.

Whole-ore treatment is typically employed when flotation fails to achieve satisfactory gold or sulfide recovery in the concentrate. Pressure hydrometallurgy offers an economically viable and environmentally compatible approach for treating certain refractory gold ores (Thomas, 2005). The conventional process operates at approximately 180-220 °C and pressures exceeding 2000 kPa. Pressure oxidation is an effective method for a wide range of refractory ores and concentrates, capable of oxidizing over 95% of the contained sulfide sulfur and achieving high gold recoveries (>90%) in subsequent cyanide leaching. The process is noted for low cyanide consumption during downstream gold recovery, as complete conversion to sulfate is achieved, but only under high-pressure, high-temperature oxidation conditions (M.D. Adams, 2005). It is a well-established, proven oxidation technique with fast kinetics, relying solely on physical and chemical principles. Feeds with high carbonate content require acid pretreatment.

Biological Oxidation: During the 1970s and 1980s, researchers at institutions including Cardiff University (Wales), the University of British Columbia (Canada), the University of New Mexico (United States), and Gencor (South Africa) explored the use of bacterial oxidation for treating sulfide-based refractory gold and silver ores (Brierly, 2014). A key benefit of this process is its relatively low capital and operating costs. However, it also presents drawbacks, such as generally lower gold recovery and less robust process control, which result from the long residence time and slow response to changes in operating conditions.

The typical flowsheet for bacterial oxidation of refractory gold concentrates involves several common stages: crushing, milling, flotation to produce a concentrate, bacterial oxidation of that concentrate, followed by cyanidation and gold recovery from the oxidized residue.

2.4.6. Gold Recovery from Cyanide Solution

Gold recovery methods include zinc cementation, carbon adsorption (such as carbon-in-pulp (CIP) or carbon-in-leach (CIL)), and resin-in-pulp (RIP) or resin-in-solution (RIL).

Zinc cementation is an electrochemical precipitation process that relies on redox (oxidation-reduction) reactions. The process is electrochemical in nature, using a less noble metal (such as zinc) to precipitate the valuable metal from solution. The cementation of gold using zinc can be represented by the following balanced equation: $2NaAu(CN)_2 + Zn \rightarrow Na_2Zn(CN)_4 + 2Au$

The Merrill-Crowe process, which employs zinc in either dust or shaving form to precipitate gold and silver from cyanide solutions, has been a well-established method in the mining industry for well over a century. Although this technique was once the dominant recovery method, it has been largely superseded by carbon-in-pulp (CIP) and carbon-in-leach (CIL) processes because of higher capital and operating costs. Nevertheless, zinc cementation remains a viable option in several specialized metallurgical applications when the silver-to-gold ratio in solution is high (Marsden and House, 2006; Hodouin et al, 1987).

Carbon adsorption involves the recovery of gold by binding it to activated carbon from an alkaline cyanide solution. The introduction of activated carbon to recover gold from cyanide leach solutions in the last quarter of the 20th century transformed the economics of gold ore processing. By replacing the Merrill–Crowe zinc cementation step, the carbon-in-pulp (CIP) and carbon-in-leach (CIL) recovery processes enabled the treatment of lower grade ores with lower capital and operating expenditures while achieving higher metal recoveries.

There are two ways of carbon adsorption applications namely carbon-in-pulp and carbon-in-leach.

Carbon-in-Pulp (CIP) is a traditional leach circuit process that has evolved into a hybrid configuration typically consisting of eight uniform tanks. In this setup, the first three tanks are dedicated to initial leaching, while the remaining five tanks facilitate additional leaching and adsorption.

Carbon-in-leach (CIL): For carbonaceous ores where the majority of the gold content is amenable to direct cyanidation, carbon-in-leach (CIL) is commonly used, although its effectiveness varies depending on the intensity of the preg-robbing characteristics. To prevent the re-adsorption or desorption of gold onto the carbonaceous material present in the ore, preg-robbing ores are typically treated in CIL circuits, as the dissolved gold is rapidly captured by the added activated carbon rather than by the native carbonaceous matter (Ryan et al., 2016).

Typically, a Carbon-in-Leach (CIL) circuit consists of six or seven agitated tanks of equal size, arranged in a staggered configuration. Each tank is fitted with an agitator and intertank screens, and the tanks are interconnected by launders or large-diameter piping, enabling the redirection of slurry flow as necessary (Martin Beyuo et al., 2016). For the same leaching residence time, CIL circuits generally involve lower capital expenditure because fewer tanks are required. However, they tend to have higher carbon and gold inventories due to the larger tank volume that holds carbon.

Resin-in-pulp and resin-in-solution are not yet well developed, commercialized and are specific to some countries mining companies use mainly for carbonaceous ores.

2.4.7. Elution, Electrowinning and smelting (for CIP/CIL)

Elution: In the elution stage, loaded carbon recovered from the leach circuit is processed for a set duration in a series of columns using a hot 1% caustic solution (sodium hydroxide) containing 0.1–0.2% NaCN under atmospheric pressure. After elution, the stripped carbon is washed with dilute hydrochloric acid and then regenerated in an indirect oil-fired furnace to eliminate impurities such as carbonates or organic compounds that may accumulate on the carbon during leaching. The regenerated carbon is cooled and screened to remove degraded fine particles before being recycled to the final leach tank in either a carbon-in-leach (CIL) or carbon-in-pulp (CIP) process. The pregnant, gold-bearing eluate from the carbon stripping section is

pumped to a pregnant solution storage tank, which provides surge capacity ahead of the electrowinning circuit.

Electrowinning is a widely used method for recovering gold and silver from eluates generated during the elution of activated carbon (Marsden & House, 2006). The gold-bearing eluate is circulated through electrowinning reactors, where an applied electric current facilitates the deposition of gold onto steel wool or mesh cathodes (Costello, 2016).

Following elution, the enriched gold solution is typically directed to electrowinning cells, where metals such as copper, platinum, and silver are deposited onto the cathode (Nicol, 2005).

Smelting: The gold plated from the cathodes is washed off, dried, mixed with a flux (borax) to remove impurities, and melted in an induction furnace to produce impure gold bars (dore).

2.4.8. Refining

The main refining methods are pyrorefining, electrorefining and hydrorefining.

The dore bars are sent to a refinery where they undergo final purification using methods like “Miller Process” and “Wohlwill Process”, pyrorefining.

In the Miller process, gold is treated with chlorine gas at a high temperature, typically 1150°C, which yields a purity of 99.6% (Miller, 1869). This partially refined gold then undergoes electrorefining via the Wohlwill process (electrolysis), achieving 99.99% purity, and the standard for investment-grade gold bars or bullion (Wohlwill, 1874).

Hydrorefining methods are used by some refineries to produce 99.6%–99.9% gold. The purity of the final product depends on the ultimate use: typically 99.6% for jewelry and monetary bullion, and >99.99% for production of coins.

Certain refineries employ hydrorefining techniques to achieve gold purities ranging from 99.6% to 99.9% . The required purity level is determined by the intended application: jewelry and monetary bullion generally utilize 99.6% pure gold, whereas coin production demands a higher purity exceeding 99.99%.

2.5. Gold Process Selection

Factors that influence process selection include: geological, mineralogical, metallurgical, environmental, geographical, economic, and political considerations. Among these, the mineralogical and metallurgical aspects directly affect gold extraction chemistry and process selection, as they govern the ore's response to chemical treatment. The remaining factors exert an indirect influence, which is contingent on specific project conditions, requirements, and overall feasibility (Marsden & House, 2006).

Geological: The grade and tonnage reserves of economic minerals in an orebody determine the type and scale of process technology that can be applied.

Mineralogical: The ore's composition and textural features define its mineralogical characteristics, which are then combined with metallurgical test data and knowledge from analogous ore deposits to guide process selection and develop process flow sheets.

The level of mineralogical detail needed for effective process selection depends on the orebody's type and its degree of variability.

Metallurgical: In metallurgy, the economic viability of an ore treatment or process flow sheet selection is directly governed by the ore's mineralogical behavior. The primary factors in this assessment include the recovery of gold and other valuable minerals, product quality and any subsequent processing requirements, throughput rate, capital and operating costs.

Low gold extraction suggests that the ore contains refractory components that do not leach effectively under direct cyanidation. This may result from any one or a combination of the following: gold locked within sulfides; gold locked within silicates (requiring finer grinding); gold associated with carbonaceous material that causes "preg-robbing" or "preg-borrowing"; high cyanide consumption due to the presence of reactive sulfides, copper, or zinc; or coarse gold that fails to dissolve completely within 24 hours under the applied conditions (Marsden & House, 2009).

Environmental: When selecting a process, it is essential to evaluate its environmental consequences across multiple dimensions, including water quality, air quality, land degradation, visual impact, noise, effects on flora and fauna.

Geographical: The selection of a mineral processing method is strongly influenced by the geographic context of the orebody and the proposed treatment facility. Key geographic considerations include climatic conditions, water availability, topography, altitude, infrastructure, the local availability of equipment, reagents, and other supplies, communication networks, the accessibility of both skilled and unskilled labour, and the presence of sites with archaeological or religious significance.

Economic and Political: The choice of a process is influenced by economic and political factors, including the market price of gold and other precious metals (such as silver, uranium, and platinum group metals), tax rates and systems, and the overall economic and political environment at both local and global levels (Marsden and House, 2009).

2.5.1. Mineralogical Consideration in gold process selections

Within the gold ore processing industry, a central emphasis is placed on comparing competing treatment technologies, along with their respective economic benefits and drawbacks. A persistent challenge is the growing prevalence of refractory and mineralogically intricate ores (Lunt and Weeks, 2016).

Numerous variables can influence gold recovery, making it challenging to establish a universally applicable classification for all gold-bearing rocks. Nonetheless, La Brooy et al. (1994) proposed a useful categorization system that distinguishes between free-milling ores, complex ores, and refractory ores.

By definition, **free-milling ore** achieves a recovery rate of more than 90% under standard processing conditions.

"**Complex ores** are those which demand elevated levels of chemical reagents, such as cyanide, oxygen, or activated carbon, to achieve economically feasible gold extraction. Such ores are often associated with base-metal mineralization, notably copper, which can lead to excessive cyanide consumption and create operational difficulties in carbon-in-pulp (CIP) circuits and during the elution (gold desorption) process. When a carbonaceous material exhibiting a "preg-robbing" behavior is present, it becomes essential to incorporate specific process steps into the flowsheet; otherwise, a significant portion of the gold may be adsorbed by the native carbon and report to the carbon-in-leach (CIL) tailings, resulting in substantial gold losses."

Refractory behavior is observed across numerous ore types, including gold-bearing iron sulfides (pyrite), arsenopyrite, pyrrhotite, tellurides, stibnite, and more recently sulfosalts such as enargite and tennantite. Consequently, refractory ores are defined negatively, as those that fail to achieve acceptable recovery without some form of pretreatment prior to cyanidation. Specifically, refractory gold ores are characterized by gold recovery rates below 80% (Marsden and House, 1992).

The selection of gold process flow sheet options is organized into four categories: (1) comminution processes, (2) free-milling ore processes, (3) complex ore processes, and (4) refractory ore processes (Lunt & Weeks, 2016).

Comminution: In comminution circuit design, the ore's competency and hardness are the primary factors governing the choice of circuit configuration (e.g., Wills & Finch, 2016; Morrell, 2004).

2.5.1.1. Free Milling Ore Process Option

For free milling ores, standard processing methods include gravity separation, cyanidation (via carbon-in-leach [CIL] or carbon-in-pulp [CIP]), and the Merrill-Crowe process. Such ores typically achieve high gold recovery when ground to a reasonably coarse particle size, with moderate oxygen and cyanide consumption (Lunt & Weeks, 2005).

Treatment of High-Silver Ores: When treating high-silver ores, numerous flowsheet options are available, and the final selection depends on the silver-to-gold ratio, the total precious metal output to be recovered, and the solid-liquid separation characteristics of the leach pulp. If the silver mass flow is excessively high, a zinc precipitation circuit should be considered, either integrated with a CIL circuit or as part of a complete Merrill-Crowe circuit (Lunt & Weeks, 2005).

2.5.1.2. Complex Ore Process selection/ Options

Complex ores are defined as those that demand high consumption of cyanide and oxygen, and/or exhibit preg-robbing characteristics (Lunt & Weeks, 2005). The issue of preg-robbing in carbonaceous ores can be mitigated through various methods, such as: introducing gold adsorbents (e.g., activated carbon or resins with a gold-absorbing capacity two orders of magnitude greater than that of the carbonaceous matter in CIL or RIL) to outcompete the carbonaceous material; deactivating or passivating the carbon through oxidation (e.g., roasting, chemical oxidation, or biochemical oxidation) (Sibrell, 1991; Afenya, 1991); or employing surface-blinding agents (i.e., chemical reagents that selectively adsorb onto or wet the carbon surface). Among these approaches, oxidative treatments are currently the most effective. Nevertheless, the ore's mineralogy and the specific properties of its carbonaceous material must be taken into account to select the most suitable method(s) for processing. Reactive ores (for example, copper ores other than chalcopyrite) and ores containing pyrrhotite can be managed by adding higher concentrations of reagents (cyanide and oxygen) than those typically used in standard cyanidation.

Treatment of High-Copper Ores: For copper-rich ores, the specific processing method, such as flotation, selective leaching, carbon-in-pulp (CIP), elution, and electrowinning (EW), depends on the copper concentration and its mineralogical form (Lunt and Weeks, 2005).

Adams (1999) categorizes gold-copper ores based on their relative concentrations, noting that ores with high copper values are consistently treated via flotation and smelting, with gold being subsequently recovered at a refinery. The solubility of copper minerals in cyanide solutions varies considerably. In cases where the level of cyanide-soluble copper is low, simply raising the cyanide concentration in the leach can be economically viable, as it helps to minimize copper loading.

Preg-robbing ores are carbonaceous materials that present processing challenges due to their natural ability to absorb soluble gold. Research has demonstrated that the carbonaceous components in such ores behave similarly to activated carbon, capturing gold that has been dissolved in a cyanide solution during the leaching process. The high degree of gold adsorption and subsequent losses during cyanidation are believed to result from the fine dissemination of carbonaceous matter, particularly particles smaller than 20 μm (Sibrell and Miller, 1991; Pyke et al., 1999).

The application of non-cyanide leaching systems has been, and remains, an ongoing area of investigation for treating preg-robbing gold ores. A review of alternative lixiviants conducted in 2005 highlighted thiosulfate as a particularly promising option (Aylmore, 2005). This method has since been successfully commercialized, first by Newmont and more recently by Barrick (Aylmore, 2005; Choi et al., 2013).

Treatment of carbonaceous ore: To address the challenges associated with preg-robbing carbonaceous ores, several strategies can be employed. These include the use of gold adsorbents such as activated carbon or resins to compete with the carbonaceous material, as well as deactivation or passivation through oxidation methods (e.g., roasting, chemical oxidation, or biochemical oxidation). Additionally, surface-blinding agents may be applied (Sibrell, 1991; Afenya, 1991). Among these approaches, oxidative treatments are considered the most effective for mitigating preg-robbing issues caused by carbonaceous ores. When choosing the most appropriate treatment method(s), it is essential to take into account both the mineralogy of the ore and the specific characteristics of the carbonaceous material (Miller et al., 2005).

Oxygen-Consuming Ores: In carbon-in-pulp (CIP) and carbon-in-leach (CIL) circuits, various ore components, particularly sulfide minerals, consume dissolved oxygen. Under typical process conditions, certain sulfides such as stibnite and pyrrhotite exhibit notably high oxygen consumption rates (Marsden & House, 2006; Adams, 2016).

2.5.1.3. Refractory Ore Process Options/selection

To render refractory gold ores and concentrates amenable to cyanidation, pre-treatment steps are necessary. These pre-treatments include roasting, pressure oxidation, bio-oxidation, ultra-fine grinding, and modified cyanidation, often preceded by a concentration method such as gravity separation or flotation (Marsden and House, 1992). The selection among these pre-treatment mechanisms is governed by ore characteristics, infrastructure availability (e.g., power supply, water quality and quantity), environmental concerns, and economic viability (Marsden and House, 1992). For instance:

Pressure oxidation pre-treatment is most suitable for very fine-grained (submicron) carbonaceous platelets dispersed throughout silicates and sulfides (Marsden and House, 1992).

Carbonaceous ores containing significant refractory gold associated with pyrite-arsenopyrite mineralization require biological oxidation pre-treatment (Marsden and House, 1992).

Treatment of Gold-Telluride Ores: In the processing of gold-telluride ores, Johnson observed that a high concentration of lime is necessary to achieve favorable leaching kinetics. Furthermore, the use of a high lime concentration together with lead nitrate during the cyanidation of calaverite ($AuTe_2$) led to a marked improvement in gold extraction (Deschênes et al., 2006).

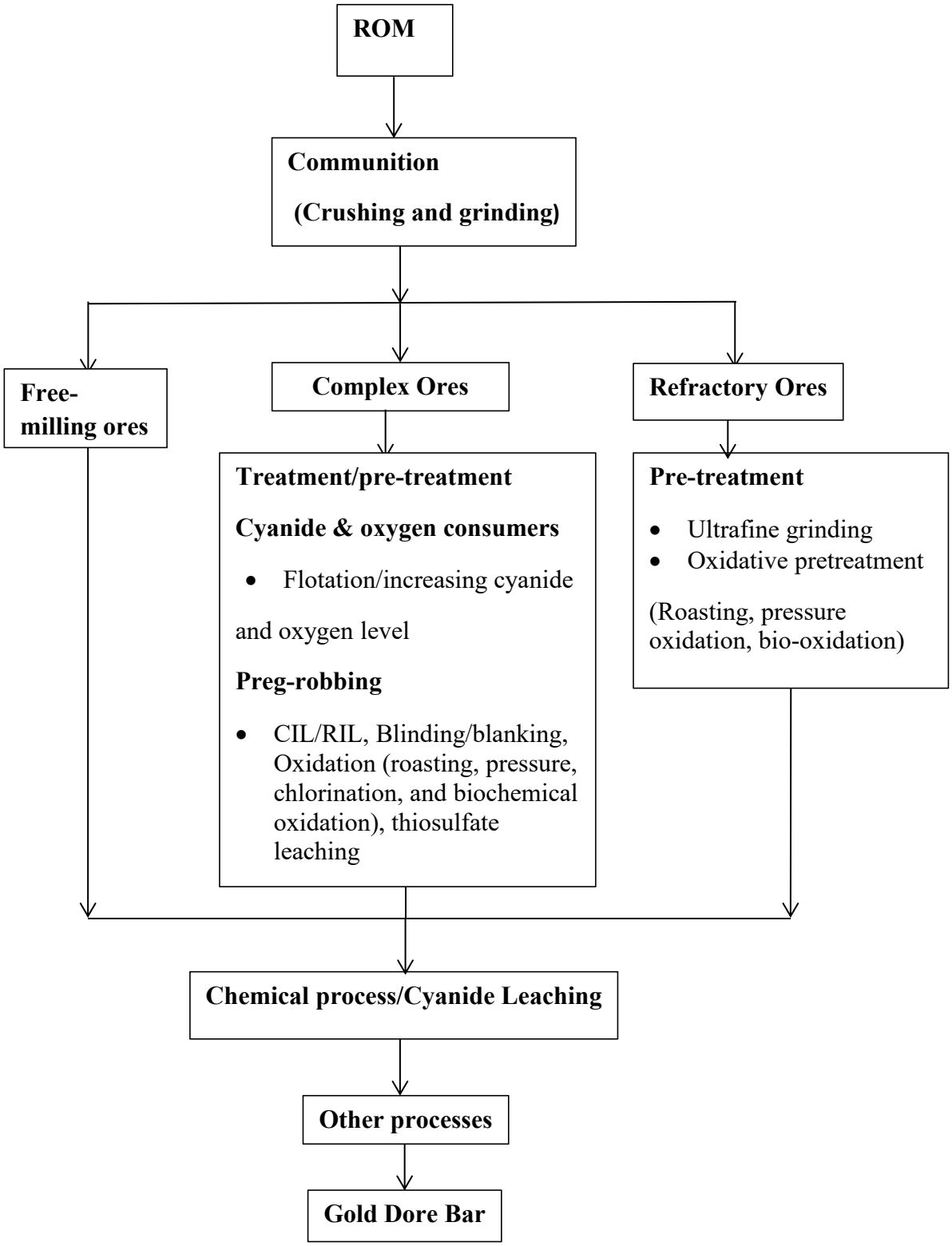


Figure 4 Gold recovery process route/selection based on types of gold ore characteristics

2.6. Previous Works on Okote Gold Deposit

2.6.1. Exploration History

Okote gold deposit being largest gold resource in Ethiopia, lies south of the Lega Dembi gold deposit. This deposit is situated within late-Precambrian metamorphosed sediments of the north-south trending, volcano-sedimentary Megado belt, part of the late-Proterozoic Adola granite-greenstone terrain in southern Ethiopia.

Before 1995, the Ethiopian Institute of Geological Survey and the Ethiopian Mineral Resources Development Corporation has conducted 1:250,000 geological mapping and prospecting, aeromagnetic and radioactive survey, helicopter borne geophysical survey in Dawa Digati area; part of the area has been conducted of 1:50,000 geological mapping and geochemical sampling; and part of the area has been conducted of 1:100,000 geological mapping and soil sampling.

Further exploration programme on the Dawa Digati Project began in 1996 by NMiC. The program included geological mapping, geochemical sampling, geophysics, trenching and drilling. Exploration has resulted in division into several subareas, each subarea with exploration reports delivered. The exploration undertaken has divided the whole Dawa Digati region into several targets including Okote, Ejersa South, Gichile, Dhugo Sefer and Burikaro for drilling, trenching and sampling work, among which Okote was the focus. Up to year 2017, a total of 88 boreholes with 10,643 samples and 20 trenches with 946 samples were assayed in North Okote target that used to determine extent to depth, mineralized lithologies, mineral resources estimation with Wire framing, data analysis and Block Modeling. Okote gold resource estimation was done in accordance NI143-101 by an independent consulting firm Venmyn rand (pty) and found as low grade large tonnage gold deposit.

2.6.2. Geology

2.6.2.1. Regional Geology

The Okote gold deposit is situated within the southern Ethiopian greenstone belt, which forms a part of the Adola granite-greenstone terrain. This terrane is defined by two narrow, roughly north–south-trending belts: the Kenticha zone and the Megado zone. The Kenticha belt comprises a heterogeneous succession of high-grade, complexly deformed gneisses that have been intruded by syn- to post-tectonic granitoids. In contrast, the Megado belt consists of a volcano-sedimentary sequence along with ultrabasic rocks that have undergone metamorphism from greenschist to amphibolite facies.

The Adola greenstone belt is a basement component of the East African Orogen, one of the largest collision zones on Earth, associated with the closure of the Mozambique Ocean, the generation of extensive juvenile Neoproterozoic continental crust, and the convergence of East and West Gondwana. As a northward extension of the Mozambique orogenic belt, the Adola region represents a segment of a late Proterozoic intracratonic trough that formed on an ancient, stabilized basement within the Mozambique belt (Bonavia & Chorowicz, 1993).

According to Kazmin (1975), the basement rocks of Ethiopia can be classified into three groups: the Lower, Middle, and Upper Basement Complexes.

In the Adola area, two major Precambrian tectono-stratigraphic units have been recognized (Tadesse, 1999): (i) the Middle high-grade gneiss complex, and (ii) the Upper low-grade volcano-sedimentary complex. Detailed structural studies of the tectonic relationship between the volcano-sedimentary and gneissic rocks indicate that their contacts are regional shear zones, specifically ductile to brittle-ductile shear zones oriented north-south (Worku & Yifa, 1992; Gebreab, 1992; Worku, 1996). These regional shear zones serve as conduits for gold mineralization.

The Okote area, part of the Megado belt, is located south of the Lega Dembi gold deposit on the eastern flank of the belt, along the tectonic contact separating low-grade metavolcano-sedimentary rocks from competent gneissic rocks (Figure 5).

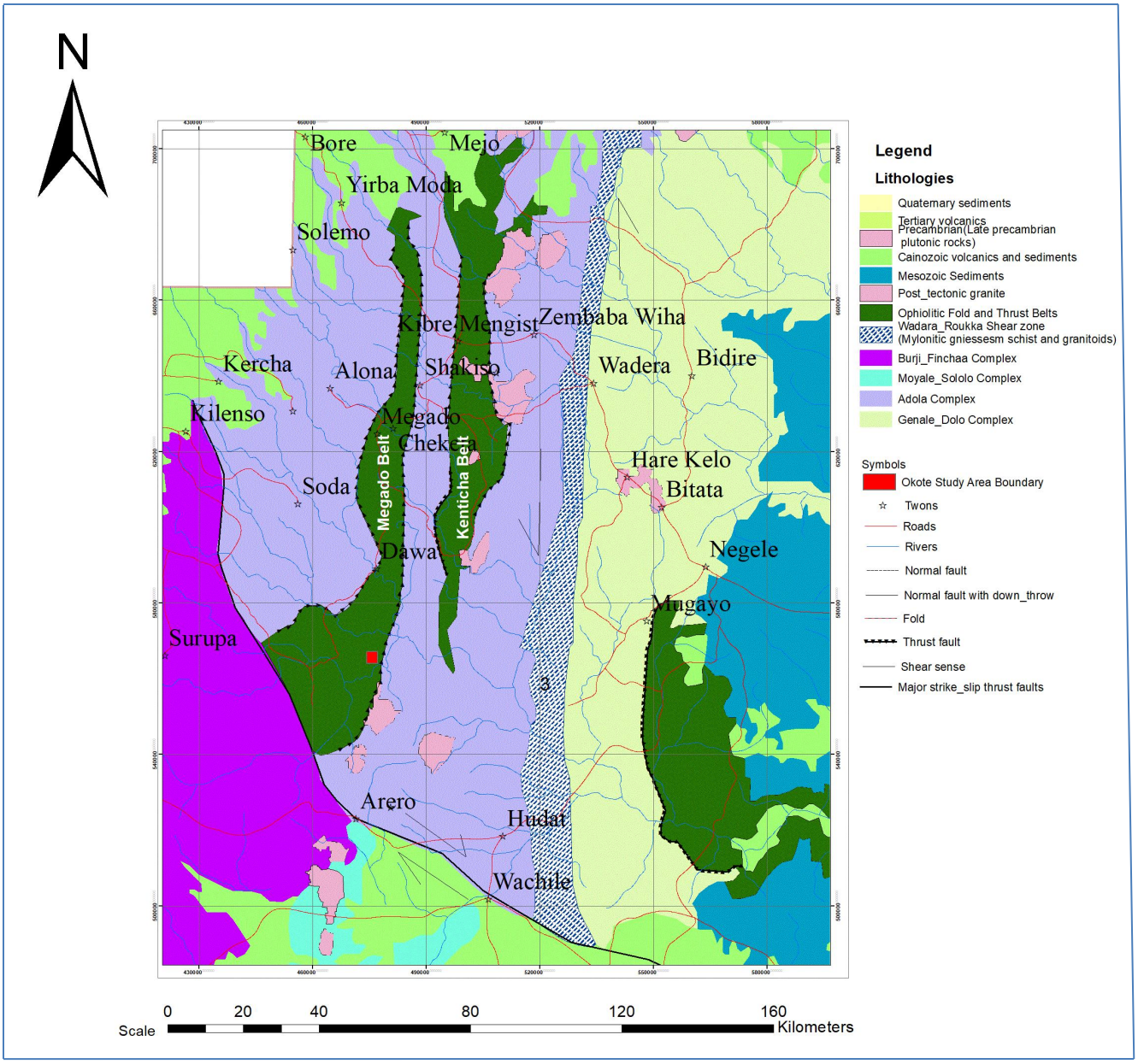


Figure 5 Regional Geology of the project area (Adapted from GIE Compilation map, 2025)

2.6.2.2. Geology of Okote Gold deposit

The Okote gold is localized in structurally controlled shear zone where lithologies are metamorphosed upper greenschist facies. The deposit is found within Neoproterozoic greenstone terrains of southern Ethiopia, characterized by Precambrian rocks comprising basic/ultrabasic and other older basement gneisses along shear zones extending for about 150 Km along NS strike (NMiC).

The area broadly comprises felsic and mafic rocks, intermixing near their contacts with felsic Meta-granodiorite and aplitic dykes. Meta-gabbro/amphibolite, Meta-diorite, chlorite-amphibole schist, chlorite schist and talc schist are the intermediate-mafic-ultramafic rock units abundantly occurring in the area. Quartz veins are hosted by both felsic and mafic rocks. The felsic rocks are repeatedly observed intruding the mafic protholith. The metavolcanics of the study area is characterized by sharp contacts. Xenoliths of mafic rocks are frequent within the Meta granodiorite intrusive rock unit when approaching the mafic country rock. Lenses of Meta-granodiorite are widespread while intruding the dominant mafic rocks.

The geology of the study area in general is expressed by the Adola group of rocks which are dominated by a series of deformed rocks of Proterozoic age. Lithologically they are comprised of schists mainly chlorite- amphibole schist, carbonate-chlorite schist, talc-tremolite schist and associated intrusive ranging from granodiorite to metagabbro of different compositions (Fig.6).

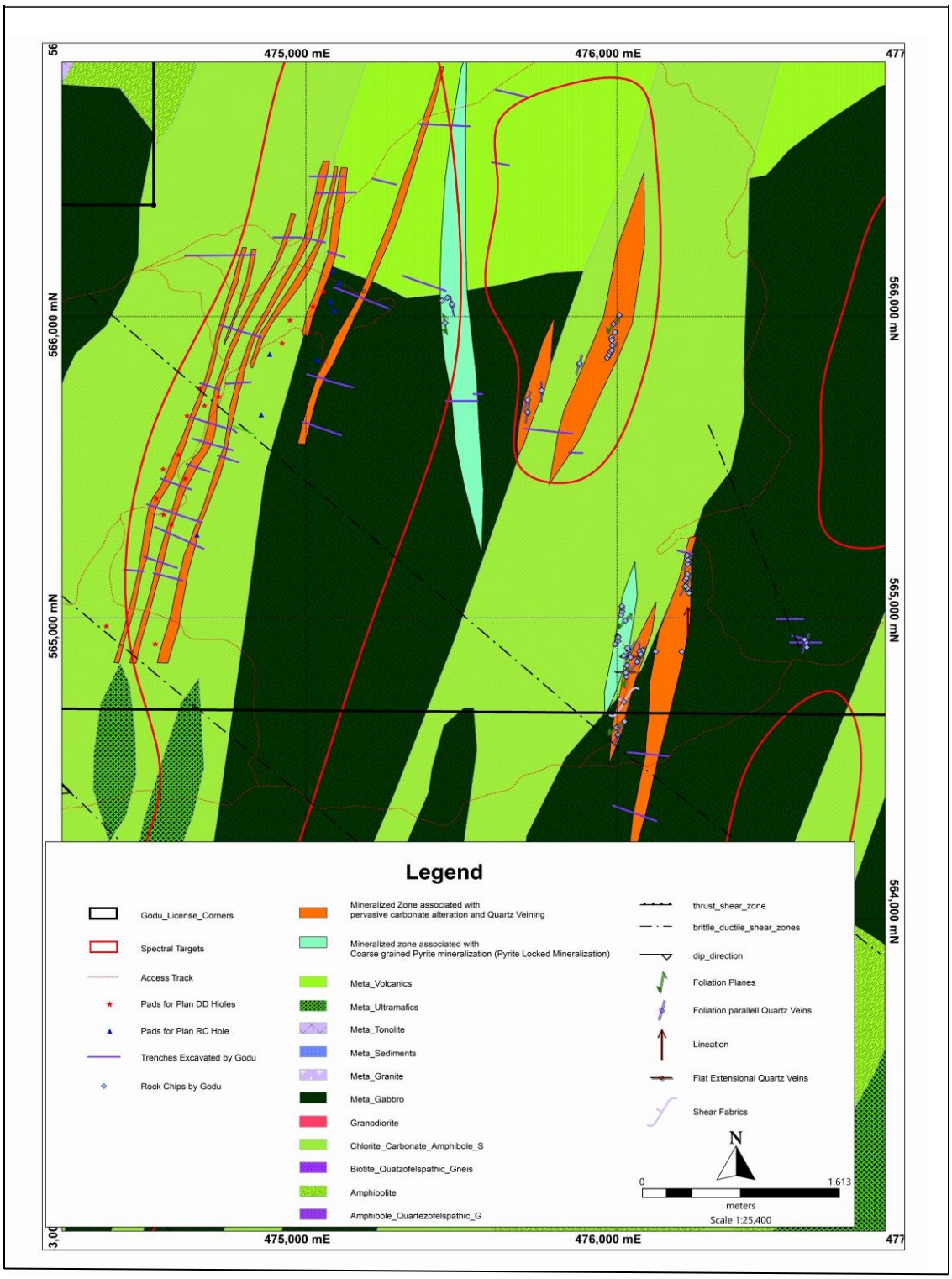


Figure 6 Local geology of Okote gold deposit (Source: Godu General Trading S.C, 2024)

2.6.3. Mineralization

Gold mineralizations identified so far are confined generally to contact zones between metavolcano sedimentary (greenstone) formations and adjacent areas of gneisses marked by shear zones. The Lega dembi gold mine, Okote primary gold deposits and other important occurrences are localized within the eastern shear contact between the Megado greenstone formations and the central gneissic terrain.

The integrated geological, geochemical and geophysical survey conducted in Okote gold project revealed gold mineralization. The gold mineralization in Okote area is related to quartz and quartz-carbonate veins and veinlets of limited strike length. The mineralized veins seem to have been localized in shear zones. So far, the drill and trench in the northern, central and southern part of Okote Prospect outlined a 2.6 km long mineralized zone (NMiC).

According to Wube, 2005, pyrite is the most dominant sulfide mineral associated with gold in veins and altered wall rock. Chalcopyrite is the next abundant sulfide but always in small quantities than pyrite more commonly encountered in silicified amphibole chlorite and amphibole schist than in quartz veins.

D.J. Deksissa and C. Koeberl, 2004 identified ore minerals of the Okote area such as pyrite being dominant, minor magnetite, chalcopyrite, pyrrhotite, and ilmenite, and accessary TiO_2-mineralization (rutile, anatase), chalcocite, covellite, native gold, galena, melonite ($NiTe_2$), and wolframite as well as common gangue minerals like chlorite, carbonate (ankerite and calcite), quartz, albite, white mica, epidote, and apatite.

3. Materials and Methods

3.1. Materials

The study was carried out on 8 samples collected from Okote gold deposit. Each sample weighs about 1kg which was taken from mineralized part of quartz veins through trenching and trench intercepting quartz/rock outcrops hosted in Meta-gabbro, Meta-volcanics and chlorite-carbonate-amphibole schist.

Materials used include GPS for sample location reading, plastic bag, laboratory polished section preparation equipment (rock cutting, grind and polishing equipment), comminution equipment (lab jaw crusher, grinder) and analytical instruments as well as data analysis and interpretation softwares.

3.2. Methods

The major methods used in the project work are desk top study (literature review and secondary data collection), field sample collection, laboratory preparation and analysis as well as laboratory result data processing and interpretation in order to indicate the possible processing methods that are suitable for Okote gold ore deposit.

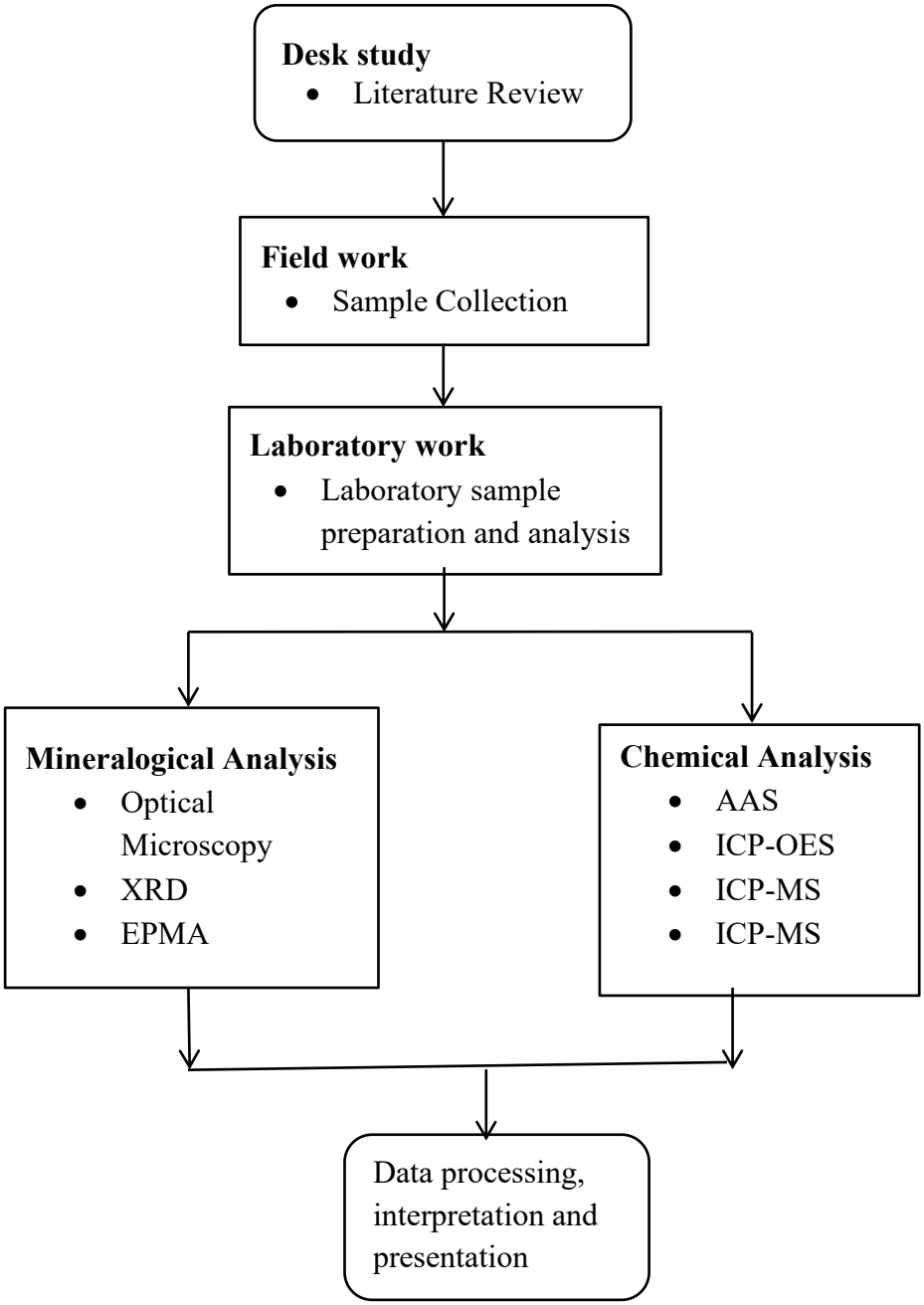


Figure 7: Flow diagram for project work methodology

3.2.1. Desk Study

Review of literature and collection of secondary data

Different books, journals/publications/previous research works as well as different reports from government organizations (MoM, GIE and) and mining company was reviewed to have a general

overview of the subject matter and potential gap identifications as well as analysis and interpretation of secondary raw data for gold process implications.

3.2.2. Field Work

Sample collection

Eight samples each weighing about 1kg was collected from mineralized section of quartz veins from trench and rock/quartz outcrops. The samples were randomly taken all over the study area in different host rocks.

Table 7: Samples field description

S/N	Sample ID	Geographical Coordinate (ADINDAN, UTM Zone 37 N)		Sample Description
		Easting	Northing	
1	OKTS1/GOK TC 1054	474559	565286	Amphibolite schist with pervasive carbonate alteration and quartz vein with pyrite and chalcopyrite mineralization
2	OKTS2/GOK TC 731	476019	564371	Quartz vein with relicts of amphibolite schist plus pyrite and chalcopyrite mineralization and carbonate alteration
3	OKTS3/GOK TC 836	475108	565615	Amphibolite schist with pervasive carbonate (travertine) alteration and silicification plus quartz veins pyrite vugues and oxidized pyrite
4	OKTS4/GOK TC 320	475714	565627	Sheared amphibolite schist with pervasive carbonate, sericite and chlorite alteration, quartz veining and pyrite plus magnetite mineralization
5	OKTS5/GOK TC 846	475036	565799	Oxidized quartz vein with oxidized pyrite as well as box works plus sericite
6	OKRCS6/GOK TR 006	476025	564656	Brecciated quartz vein with carconate alterations on fracture planes and pyrite mineralization. It is hosted near the contact between Amphibole schist and Metadiorite
7	OKRCS7/GOK RK 007	476031	564805	Foliation parallell Quartz vein hosted within pervasively carbonate and limonite altered amphibole schist
8	OKRCS8/GOK RK 010	475995	564913	Coarse grained pyrite rich, foliated, strongly oxidized, yellowish colored amphibole schist hosting quartz stringer with pervasive carbonate and weak sericite alteration

Approach for sample collection

- sample collected from trenches are in the manner of that:
  - ✓ trench dug across mineralization
  - ✓ Samples were collected by channel sampling method from the wall of trench down to the base length in the form of bench every one meter interval.

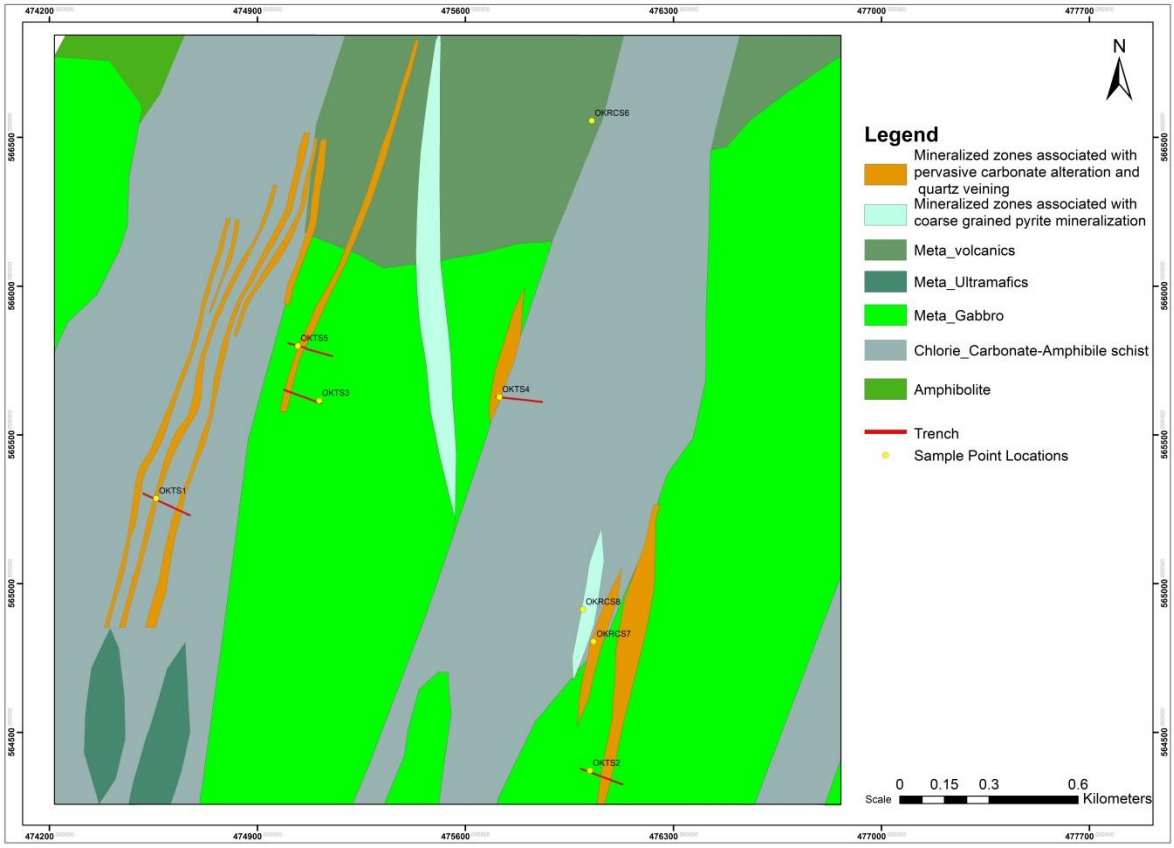


Figure 8 Geological map of Okote gold deposit and sample point locations (adopted from Godu General Trading S.C exploration work, 2024)

3.2.3. Post Field/Laboratory work

a. Sample Preparation

- The samples preparation was done at Geological Institute of Ethiopia Geoscience laboratory and Czech Geological Survey laboratory.

Chemical and Mineralogical sample preparation

Samples were given field and laboratory code separately; crushed with laboratory jaw crushers and pulverized using grinding mill. The samples were weighted, dried and crushed with

primary/bigger size jaw crusher to minus 5mm products. The <5mm products again crushed by secondary/small size jaw crusher further to minus 1mm products. The <1mm sample products were homogenized, quartered and 200gm samples were taken and pulverized down to -200 mesh (-75µm) and packed for mineralogical (XRD) and geochemical analysis.

i. Polished Section Sample Preparation for Optical Microscope study

Polish section samples were prepared by cutting the rock/ore sample into slabs, grinding and polishing. Cutting into slab was done using rock cutter/diamond saw. Grinding one face of the rock/ore slab was first done on diamond-impregnated wheel (120-181µm) to make smooth surface and uniform thickness/ remove irregularities from specimen surface. Further grinding was done to make very smooth surface on glass plate using 400, 600 and 1200 grit silicon carbide abrasive powder successively from coarse to fine grinding. Finally, the samples were polished to shine surface using Aluminum oxide paste of 6µm, 3µm, 1µm and 1/4 µm sizes through oiling by mechanical polishing machine.

ii. Polished thin section sample preparation for Electron Microprobe Analysis

Polished thin section sample preparation for sample ID GOK-RK-007, GOK-RK-010, GOK-TC-731 and GOK-TC-1054 was done in Laboratory Department of Geosciences, Faculty of Science, Masaryk University in Brno, Czech Republic.

Polished thin section is prepared through cutting the samples, grinding and polishing. Samples are cut into slabs and grinded. The grinded face side is mounted and cemented on or glued to glass slide using resin and hardener (epofix, or petroxy). The mounted and cemented slabs further go through re-sectioning, grinding and polishing. Since the electron beam penetrates only to a shallow depth, specimens have to be well polished so that surface roughness does not affect the results.

iii. XRD sample Preparation

Samples are crushed, ground to 200 mesh (-75µm) out of which -10µm is taken for XRD analysis to AAU-college of Natural and Computational Science.

b. Laboratory analysis

Laboratory analysis was including chemical and mineralogical analysis. From eight samples collected, four samples (samples with ID GOK-RK-006, GOK-TC-320, GOK-TC-836, and GOK-TC-846) were analyzed in GIE, EMC and AAU-college of Natural and Computational Science laboratories for (major, minor and trace elements), optical observation and XRD; whereas the rest four samples (samples with ID GOK-RK-007, GOK-RK-010, GOK-TC-731 and GOK-TC-1054) were analyzed in Czech Republic country, Central Europe for (major, minor and trace elements) and mineralogical and elemental composition.

Sample ID GOK-RK-006, GOK-RK-007 and GOK-RK-010 are rock chip samples collected from quartz veins intercepting trenches dug in the area. They are found hosted: near contact between amphibole schist and metadiorite (GOK-RK-006), within pervasively carbonate and limonite altered amphibole schist (GOK-RK-007) and within yellowish colored amphibole schist with pervasive carbonate and weak sericite alteration.

Sample with ID GOK-TC-320, GOK-TC-731, GOK-TC-836, GOK-TC-846 and GOK-TC-1054 are trench samples collected from quartz veins hosted within amphibole schist with pervasive carbonate alteration and silicification, seritization and chloritization alterations.

i. Chemical Analysis

Analysis for major and minor oxides, gold and trace elements were done at GIE & EMC in Ethiopia for samples with ID GOK-RK-006, GOK-TC-320, GOK-TC-836, GOK-TC-846 and the rest in abroad Czech Republic country.

Analysis for major and minor oxides complete silicate analyses ($LiBO_2$, Fusion, HF attack and AAS finish analysis) as well as analysis for base metals (Cu, Zn, Pb) (four acid HCl, HNO_3, HClO, HF and AAS finish analysis) was done at GIE lab. Analyses for gold and silver by mixed acid attack & AAS finish as well as analyses for total sulfur and organic carbon were done at EMC laboratory.

Chemical analysis for major, minor and trace elements of samples with ID: GOK-RK-007, GOK-RK-010, GOK-TC-731 and GOK-TC-1054 were carried out in the Bureau Veritas Laboratories (https://www.bvna.com), Czech Republic using ICP-OES and ICP-MS analytical techniques. Major and minor elements oxide concentrations and gold were obtained by inductively coupled plasma optical emission spectrometry (ICP-OES) while trace-element concentrations were obtained by inductively coupled plasma mass spectrometry (ICP-MS). The dissolution of the sample powders in both cases followed fusion with $LiBO_2/Li_2B4O_7$ flux. Loss on ignition (LOI) was calculated from the weight difference after ignition at 1000^{o}C.

ii. Mineralogical analysis:

Optical microscopy is an invaluable tool for the mineralogical characterization of ores and rocks, for which polished sections of ores and thin sections of rocks are routinely prepared (Deer, Howie, & Zussman, 1992). Ores and ore-forming minerals are examined under reflected light microscopy, whereas rocks and rock-forming minerals are studied using transmitted light microscopy (Craig & Vaughan, 1994). Mineral identification is primarily based on optical properties, which vary from one mineral to another due to differences in crystal structure, chemical composition, and the relative positions of atoms within the crystal lattice (Nesse, 2012). In such cases, advanced characterization methods, such as X-ray diffraction (XRD), scanning electron microscopy (SEM) coupled with (EDS or WDS), and electron probe microanalysis (EPMA), are employed (Goldstein et al., 2017). These techniques are essential for reliably verifying mineral phases. Conversely, optical microscopes remain important for examining textural features and liberation characteristics (Petruk, 2000).

XRD analysis helps identify minerals, quantify their abundances, and understand their physical properties. Mineral Identification- XRD patterns (the diffraction pattern of X-rays as they interact with the mineral) are unique for each mineral. Databases containing the XRD patterns of known minerals are used for comparison and identification.

Quantitative X-ray diffraction (XRD) analysis enables the determination of the relative abundances (in weight percent) of different minerals within a sample (Moore & Reynolds, 1997). Several techniques can be applied to quantify mineral proportions, such as the Rietveld refinement, the reference intensity ratio (RIR) method, and the Le Bail method (Young, 1993). In many geological studies, XRD serves as a complement to other mineralogical techniques, including optical light microscopy, electron microprobe analysis, and scanning electron microscopy (Schoenborn, 2019). Because each mineral possesses a unique crystallographic structure, its d-spacings are distinctive, and the resulting set of diffraction peaks follows Bragg's law, making XRD a fast and reliable tool for routine mineral identification (Cullity & Stock, 2014). The method is particularly useful for identifying clay minerals; however, it is limited when a mineral constitutes less than 3 volume percent of the sample (Brindley & Brown, 1980).

For trace phases of extremely small grain size that cannot be resolved by optical microscopy or XRD, scanning electron microscopy (SEM) and electron probe microanalysis (EPMA) offer high-resolution imaging at very high magnifications, coupled with chemical analysis via energy-dispersive X-ray spectrometry (EDX) or wavelength-dispersive X-ray spectrometry (WDX) (Reed, 2005). From such chemical data, an empirical formula can be calculated, leading to mineral identification (Goldstein et al., 2017).

Mineralogical analyses of the eight samples were done using optical microscopy, XRD and electron probe microanalysis.

Optical microscope observation was carried out at GIE and AAU-College of Natural and Computational Science. XRD and EPMA analyses were done at AAU-College of Natural and Computational Science and Czech Republic laboratories respectively.

Optical Microscopy: Three chips samples were taken from mineralized quartz veins in the trenches. Polished sections were prepared taking into consideration important mineralization features. The prepared polished sections were examined using ore petrography microscope for ore and gangue minerals as well as their textures.

XRD: Four samples were prepared and sent to Addis Ababa University, college of Natural and Computational Science, Chemistry Department for XRD analysis.

EMPA: Electron microprobe analysis is a nondestructive technique used to determine chemical/elemental composition of a mineral or small area of selected solid sample, in which x-rays are excited by a focused beam of electrons. The x-rays emitted from a specimen are detected/ measured using either energy dispersive spectrometry (EDS) or wavelength dispersive spectrometry (WDS). Electron probe microanalyses incorporate an optical microscope for viewing the specimen, as an aid to the selection of points for analysis.

Electron Probe Microanalysis (EPMA) is a powerful tool in characterizing gold mineralization by providing in-situ elemental analysis of minerals at a microscale. It allows for the determination of the chemical composition of gold and its associated minerals, including the speciation and distribution of gold within ore samples. This information is crucial for understanding ore genesis, predicting recovery rates, and developing appropriate processing strategies.

Polished thin section of Okote samples (coded as GOK-RK-007, GOK-RK-010, GOK-TC-731 and GOK-TC-1054) were prepared and analyzed using Cameca SX-100 electron microprobe analyzer at the joint Laboratory Department of Geosciences, Faculty of Science, Masaryk University in Brno, and Czech Geological survey, Brno; Czech Republic.

4. RESULTS AND DISCUSSION

4.1. Results

4.1.1. Chemical Analysis

a. Complete Silicate analysis

Chemical analysis results for major and minor elements show that Silica, and calcium is the major components in the ore with an average percentage vary from 55.60% to 71.15% and 11.36 to 16.26% respectively (Table 8 and 9). Five samples (table 8 and 9) showed 13.4-28.20%CaO and 10.53-19.7% LOI that may be related to quartz-carbonate vein type of mineralization and in which the main gangue minerals could be quartz and carbonates. Highest value of SiO_2 (96.8%) in sample GOK-TC-846 and 91.76% in sample GOK-TC-731 indicate the sample is form quartz vein almost quartz gangue mineral in composition.

Table 8: AAS complete silicate analysis result for major and minor oxides

Sample code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
GOK-TC-836	34.10	10.46	4.10	22.4	5.14	2.88	0.90	0.10	0.06	0.6	0.93	18.69
GOK-TC-320	52.12	14.46	3.76	13.40	2.36	1.20	0.28	0.08	<0.01	0.22	1.08	10.53
GOK-RK-006	39.32	4.30	1.52	28.20	7.22	1.98	0.22	0.06	0.42	0.14	0.38	17.57
GOK-TC-846	96.80	0.80	1.60	1.04	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	0.29	0.75
Average	**55.60**	**7.5**	**2.74**	**16.26**	**3.68**	**1.52**	**0.35**	**0.065**	**0.125**	**0.243**	**0.67**	**11.89**

Table 9: Inductively coupled plasma optical emission spectrometry (ICP-OES) analysis for major and minor oxides

	%										
Sample ID	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	Ti_2O	P_2O_5	MnO	LOI
GOK-TC-731	91.76	4.17	1.15	0.85	0.16	0.21	0.03	0.38	<0.01	0.01	1.2
GOK-TC-1054	87.88	3.6	1.82	0.38	2.33	1.05	0.14	0.08	0.02	0.03	2.6
GOK-RK-007	51.98	2.17	3.77	0.9	21.45	0.06	0.15	0.03	<0.01	0.09	19.13
GOK-RK-010	53.01	2.67	1.88	0.94	21.5	0.04	0.1	0.08	0.02	0.03	19.7
Average	**71.15**	**3.15**	**2.15**	**0.76**	**11.36**	**0.34**	**0.105**	**0.14**	**0.02**	**0.04**	**10.65**

b. Gold and trace elements analysis

From trace elements analysis nickel and copper are the most abundant element in the deposit which shows considerable variation within the deposit. Among the eight samples analyzed for gold only two samples showed substantial amount of gold content.

Table 10: AAS and Gravimeter elemental analysis results

Sample code	Au (ppm)	Ag (ppm)	Cu(ppm)	Zn(ppm)	Pb(ppm)	Co(ppm)	Ni(ppm)	S_{ToT} (%)	C_{TOT}	C_{ORG} (%)
GOK-TC-836	16.95	0.51	46.400	43.000	<0.01	44.800	161.200	2.25	2.32	1.98
GOK-TC-320	<0.01	<0.02	68.800	32.400	<0.01	41.000	97.400	0.12	2.15	1.59
GOK-RK-006	<0.01	<0.02	<0.01	13.000	<0.01	17.600	42.400	0.98	1.66	1.09
GOK-TC-846	<0.01	<0.02	352.600	27.400	<0.01	5.400	22.200	0.65	0.97	0.39
Average	**4.24**	**0.32**	**116.95**	**28.95**	**<0.01**	**27.2**	**80.80**	**1.0**	**1.78**	**1.26**

Table 11: Inductively coupled plasma mass spectrometry (ICP-MS) chemical analysis for trace elements

Sample ID	Au	Ag	Cu	Zn	Pb	Ni	As	C_{TOT}	S_{TOT}	Sb	Hg	Se
GOK-TC-731	>100	0.6	6.4	2	0.3	10.8	3.5	0.02	<0.02	0.3	<0.01	<0.5
GOK-TC-1054	0.415	<0.1	18.3	4	0.7	7.3	1.9	0.45	<0.02	<0.1	<0.01	<0.5
GOK-RK-007	0.008	<0.1	16.6	18	2.4	56.8	2.2	4.69	<0.02	0.3	<0.01	<0.5
GOK-RK-010	0.015	<0.1	13.9	10	1.1	20.4	0.8	4.7	<0.02	<0.1	<0.01	<0.5
Average												

Note: C_{TOT} and S_{TOT} are in % and others in ppm.

Table 12: Chemical analysis result (Wardell Armstrong International [WAI, NMiC (2011)]

Sample ID	Elements											
	Au (ppm)	Ag (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Te (ppm)	As (ppm)	Sb (ppm)	S_{ToT} (%)	S_{SoL} (%)	C_{ORG} (%)	C_{TOT}(%)
HG-CS1	6.25	0.16	92.1	12.1	74	0.2	25.1	0.92	1.72	0.08	0.01	1.46
LG-CS2	0.215	0.08	65.8	9.7	67	0.18	6.4	0.39	0.76	0.08	0.03	1.14
Average	3.23	0.12	78.95	10.9	70.5	0.19	15.75	0.655	1.24	0.08	0.02	1.3

Note: $C_{TOT,}$ S_{SoL} and S_{TOT} are in % and others in ppm. C_{TOT} =Total carbon, S_{SoL}=sulfur in sulphate and S_{TOT} =Total sulfur

The table above shows the chemical composition of two composite borehole samples: high grade composite sample (HG-CS1) and low-grade composite sample (LG-CS2) laboratory results of Okote gold ore.

The presence of sulfide minerals and carbonaceous matter can affect the recovery of gold from the ore. High content of silver can also affect the recovery of gold using cyanidation method when found in higher concentration. The samples result in the table above shows low levels of silver and arsenic as well as both total sulphur and sulphate sulphur. The levels of organic carbon are also low, indicating that preg-robbing was unlikely to occur. Base metals (Cu, Pb, Zn), silver (Ag), antimony (Sb), selenium (Se) and tellurium (Te) are also low.

Table 13: Chemical analysis results (BGRIMM, 2016: NMiC)

Component	Au (ppm)	Ag (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	As (ppm)	Sb (ppm)	S (%)	C (%)
Content	2.05	2.54	150	90	200	16	27	0.65	0.93
Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O		
Content (%)	57.80	13.11	7.10	6.30	3.20	0.82	2.39		

Chemical composition results (table 13) were a composite sample of 6 mineralized samples (CS1-6) taken from carbonaceous-chlorite schist (CCS), Meta-granodiorite (MGD), Low-grade drill core (LG), middle-grade drill core (MG), high-grade drill core (HG) and laboratory left overs (LLO) of Okote gold deposit.

4.1.2. Mineralogical Analysis

i. Optical Microscopy

Three polished sections coded as GOk-RK-006, GOK-TC-320 and Gok-TC-836 were observed under ore petrography microscope. The minerals identified under microscope include pyrite, magnetite, hematite, rutile and others rock forming minerals. The pyrites observed generally are fine to very fine, relict, randomly distributed and some forming alignments, veinlet and fracture fill, idio-xenoblastic in texture (Fig. 9).

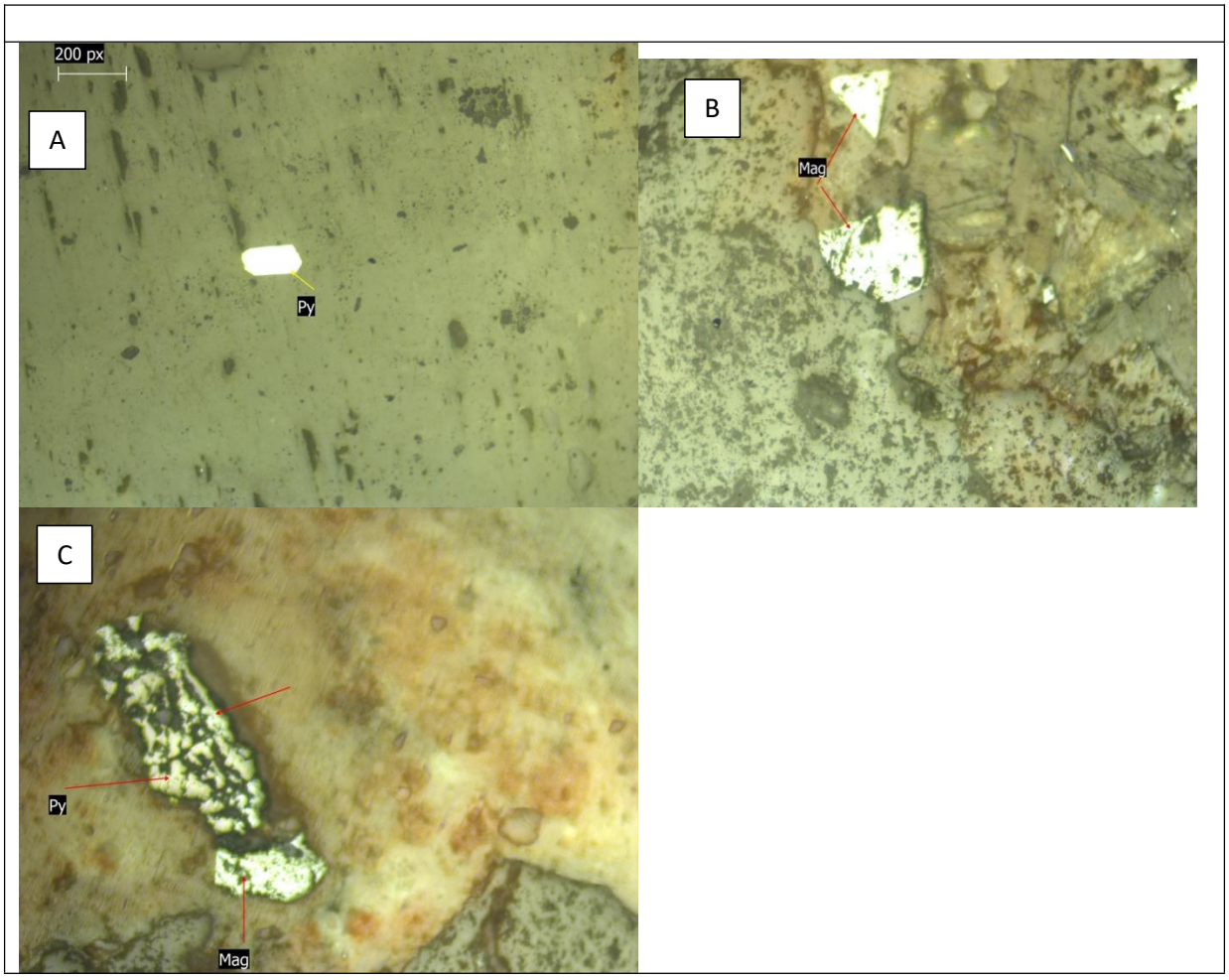


Figure 9 Photomicrograph of samples GOK-RK-006, GOK-TC-320 and GOK-TC-836 in PPL Py: pyrite and gangue (black and grey), Sample GOK-RK-006 (A); Py: pyrite) and gangue (black and grey), Sample GOK-TC-320 (B); Py: pyrite, Mag: Magnetite and gangue (black and grey), Sample GOK-TC-836(C).

Another optical microscopic study on samples from low, medium and high-grade borehole as well as composite samples showed the presence of native gold and gangue minerals such as pyrite, pyrrhotite, magnetite, rutile, quartz, calcite, chlorite, hornblende, feldspar, biotite, muscovite and their mode of occurrence (Fig. 10, and 11)

A. Gold dissemination characteristics

Native gold in the ore mainly exists between gangue minerals or gangue minerals and metallic minerals as irregular, granular shaped grains and gold grains distributed unevenly in the fractures

of gangue minerals as granular and micro-granular as well as veinlets inclusions. Gold grains also occasionally enclosed in sulfides. (Fig.10). Native gold exits as three different types, intergranular, fissure/fracture-filled and enclosed gold.

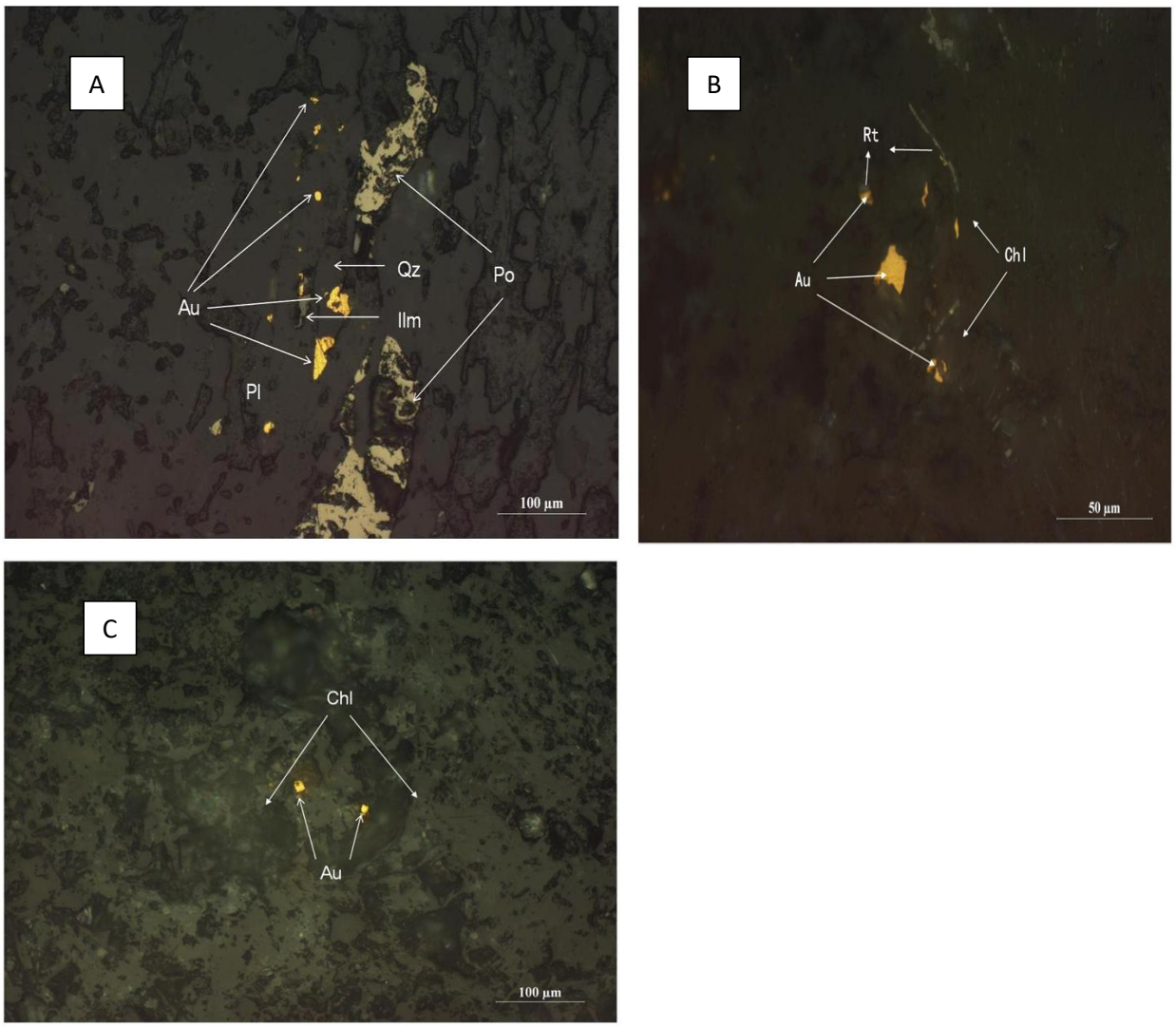


Figure 10 Native gold distribution observation under optical microscope reflected light for samples LG and MG. Native gold distributed among gangue minerals as granular, irregular shaped grains from medium gold grade borehole sample/MG (A); Native gold enclosed in Chlorite (Chl) grains as micro-granular, veinlet shaped grains from low grade borehole sample/LG (B); Native gold (Au) grains distributed in Chlorite (Chl) fractures from low grade borehole sample/LG (C). (Au=Native gold, Qz=Quartz, Pl=Plagioclase, Po= Pyrrotite, Ilm=Ilmenite); (BGRIMM, 2016; NMiC).

B. Pyrite and pyrrhotite dissemination characteristics in the ore

Pyrite mainly occurs in gangue minerals as idiomorphic-hypidiomorphic granular shaped grains （image A） There are coarse-grained chalcopyrite and gangue mineral inclusions enclosed in some coarse pyrites, besides, a little colloform pyrites occurs in the ore also. Trace amount of gold inclusions are enclosed in pyrite (B). The size of pyrite grains is an unevenly distributed, mainly in 50-500μm size.

Pyrrhotite mainly distributes among gangue minerals as irregular, granular shaped grains (C), and part of pyrrhotite is paragenetic adjacently with magnetite, ilmenite, pyrite and chalcopyrite (D). There are also a small amount of coarse pyrrhotite grains enclosing micro-grained gangue minerals, chalcopyrite, pyrite, magnetite etc. (E). Only very small amount of native gold distributes between pyrrhotite and gangue minerals (F). The size of pyrrhotite grains is relatively coarse and distributes unevenly, mainly in 150-850μm.

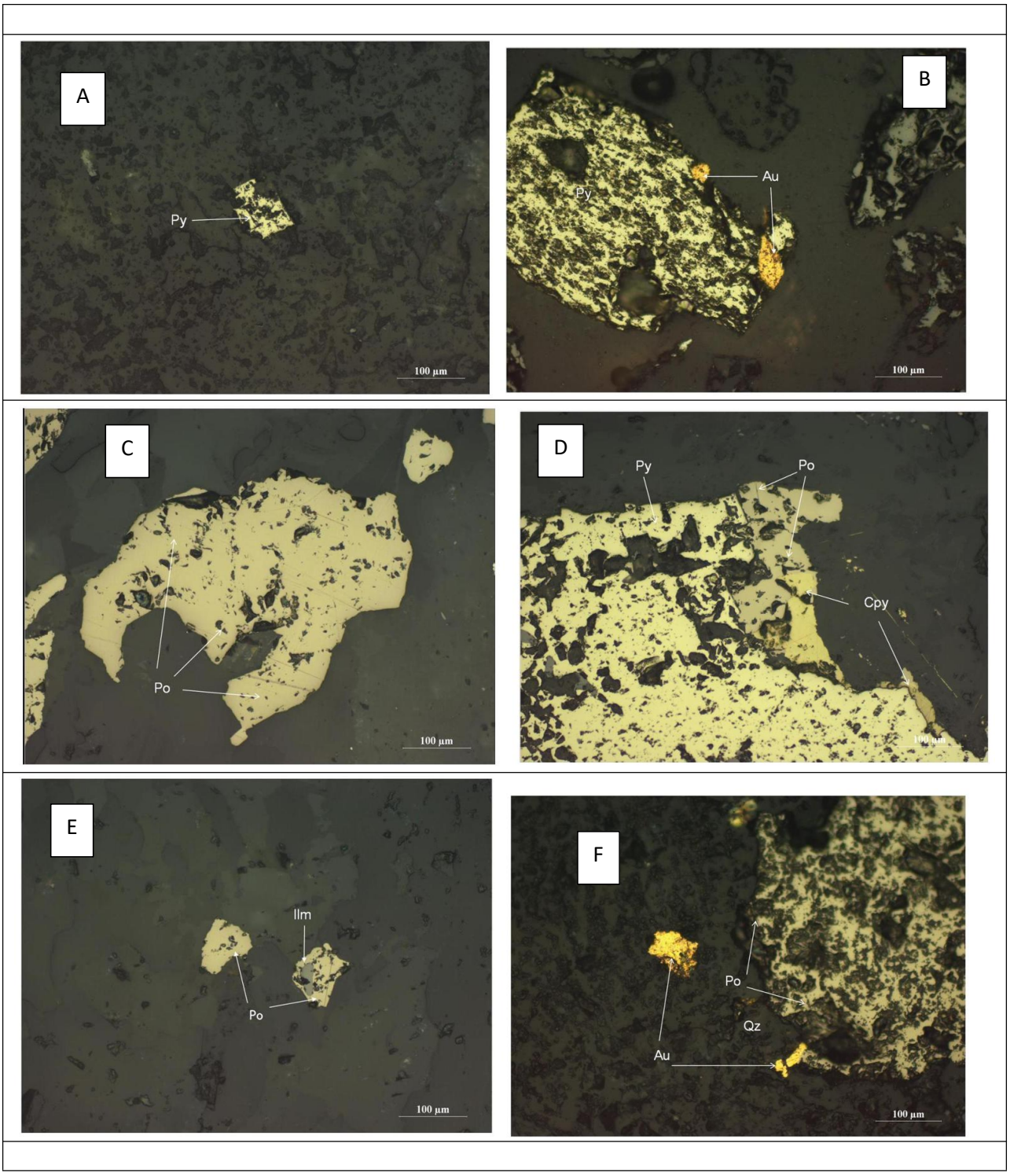


Figure 11 Pyrite and pyrrhotite distribution observation under optical microscope reflected light. Pyrite (Py) distributed among gangue minerals as idiomorphic– hypidiomorphic granular grains in LG sample (A); Irregular- grained native gold (Au) inclusions enclosed in coarse-grained Pyrite (Py) in Composite samples (B); Pyrrhotite (Po) distributed among gangue minerals as irregular, granular shaped grains in MG (C); Pyrrhotite (Po) paragenetic adjacently with pyrite (Py) and Chalcopyrite (Cpy) in HG (D); Micro-granular Ilmentite (Ilm) enclosed in Pyrrhotite

(Po) grains in MG (E); and Native gold (Au) distributed between Pyrrhotite (Po) and gangue minerals (GM) in LG (F). (BGRIMM, 2016).

Optical microscope study in Beijing, China by BGRIMM indicated that native gold is found as itergranular (60.4%), fissure/fracture filled (33.78%) and enclosed (6.18%) in the gangue minerals such as quartz, chlorite, plagioclase, pyrite, pyrrhotite, biotite, rutile and calcite.

According to (BGRIMM, 2016) mineralogical test using optical microscope observation and scanning electron microscope (SEM) analysis, most of the gold minerals are native gold, and there are only trace amount of electrum, petzite etc. The Au distribution rate in native gold is 99.51%, 0.48% in electrum, only 0.01% in petzite.

Another optical microscope study Okote gold deposit showed on composite sample HG-CS1 contained quartz (58%), calcite (16%) and hornblende (9%). The sample also contained feldspar, pyrite, biotite, muscovite, and magnetite. One 50-micron grain of gold was observed in this sample. Sample LG-CS2 contained quartz (44%), calcite (18%) and hornblende (14%). The sample also contained feldspar, pyrite, biotite, muscovite, and magnetite. No gold was observed in this sample (WAI, 2011).

Table 14: Modal composition of gangue minerals from optical microscope observation (WAI, 2011)

Sample ID	Gangue minerals (%)			
	Quartz	Calcite	Hornblende	Others (feldspar, pyrite, biotite, muscovite, magnetite etc)
High grade borehole sample (HG-CS1)	58	16	9	17
Low grade borehole sample (LG-CS2)	44	18	14	24
Average	**51**	**17**	**11.5**	**20.5**

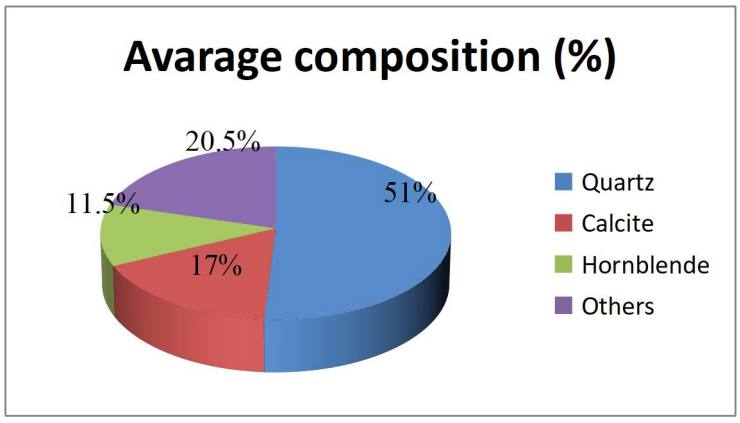


Figure 12: Pie chart showing modal distribution of gangue minerals

ii. XRD

Okote gold ore deposit gangue mineralogy identified using XRD include: quartz, chlorite, calcite, plagioclase-albite, clay, rutile, geothite, and hematite among which quartz and calcite are the dominant.

(A). Minerals Identification

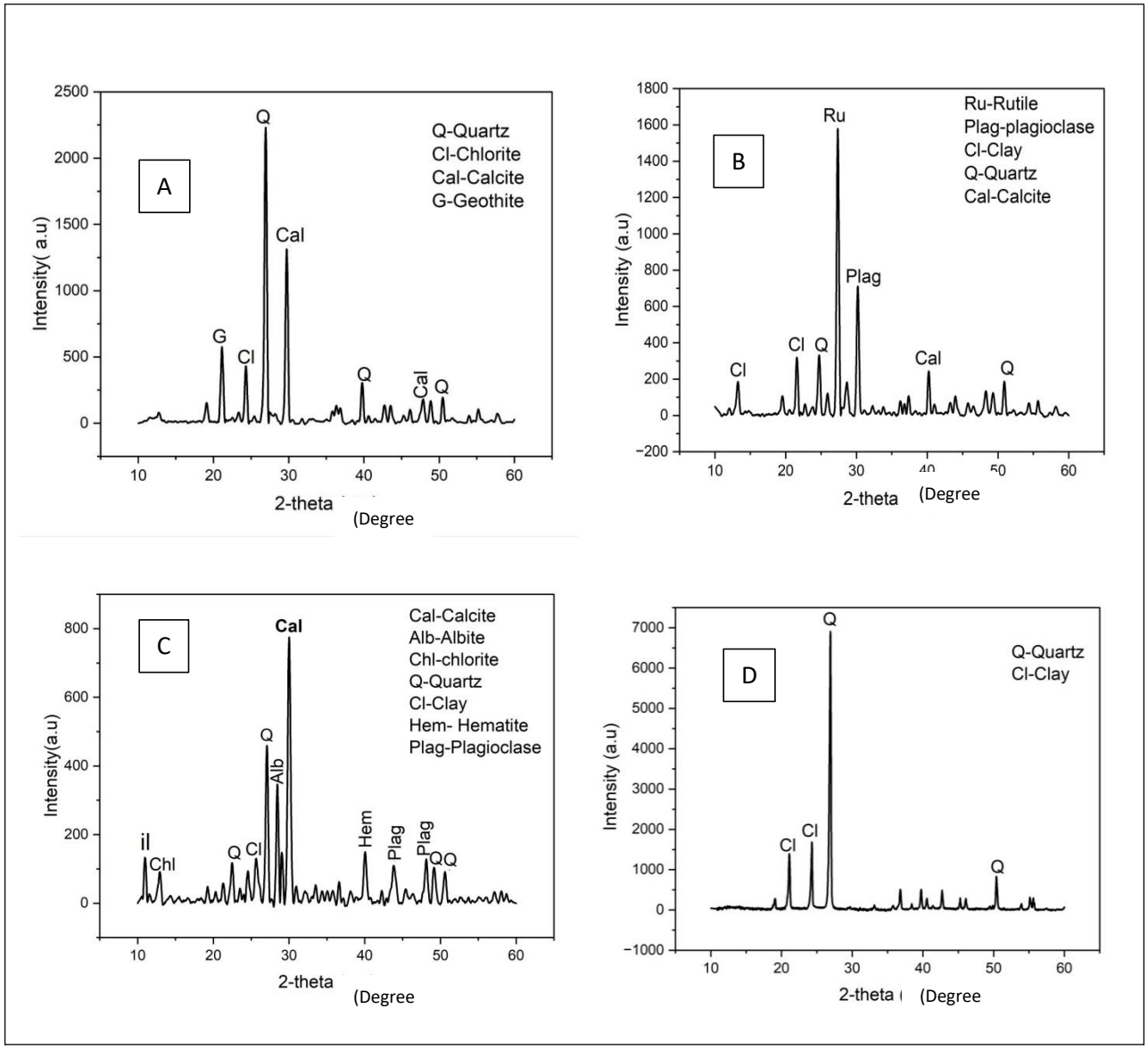


Figure 13 XRD analysis results for samples GOK-RK-006(A); GOK-TC-320 (B); GOK-TC-836(C) and GOK-Tc-846 (D)

(B). Modal composition of Major minerals in the samples



Figure 14 Diffraction pattern and phase modal composition of sample ID GOK-RK-006 (A); GOK-TC-320 (B); and GOK-TC-836 (C).

Table 15: Summary of XRD analysis results

Minerals/phase composition	Sample ID and respective minerals modal composition (%)			Average Composition (%)
	GOK-RK-06	GOK-TC-320	GOK-TC-836	
Quartz (SiO_2)	65.6	88.3	38.5	52.05
Calcite ($CaCO_3$)	34.4		61.5	47.95
Tennantite ($Cu_{12}As_4S_{13}$)		11.5		11.95

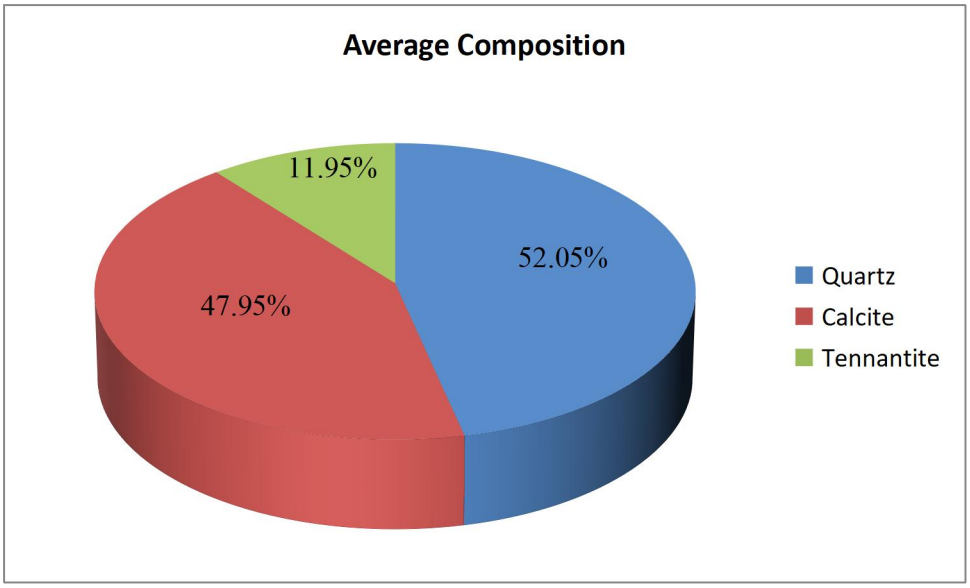


Figure 15 Pie diagram showing average composition of major minerals identified by XRD

Table 16: XRD modal composition of gangue minerals (WAI, 2011)

Sample ID	**Mineral content (%)**								
	Illite + mica	**Chlorite**	**Quartz**	**K-feldspar**	**Amphibole**	**Calcite**	**Dolomite**	**Jarosite**	**Pyrite**
HG-CS1	29	23	32	1	1	3	12	0	1
LG-CS2	36	33	19	0	3	3	4	0	2

The samples contained significant levels of clay minerals, namely illite/mica and chlorite, which may result in increased solution viscosity. The samples also contained moderate levels of quartz and HG-CS1 contained 12% dolomite.

iii. Electron Probe Micro Analysis (EPMA)

Minerals identified by EPMA in the Okote gold deposit include native gold, pyrite, goethite, limonite, calcite, chlorite and muscovite.

Microprobe gold point analysis for sample GOK-TC-731 in average weight percent indicate 99.683% Au, 0.38975% Ag, 0.0625%Cu, 0.00725% Zn, 0.00025%Fe, 0.00325% Ni, 0.00725% As, 0.004% Se, 0% Sb, 0.00575% Pb, and 0% Bi.

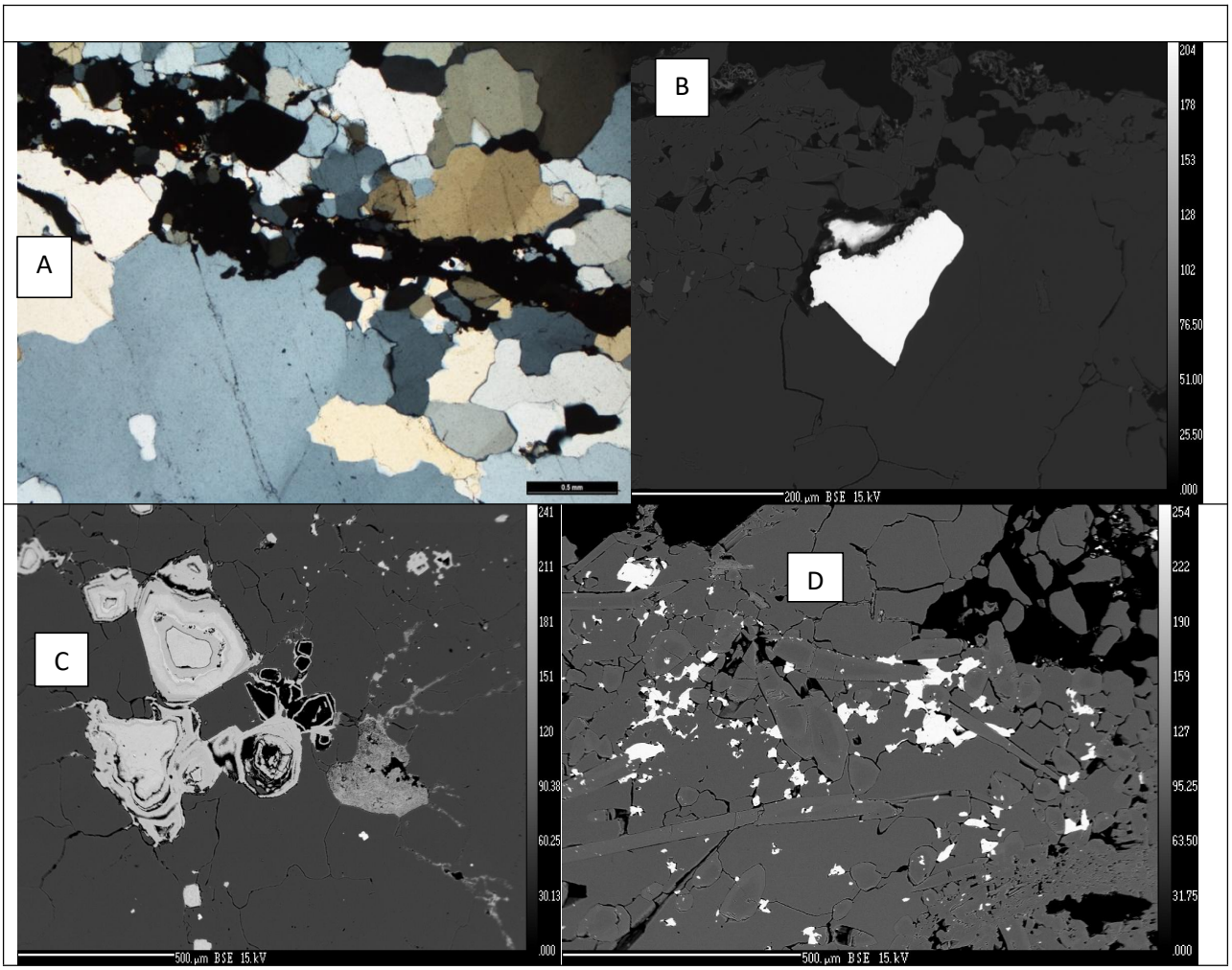


Figure 16 Electro microprobe analysis for mineralogical and elemental compositions (sample ID: GOK-TC-731). Sample ID: GOK-TC-731 showing quartz, gold, pyrite partially replaced by goethite, tourmaline content (A); gold in quartz (B); limonitization of pyrite in quartz vein (C); and pyrite in tourmaline aggregate (D)

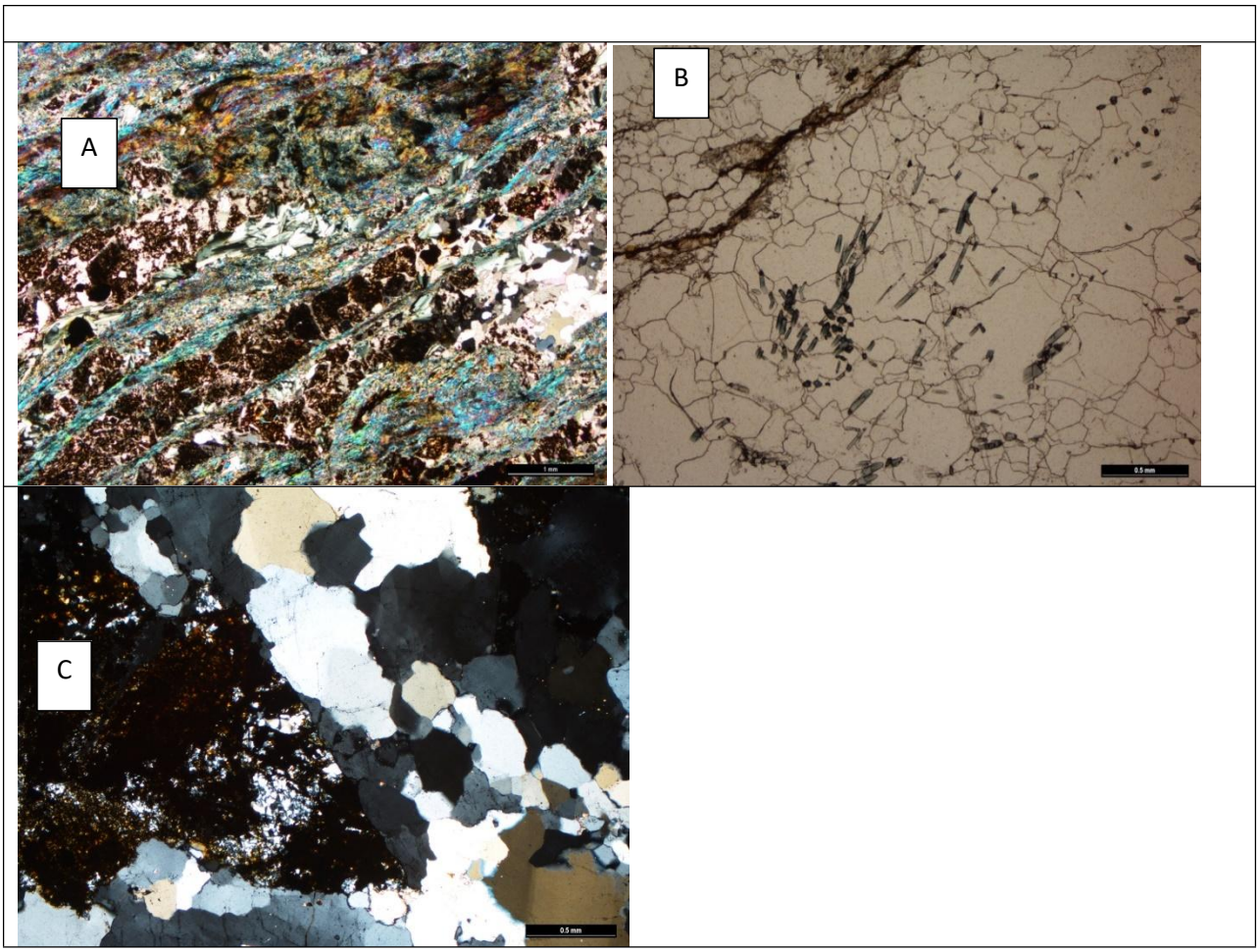


Figure 17 Electron microprobe mineral composition analysis results (sample ID: GOK-RK-007, GOK-RK-010 and GOK-TC-1054): Quartz vein, phyllite (calcite, chlorite, and muscovite) [Sample ID: GOK-TC-1054](A), Quartz, tourmaline, calcite, chlorite, limonite [Sample ID: GOK-RK-007] (B) and Quartz, calcite, chlorite, and limonite [Sample ID: GOK-RK-010) (C).

4.1.3. Gold Grain Size Distribution and Occurrences

a. Gold grain size Distribution

According to BGRIMM, 2016; NMiC, the gold grain size distribution of Okote gold ore deposit accounts 15.59% over 74µm, 40.07% -74 µm +37µm, 28.01% -37µm +10.0 µm, 10.39% -10 µm+5µm, and 5.94% -5µm.

Table 17: Gold particle/grain size distribution

Size (microns)	Nominal Size (microns)	Mass (%)	Cumulative Passing (%)	Cumulative Retained (%)
+74	74	15.59	84.41	15.59
-74+37	37	40.07	44.34	55.66
-37+10	10	28.01	16.33	83.67
-10+5	5	10.39	5.94	94.06
-5	0	5.94	0	100
Total		100		

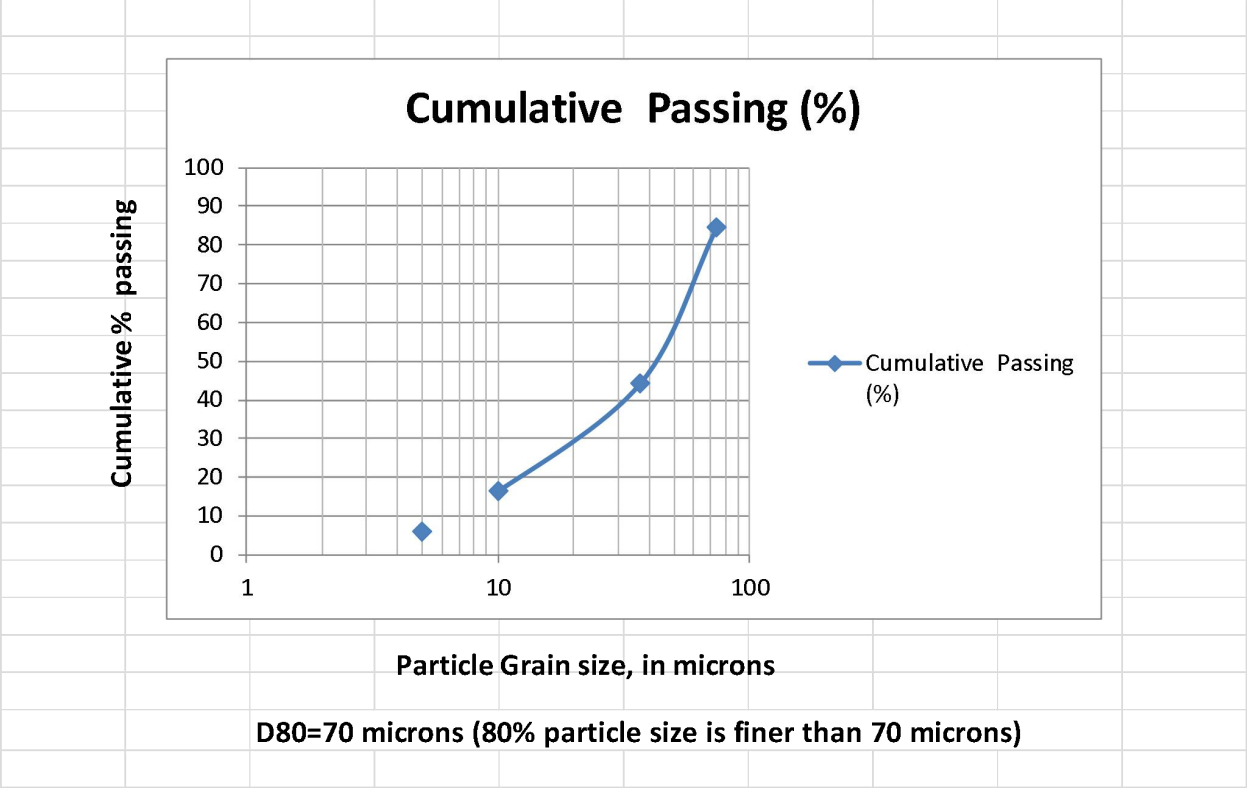


Figure 18 Semi-log scale plot showing grain size distribution of gold

b. Gold occurrence/distribution in the ore deposit

Optical microscope observation and study showed that native gold of Okote gold deposit is found distributed as intergranular (60.4%), fracture filled (33.78%) and enclosed in gangue minerals as well as associated minerals (6.18%) [BGRIMM, 2016].

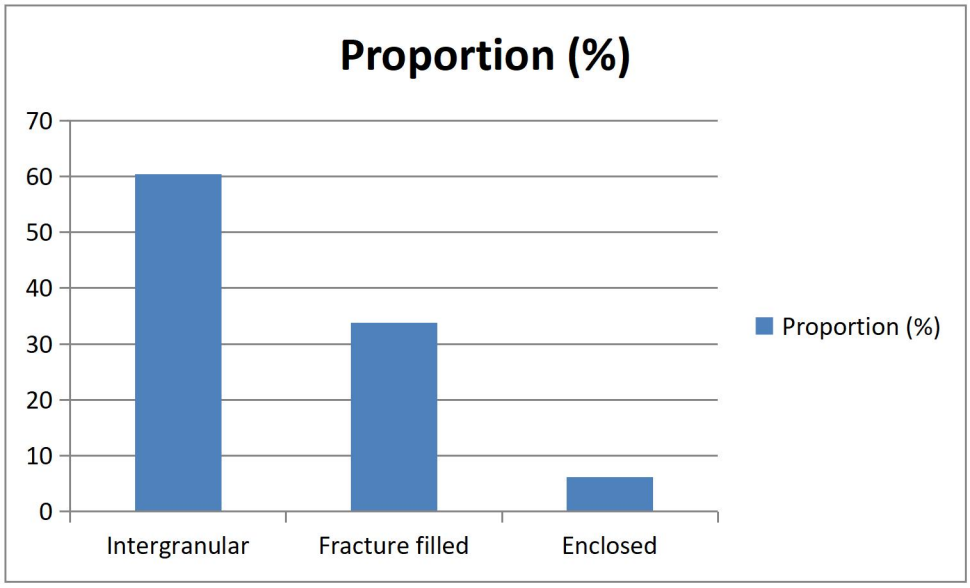


Figure 19 Native gold occurrences in OKote ore deposit

Table 18: Dissemination size and occurrence of native gold (BGRIMM, 2016)

Size fraction, μm	Distribution, %		
	Intergranular	Fissure-filled	Enclosed
+74	25.97	0.00	0.00
-74+37	31.45	62.67	00
-37+10	27.40	23.63	52.53
-10+5	11.91	7.89	8.67
-5	3.28	3.80	38.80
Total 100.00	100.00	100.00	100.00

The table shows that intergranular and fissure-filled gold are relatively medium, while the enclosed gold is finer. The enclosed gold mainly concentrates in -37μm+10μm, and secondly under 5μm. Thus, the enclosed gold size is relatively fine, and hard to become liberated or to expose gold, so that this kind of native gold is tend to be lost unless treated in especial way.

4.1.4. Metallurgical test for mineralogical study

Preliminary metallurgical test were done using diagnostic leach test and flotation to study gold associated minerals and occurrences.

a. Diagnostic Leach Test

A one-kilogram sample was ground to 80% passing 100 microns and subjected to a standard Diagnostic leach test to determine the gold associations. In summary, the test involves a head cyanide leach to determine cyanide recoverable gold. The leach residue is then treated with nitric acid to oxidize sulphide minerals which may be gold-bearing and a further cyanide leach test is undertaken to determine "gold associated with sulphide minerals". The residue from this test is then analyzed using a perchloric acid attack and any gold remaining is reported as "Encapsulated gold". [Wardell Armstrong International (WAI), 2011].

Table 19: Diagnostic leach test result

Phase	Au Distribution (%)		Average Au distribution (%)
	HG-CS1	LG-CS2	
Cyanide recoverable	82.5	87.5	85
Gold in sulphides	10.5	8.3	9.4
Encapsulated gold (gold inside other minerals)	7.0	4.2	5.6
Total	100	100	

Note: HG-CS1 is sample code for high-grade composite sample (6.25ppm Au) and LG-CS2=low-grade composite sample (0.215ppm Au).

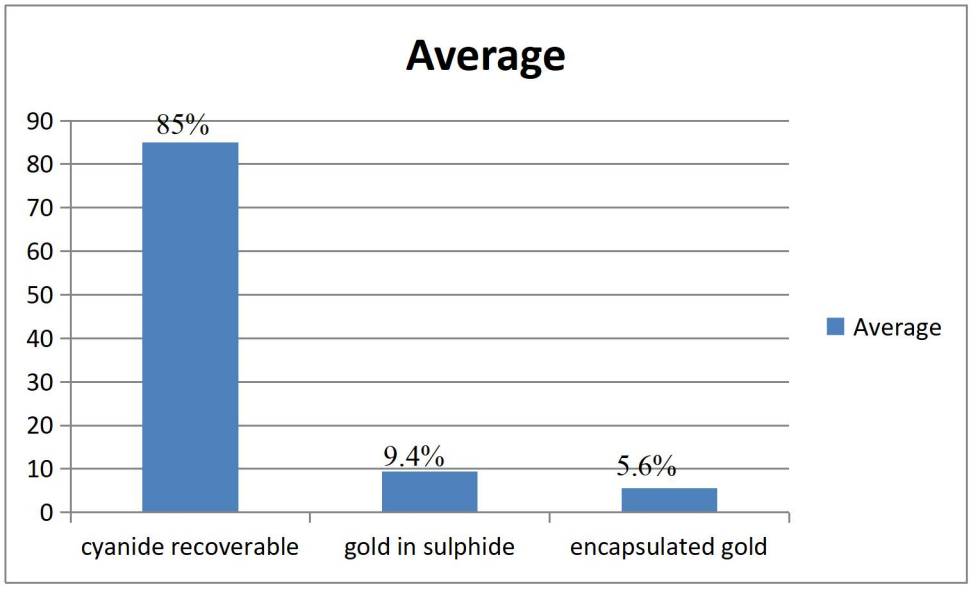


Figure 20 Diagnostic leach test gold distribution in samples HG-CS1 and LG-CS2

b. Flotation concentrate and tailing of 70% particle size passing 74μm microscopic examination

The microscopic examination indicated that the flotation concentrate contains mainly metallic minerals, and fewer amounts of gangue minerals. The main metallic minerals are pyrrhotite and pyrite, followed by ilmenite, magnetite and chalcopyrite, less amount of hematite, limonite and covellite, trace amount of sphalerite, arsenopyrite, galena, bornite and molybdenite. Most of metallic minerals occur as free particles, less amount as intergrowths with gangue minerals (A).

Most of native gold occur as free particles (B) and less amount as intergrowths associated with sulfide minerals or gangue minerals (C). Grains of the native gold are in the size range 40μm-5μm, mostly between 20μm and 10μm.

The microscopic examination indicated that the tailings contain mainly gangue minerals, and fewer amounts of metallic minerals. The main metallic minerals are magnetite, ilmenite, hematite and limonite, less amount of pyrrhotite and pyrite, trace amount of chalcopyrite and rutile. Most of metallic minerals occur in particles of intergrowths associated closely with gangue minerals (D). Grain sizes of the metallic minerals are all under 50μm, mostly in the size range 25μm-10μm. Most native gold in the tailings are enclosed grains finer than 5μm locked in gangue minerals (E), which can hardly be recovered by flotation.

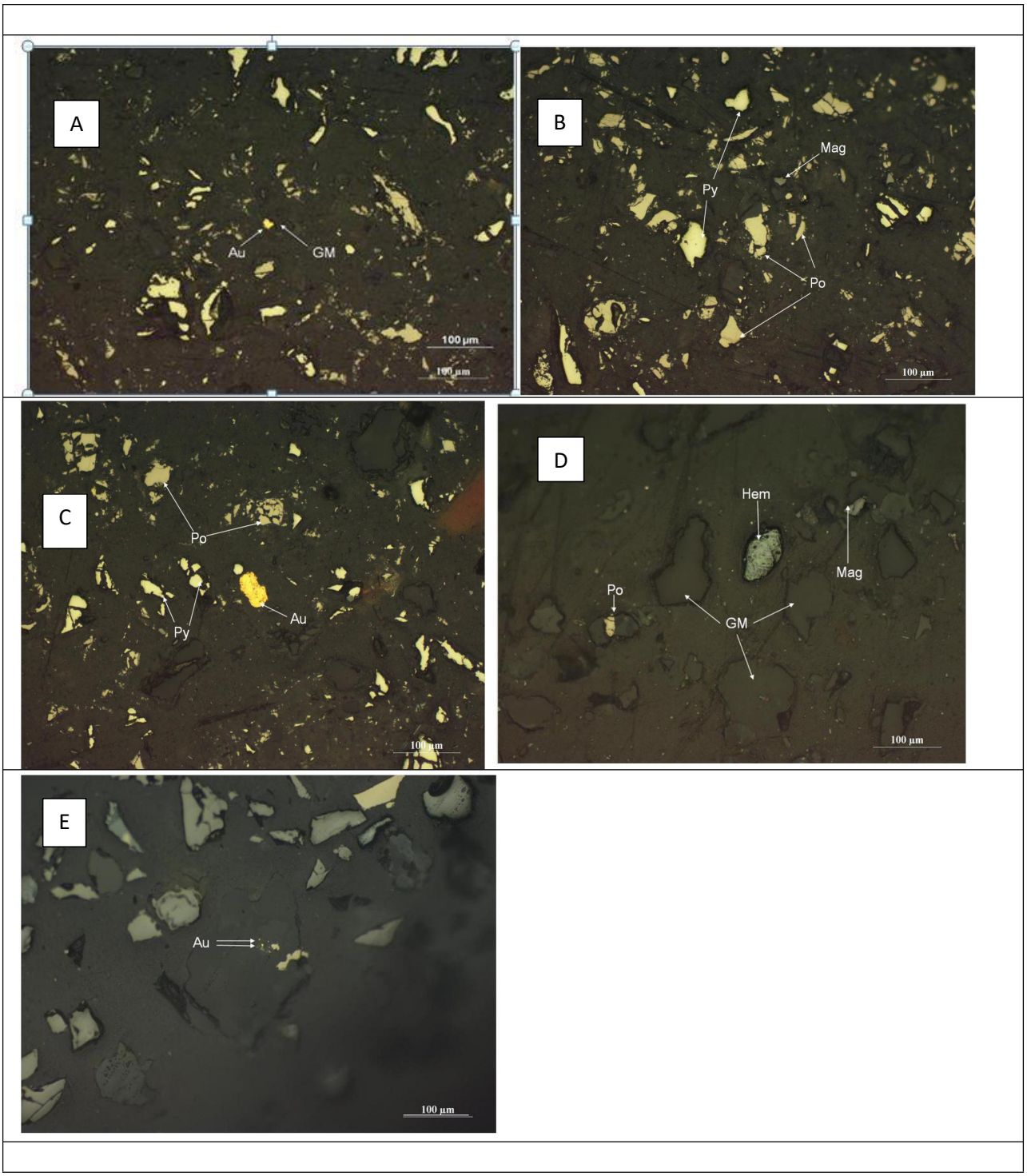


Figure 21 Flotation concentrates and tailing test for mineralogical composition under optical microscope reflected light. Pyrrhotite, pyrite as free and locked particles in flotation concentrate (A); Native gold as free particles in flotation concentrate (B); Native gold as intergrowths in flotation concentrate(C). Gangue minerals, pyrrhotite, hematite and magnetite in tailings (D), Intergrowth particle with locked native gold grains in tailings (E). (Au= gold, Py=pyrite, Po=pyrrhotite, Mg=magnetite, Gm=gangue minerals, He=hematite); optical microscope, reflect light (BGRIMM, 2016; NMiC).

c. **Chemical phase analysis results of Au**

Table 20: chemical phase analysis result of Au with grinding fineness 95% passing 38μm

Phase	**Exposed gold**	**Enclosed gold in sulfide minerals**	**Enclosed gold in other minerals**	**Total**
Au content, g/t	1.91	0.03	0.11	2.05
Distribution, %	93.39	1.26	5.35	100.00

The result shows that the Au in this analysis sample mainly occurs as exposed gold with the distribution rate of 93.39%. The distribution rate of enclosed gold is relatively low, of which1.26% exists in sulfide minerals, and 5.35% exists in other minerals.

4.2. Discussion

4.2.1. Chemical and Mineralogical composition and gold grain size distribution of Okote gold ore deposit

a. Chemical composition

Table 21: Summary of total major and minor oxides chemical assay results of rock samples

Chemical assay (%)	Sample ID											
	GOK-RK-006	GOK-RK-007	GOK-RK-010	GOK-TC-320	GOK-TC-731	GOK-TC-836	GOK-TC-846	GOK-TC-1054	HG-CS1	HG-CS2	CS1-6	Average
SiO_2	39.32	51.98	53.01	52.12	91.76	34.10	96.80	87.88	62.5	58.3	57.80	62.32
Al_2O_3	4.30	2.17	2.67	14.46	4.17	10.46	0.80	3.6	10.14	12.65	13.11	7.14
Fe_2O_3	1.52	3.77	1.88	3.76	1.15	4.10	1.60	1.82	8.76	7.62	7.10	3.92
CaO	28.20	21.45	21.5	13.40	0.16	22.4	1.04	2.33	6.68	7.86	6.30	11.94
MgO	7.22	0.9	0.9	2.36	0.85	5.14	<0.01	0.38	2.66	3.57	3.20	2.72
Na_2O	1.98	0.06	0.04	1.20	0.21	2.88	<0.01	1.05	1.86	2.15	2.39	1.38
K_2O	0.22	0.15	0.1	0.28	0.03	0.90	<0.01	0.14	0.70	0.88	0.82	0.422
TiO_2	0.14	0.03	0.08	0.22	0.38	0.6	<0.01	0.08	0.51	0.33	0.34	0.271
LOI	17.57	19.13	19.7	10.53	1.2	18.69	0.75	2.6				11.27

Table 21 shows: silicon, aluminum, iron, calcium and magnesium are the dominant elements in the deposit. Also, sodium is present in sizable amount. High content of CaO (13-28%), MgO (up to 7.5%) and LOI (10.5-19.7%) in samples GOK-RK-006, GOK-RK-007, GOK-RK-010, GOK-TC-320, and GOK-TC-836 indicate carbonate altered host rock. High LOI confirms abundant calcite/dolomite. The presence of TiO_2 (up to 0.6%) indicates minor detrital rutile/ilmenite occurrence in the deposit. Samples like GOK-RK-006 (28.2% CaO, 7.2% MgO), GOK-RK-007 (21.5% CaO), and GOK-TC-836 (22.4% CaO) may consume large amounts of cyanide and lime (or acid in pre-treatment).

High SiO_2 samples (e.g., GOK-TC-846, 96.8% SiO_2): Will be abrasive, increasing mill liner and media wear. However, they are chemically benign for leaching if gold is liberated.

Moderate Al_2O_3 samples (10-13% Al_2O_3 in HG-CS1, CS1-6): Indicate clay minerals (kaolinite, illite). Clays cause pulp viscosity issues, slow settling in thickeners, and can adsorb gold-cyanide complexes (preg-robbing)-especially problematic if organic carbon is also present.

Iron Oxides (Fe_2O_3 up to 8.8%) content indicate the presence of iron minerals (such as hematite, goethite, or possibly pyrite) can consume oxygen and cyanide via side reactions, and may encapsulate fine gold.

Sodium and Potassium (Low to Moderate): Na_2O and K_2O levels are generally low (<2.4%), indicating minimal feldspar or mica; no major alkali-related processing issues expected

Table 22: Summary of total elemental analyses results of rocks

Chemical assay	Sample ID											
	GOK-RK-006	GOK-RK-007	GOK-RK-010	GOK-TC-320	GOK-TC-731	GOK-TC-836	GOK-TC-846	GOK-TC-1054	HG-SC1	HG-SC2	CS1-6	Average
Au (ppm)	0.01	0.0084	0.015	0.01	16.95	100	0.01	0.415	6.25	0.215	2.05	3.90
Ag (ppm)	<0.02	0.1	0.1	<0.02	0.6	0.51	<0.02	0.1	0.16	0.08	2.54	0.38
Cu (ppm)	0.01	16.60	13.90	68.80	6.40	46.40	352.6	18.2	92.1	65.8	150	75.53
Zn (ppm)	13.00	18.0	10.0	32.40	2.0	43.0	27.40	4.0	74.0	67.0	200	44.62
Pb (ppm)	0.01	2.4	1.1	0.01	0.3	0.01	0.01	0.7	12.1	9.7	90	10.57
Ni (ppm)	42.4	56.8	20.4	97.4	10.8	161.1	22.2	7.3	36.4	48.2	-	50.3
As (ppm)	-	2.2	0.8	-	3.5	-	-	1.9	25.1	6.4	16	7.98
Sb (ppm)		0.3	<0.1		0.3			<0.1	0.92	0.39	27	4.16
Te (ppm)									0.2	0.18	-	0.19
S_{ToT} (%)	0.98	<0.02	<0.02	0.12	<0.02	2.25	0.65	<0.02	1.72	0.76	0.65	0.66
S_{SoL} (%)									0.08	0.08	-	0.08
C_{ToT} (%)	1.66	4.69	4.7	2.15	0.02	2.32	0.97	0.45	1.46	1.14	0.93	1.86
C_{ORG}(%)	1.09			1.59		1.98	0.39		0.01	0.03	-	0.85

Table 22 Elemental analysis result shows various elements such as Ag, Cu, Zn, Ni, As, Sb, Te, S and C are found associated with gold in the deposit. Over all the amount of preg-robbing mineral-organic carbon and cyanicides (such as Cu and S minerals) are moderate and low respectively. However when we consider each sample the impact on gold processing can be discussed as follow:

Sample GOK-TC-836 result showed high gold associated with high total sulfur content. This may indicate that significant sulfide minerals such as pyrite and pyrrhotite occur in the deposit. These minerals may have an effect on gold cyanidation as they consume both cyanide and oxygen. The organic C (1.98%) level is a critical issue as organic carbon is known to preg-rob dissolved gold during cyanidation, lowering gold recovery. The nickel Ni content (161ppm) is harmless at this level. The carbon and sulfur combination make this sample refractory.

Sample GOK-TC-731 (16.95 ppm Au) indicate Potentially Free-Milling S_{ToT} <0.02% – negligible sulfides. C_{ORG} not reported, but C_{ToT} = 0.02% (very low)-no organic carbon issue. As, Sb low (3.5 and 0.3 ppm) - no cyanidation problem; direct cyanidation (CIL/CIP) is possible.

Sample HG-SC1 (6.25 ppm Au) indicates Mild Refractoriness from Sulfides & Arsenic, S_{ToT} (1.72%) moderate sulfide content. As (25.1ppm) indicate relatively low for arsenic sulfide (arsenopyrite typically % levels). At this ppm level, it will not significantly hinder cyanidation, but if As is present as arsenopyrite, gold could be locked inside. C_{ORG} (0.01%) indicate no preg-robbing effect. This sample can be categorized as semi-refractory; could be treated by fine grinding and cyanidation. Flotation might be considered to concentrate sulfides and then oxidize, but with only 1.7% S, direct cyanidation after grinding to 75 µm may still achieve 70–85% recovery.

Sample CS1-6 (2.05 ppm Au)-High Sb & Base Metals: Cyanicide Risk. Sb (27 ppm) is significantly elevated. Antimony (especially stibnite) reacts with cyanide to form insoluble Sb(III) and Sb(V) complexes, consumes cyanide and can precipitate as sodium antimonate, potentially blinding gold surfaces. Pb (90 ppm), Zn (200 ppm) indicates both are cyanide consumers and also Pb can cause passivation. Cu (150 ppm) is moderate cyanicide. As (16 ppm) is minor. S (0.65%) shows low to moderate sulfides. These results of the sample indicate high reagent consumption for direct cyanidation; need pre-aeration or lead nitrate addition to mitigate Sb/Pb effects.

Sample GOK-TC-846 (0.01 ppm Au) but 352.6 ppm Cu may pose copper Interference: high Cu (353 ppm) in bulk ore processing would increase cyanide consumption significantly.

Other Samples (Low Au, variable S & C): GOK-RK-006 (0.01 ppm Au, 0.98% S, 1.09% C_{ORG}) indicate organic carbon without gold is not a problem for processing, but if blended with high-Au ore, it could introduce preg-robbing. GOK-RK-007 & 010 (very high C_{ToT} 4.7% but C_{ORG} not measured) these samples results most likely indicate carbonate carbon (since no organic carbon reported), so no preg-robbing; but need to be confirmed by acid leach vs. combustion.

b. Mineralogical composition

Okote gold ore mineralogical composition identified using optical microscope, X-ray diffraction and electron probe microanalysis techniques. These include:

- Gold ore minerals: native gold, electrum and petzite;
- Associated ore minerals: pyrite, pyrrhotie, chalcopyrite, covellite sphalerite, rutile, goethite, limonite, hematite, and magnetite which are not economically recoverable and can be considered as gangue minerals in case of Okote gold deposit.

- Gangue minerals: quartz, chlorite, carbonates (calcite being the dominant, dolomite, and ankerite), plagioclase and k-feldspars, clay-illite, mica (muscovite, biotite), tourmaline and etc.

Table 23: Overall modal composition of gangue minerals in Okote gold deposit obtained from optical microscope and XRD analyses.

Sample ID	Mineral content (%)								
	Illite + mica	Chlorite	Quartz	Amphibole-hornblende	Calcite	Dolomite	Tennantite	Pyrite	others
GOK-RK-06			65.6		34.4				
GOK-TC-320			88.3				11.7		
GOK-TC-836			38.5		61.5				
HG-CS1	29	23	32	1	3	12	0	1	
LG-CS2	36	33	19	3	3	4	0	2	
HG			58	9	16				
LG			44	14	18				
Average	**9.30**	**8**	**49.34**	**3.86**	**19.41**	**2.28**	**1.67**	**0.43**	**5.72**

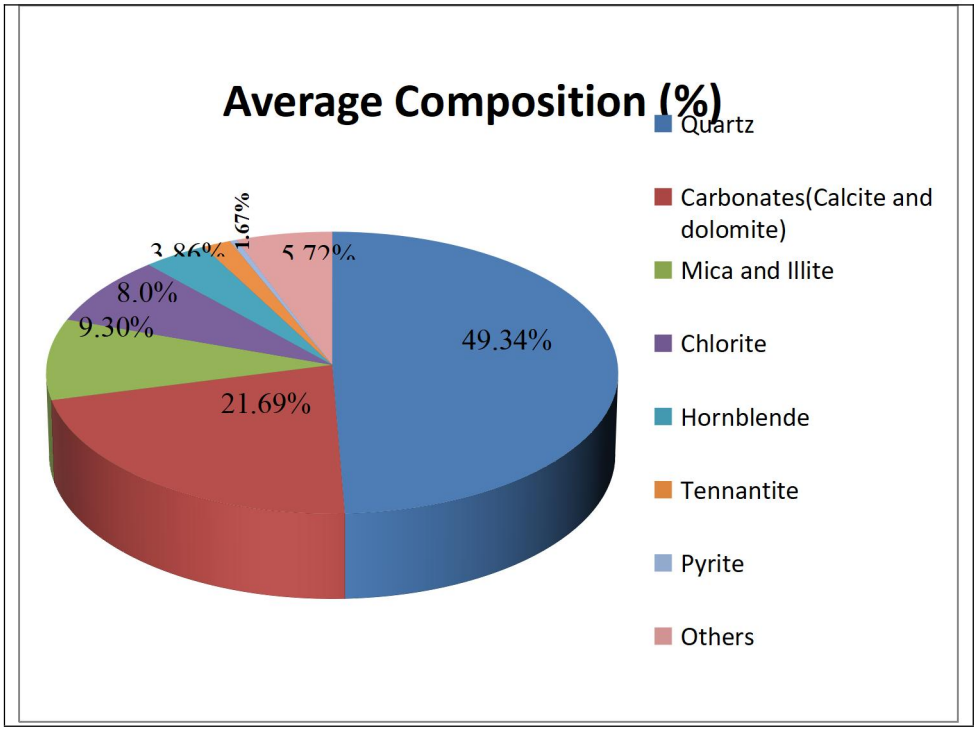


Figure 22 Pie chart showing cumulative gangue minerals modal compositions of OKote gold deposit

c. Gold grain size distribution

Gold grain size distribution of Okote gold deposit is found as over 74µm (15.59%), -74µm+37µm (40.07%), -37µm+10µm (28.01%), -10µm+5µm (10.39%), and -5µm (5.59%). Native gold of Okote gold deposit is found distributed as intergranular (60.4%), fracture filled (33.78%) and enclosed in gangue minerals as well as sulphide minerals (6.18%).

According to Chryssoulis and McMullen (2016), gold particle classification as very fine (~2-<0.1µm), fine (~20-2µm), medium (~200-20µm), coarse (~500-200µm), and very coarse (>500µm); most of Okote gold particle grain size rage is from fine to medium.

4.2.2. Process implication

Mineral processing is the extraction of valuable mineral/s by separating from the gangue minerals or wastes. This involves the liberation of minerals from the gangues through comminution (crushing, grinding) and classification, followed by gravity separation, flotation and cyanidation as well as a combination of two or three of these techniques.

Comminution size is determined based on the valuable mineral grain size distribution in the ore deposit. The downstream separation techniques are also chosen based on grain size distribution of the mineral in need. In addition to particle size distribution effective or efficient separation is governed by certain mineral properties such as density, magnetic susceptibility, electrical conductivity, surface chemistry and chemical compositional response towards certain reagents and chemicals.

Generally recovery of valuable mineral is dependent on certain mineralogical factors such as physical properties (mineral texture-shape, grain size, nature of interlocking, etc.), chemical content/ properties (grade, surface chemistry and response to certain reagents/chemicals), mineralogical properties (ore mineralogy, gangue mineralogy and associated minerals) and so on.

Mineralogical factors control the efficiency of processing and metal recovery, influencing every phase from feasibility studies and mine/process development through to active operations. These factors primarily include the texture of ore minerals, the composition of both ore and gangue minerals (such as the presence of cyanicides and oxygen consumers), the occurrence of preg-robbers, and the existence of refractory gold minerals; particularly submicroscopic gold hosted within sulfides and other mineral structures.

Based on the effectiveness of gold extraction and the complexity of the processing methods involved, gold ores are categorized as free-milling, complex, or refractory.

Free-milling ores are those from which more than 90% of the gold can be recovered using standard cyanide leaching.

Complex ores refer to ores from which high gold recoveries are possible, but under modified or more intense leaching.

Refractory ores are ores from which acceptable gold recoveries cannot achieved using standard procedures as they are physically and chemically locked/in the solid solution state in sulfides and other minerals in which gold is inaccessible to lixiviants(reagents, chemicals/cyanide and others). These ore need pretreatments such as ultrafine grinding, roasting, pressure oxidation, and biological/bacterial oxidation.

Okote gold ore behave mainly as free-milling ores due to its occurrences mostly as intergranular-along gangue minerals grain boundaries and fracture filling that can be liberated easily. There are moderate level of organic carbon, and low level of copper minerals and tellurides.

The main gold-bearing mineral in the ore deposit is native gold. Other gold minerals in trace amount are electrum and petzite. The gold minerals are found distributed as intergranular and fracture fill gold as well as few fine grains enclosed gold, and can be categorized as free milling gold ores and refractory ores.

Understanding and managing gold ore texture/grain size distribution, gold ore and gangue minerals is essential for improving gold recovery, minimizing process costs, and avoiding metallurgical challenges (https://www.911metallurgist.c).

Mineralogical factors most likely affect gold recoveries are discussed as follow:

a. Effect of grain size/texture in gold processing

Texture of the ore (shape/morphology, grain size, and nature of interlocking/gold occurrence) has a significant effect on metal recovery which is a determinative in feasibility study and processing plant design. Grain size and textural relationship of valuable minerals helps in deciding the size reduction and liberation in mineral processing. The grain size distributions determine the liberation size of gold from the gangue minerals during comminution.

Based on mineralogical analysis so far done, native gold was found exclusively dominant type of gold ore mineral that exhibit dominantly fine to medium in grain size, and the majority of which is found situated between gangue grain boundaries/as intergranular and micro fracture fill that can easily be liberated at fine grinding. However, few part of the gold is found as enclosed/encapsulated within the gangue minerals mainly quartz, pyrite and chlorites. Gold grain sizes analysis showed that 15.59% of the gold is above 74µm, 68.08% fall between 74µm and 10µm; and 15.98% below 10µm.

Based on these gold grain size distributions results, the Okote gold deposit generally need fine-ultrafine grinding to reclaim gold from the gangue minerals. However, concentrating fine grained gold particles is a challenge for both flotation and direct cyanide leaching as it creates a slime that may clog the downstream flotation cells and thickener processing equipment. Beside the clogging downstream process equipment, fine grinding can increase the amount of impurities that can affect concentrate quality.

According to Marsden et al. (1992), poor cyanidation performance can result from very fine gold particles (<10 μm) that are associated with sulfide minerals. The same authors also note that the encapsulation of visible gold within sulfide and silicate minerals frequently leads to gold losses. Furthermore, very fine particulate gold (<10 μm) locked in sulfide or other gangue may not be exposed to cyanide solutions at conventional grind sizes (e.g., 80% passing 75 μm), which may necessitate finer to ultra-fine grinding (e.g., 80% passing 20 μm or 80% passing 10 μm) to expose the gold (Marsden et al., 1992).

Gravity concentration is useful for coarse gold grain sizes >150μm that are difficult to recover effectively by flotation and cyanide leaching. Advanced gravity centrifugal concentrators like knelson and Falcon concentrators are suitable for gold grain sizes down to 20μm. Gold grain size/particle grain size appropriate for flotation range from 150μm to 5μm. Agitated tank cyanide leaching are suited for gold grain size below 150μm.

Consequently, proper management for liberation of fine particles is important by taking into consideration the adverse effect of fine grinding.

Advanced gravity centrifugal concentrators, flotation and cyanide leaching techniques can be employed by managing appropriate particle size distributions to concentrate Okote gold ores.

Gold grain size classification according to Chryssoulis and McMullen, 2016 is (i) very fine -2<0.1 μm, fine -20-2 μm, medium -200-20 μm, coarse -500-200 μm and very coarse >500μm. From gold grain size distribution analysis, it was found that about 94.06% of gold is above 5μm which fall under fine to medium gold grain size classification category.

Generally, texture of the ore shape/morphology-granular, irregular and elongated, grain size- that is fine to medium class and nature of interlocking-between grain boundaries and microfracture fill as well as enclosed/encapsulate of gold ore in the Okote gold deposit has a significant effect in the recovery of gold metal.

Therefore, it is important to carefully consider the ore texture/grain size distribution of Okote gold deposit during feasibility study and process selection for processing plant design.

b. Effect of gold ore mineralogy in gold processing

The mineralogy of gold ore minerals (types, abundance and associations of minerals present) has a significant effect on efficiency, cost and environmental of gold processing.

The main gold ore mineral identified in the Okote gold deposit is native gold accounting 99.51% and others such as electrum and petzite. Associated minerals include pyrite (dominant), minor chalcopyrite, pyrrhotite, magnetite, and accessory rutile, chalcocite, covellite, sphalerite, galena and others.

Gold- silver minerals: the main gold-silver minerals are native gold and electrum. Silver dissolve faster in cyanide than gold and can result in high consumption of cyanide when found in higher concentration. Gold and silver always co-exist as an alloy and their separation can extend to final smelting/refinery process. Higher Ag content affects "Dore" composition.

Sulfides: According to Chryssoulis and McMullen (2016), several sulfide minerals hinder gold recovery during cyanidation: copper minerals form cyanide complexes that are stronger than those of gold; elemental sulfur generates new radicals such as SCN^-; pyrite adsorbs cyanide radicals; and pyrrhotite consumes dissolved oxygen.

Fink and Putnam (1950) reported that even dissolved sulfide concentrations as low as 0.5 mg/L (0.05%) can reduce the gold leaching rate by half, an effect they attributed to the formation of an insoluble aurous sulfide layer on the surfaces of gold particles.

From the laboratory analyses result the Okote gold deposit found to contain 0.08% sulfur in sulfide form, accordingly a similar slowdown of the leaching process could be expected.

Rees and van Deventer (2000) observed that, under cyanide-deficient conditions, chalcopyrite adsorbs gold almost immediately from solution, whereas pyrite adsorbs about half that amount; this adsorption occurs not only because of the cyanide deficiency but also due to the presence of reactive sites on the sulfide surfaces.

Deschênes (2005) noted that, in addition to consuming oxygen and cyanide, sulfide in gold ore forms a coating on gold grains; this passive layer reduces gold leaching kinetics and overall extraction. Adding lead nitrate is a possible strategy to minimize such gold passivation.

Even though majority of Okote gold ore deposit can be considered as free milling ore, it may also contain both complex ores like copper ores such as chalcocite and covellite as well as pyrrhotite; and refractory ores of sulfides (pyrite and pyrrhotite).

Gold bearing sulfides (Pyrite, arsenopyrite, pyrrhotite): Common iron sulfide minerals such as pyrite (FeS_2), arsenopyrite (FeAsS) and pyrrhotite (Fe_{1-xS}) have significantly influence on gold processing.

Pyrite: pyrite is a common host for sub-microscopic (invisible) gold. Pyrite is best concentrated using flotation. Cyanidation is applicable if gold associated with pyrite is free and surface attached. For gold enclosed or locked in pyrite, cyanide leaching is possible after concentration of pyrite using flotation followed by pre-treatments such as roasting, pressure oxidation and bio-oxidation.

Pyrrhotite: pyrrhotite may host or encapsulate gold and it is a reactive mineral and consumes oxygen during cyanidation. Due to its less stability and reactive nature, concentration of pyrrhotite using flotation method is difficult. So that pyrrhotite management in

cyanidation/cyanide leaching requires reagents (oxygen and cyanide) adjustment and in flotation consideration for selective depressants is important.

Arsenopyrite: arsenopyrite is a major carrier of refractory gold/locked gold and recovery of gold using cyanidation require oxidative pretreatments. Arsenopyrite oxidative treatment can create environmental and metallurgical issues. Roasting of arsenopyrite produce arsenic-gas which is toxic compound and need gas capture and treatment facility.

Sulfide minerals (dominantly pyrite and pyrrhotie) in the Okote gold deposit accounts for about 9.4% Au content. The recovery of the refractory ore of Okote gold deposit using cyanidation can be dealt by employing finer grinding to ultrafine grinding or oxidative pretreatment (like pressure oxidation/ roasting/bio-oxidation) after gravity/flotation concentration.

Base metals (Cu, Zn and Pb ores): In the context of base metal ores (copper, zinc, and lead), the cyanide complexes formed with metal ions such as Fe^{2+}, Ni^{2+}, Cu^{+}, Zn^{2+}, and Mn^{2+} do not directly interfere with the gold cyanidation process. However, their formation can reduce the availability of free cyanide in the leaching solution, thereby slowing the dissolution of gold. Notably, ferricyanide acts as an oxidizing agent capable of leaching gold directly (Putnam, 1950).

Copper ore minerals: Common copper sulfide ore minerals include Chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4), chalcocite (Cu_2S). There are also other varieties of copper ore minerals which are native copper, oxides, and carbonates. Flotation is the favorable concentration for copper sulfides when found in high concentration.

The presence of cyanide-consuming species at levels below 100 ppm, particularly secondary copper minerals such as chalcocite, covellite, malachite, and azurite, can lead to extremely high cyanide consumption (Adams et al., 2008). Elevated cyanide usage often results in poor gold recovery because the cyanide preferentially reacts with the more abundant copper, being consumed before it can effectively dissolve gold. Since copper forms stronger complexes with cyanide than gold does, a general rule is that a five-to-one molar ratio of cyanide to soluble copper is required for gold leaching (Venter et al., 2004). In addition, the precipitation of copper and gold as insoluble cyanide salts may further contribute to lower gold recoveries.

Copper minerals are cyanide consumer except for chalcopyrite and can reduce the recovery of gold. These reactive/cyanide consumer copper ore minerals can be controlled by adding more cyanide than that used for the conventional/standard cyanidation.

Okote gold deposit contain copper ore minerals such as chalcopyrite, chalcocite and covellite among which both chalcocite and covellite are considered to consume cyanide but depending on their abundance.

Zinc ore minerals: Most common ore mineral is sphalerite (ZnS). Shphalerite may host gold and flotation need activated Cu^{2+} and it has little effect in cyanidation.

Lead ore minerals: Galena (PbS) is common lead ore mineral; can trap or host gold and has good floatability. However, it inhibits leaching and precipitate gold as Pb-Au alloys in cyanidation (Jin et al, 1998).

Over all Okote gold deposit contain very small lead which may have no or little effect in gold processing.

Tellurides: Tellurides are gold-bearing minerals in which gold occur in compound form with tellurium. Most common gold-bearing tellurides include calaverite ($AuTe_2$), sylvanite [$(Au,Ag)Te_2$], and petzite (Ag_3AuTe_2). They are dense and can be recoverable by gravity methods if liberated. Also, concentration of tellurides together with sulfides is possible using flotation methods provided that tellurides are not oxidized.

Gold tellurides are highly refractory to cyanide leaching in that they are chemically locked and cannot dissolved by cyanide alone and tellurium compounds interfere with leaching chemistry, forming passivation films. These properties of gold bearing tellurides pose difficulty during cyanidation and highly reduce gold recovery. To process telluride ores, flotation followed by oxidative pretreatment, particularly using roasting along with toxic tellurium oxide gas capture system and cyanide leaching is an appropriate approach for gold recovery.

In case of Okote gold deposit, the identified telluride mineral is petzite with 0.01% gold content; is not a threat for gold recovery using cyanidation method.

c. Effect of gangue mineralogy in gold processing

Gangue mineralogy-the type and nature of gangue minerals which are non-economic minerals associated with gold ores has an effect on gold processing.

Dominant gangue minerals of Okote gold deposit identified using OM, XRD and EMPA analytical techniques include quartz, chlorite, clay (illite, kaolinite), mica, calcite, and amphibole-hornblende. There are also other gangue minerals like plagioclase-albite and clay (kaolinite).

Silicate gangues (quartz and feldspars): Quartz being the dominant gangue in the ore with hardness of 7 on Mohs scale can create difficulties in grinding, leading to high energy cost. It increase wear on grinding equipment and requires higher energy input. Quartz being the dominant gangue mineral in the Okote gold deposit; is found hosting very fine-medium gold. Hardness of quartz affects liberation size of gold and appropriate equipment selection for fine to ultra-fine grinding is required to free gold from the gangue.

Clay, micas, and chlorite: Clay minerals, micas and chlorite are the main gangue minerals after quartz in the Okote gold deposit, can significantly affect gold processing particularly during grinding, flotation, and cyanidation.

In their study of shale material from the Beatrix Gold Mine in South Africa, Van Vuuren et al. (2000b) observed that strong alkaline solutions break down phyllosilicates, specifically pyrophyllite, muscovite, and chlorite, causing a decrease in pH. Consequently, gold co-precipitated with colloidal $Mg(OH)_2$ and $Fe(OH)_3$ onto the ore surface, indicating that pyrophyllite and muscovite may be instrumental in the adsorption of gold from solutions onto the solid surfaces of ore particles.

Clays cause slimes in mineral processing which is a problem for proper filtration during thickening/dewatering. Also clay minerals act as preg-borrowers (Venter et al., 2004).

Clays form ultrafine particles (slimes), coat gold-bearing sulfides making separation difficulty during flotation and reduce gold recovery. Clays adsorb water and create viscous slurries as well as increase pulp viscosity creating difficulties in slurry handling, agitation and liquid-solid separation. Clays reduce permeability during heap leaching resulting in low gold recovery.

Micas (muscovite, biotite) form flat and flacky particles that can come up with froth during flotation and reduce grade of concentrate. Fine mica particles may physically trap or occlude gold grains.

Chlorite being soft mineral is prone to produce ultrafine particles during grinding. This ultrafines create slimes and increase viscosity of the pulp which are a challenge in downstream processing. Chlorite slimes create a coating behavior; reduce the flotation of gold bearing sulfides like pyrite and arsenopyrite and coating of free gold during cyanide leaching, affect gold recovery. Chlorite can host gold minerals in the form of encapsulation or locked in its matrix make gold inaccessible to cyanide leaching also reduce gold recovery unless treated by roasting and pressure oxidation before leaching.

Okote gold deposit possess high amount of clay, micas, and chlorite that may create slime, viscosity, coating and preg-borrowing issues.

Preg-borrowing is a reversible effect and issues related to slime and viscosity formation for both group of minerals can be solved through: (1) pre-desliming-removal of fines using hydrocyclones or screens (2) use of dispersants/modifiers- addition of flocculants can improve filtration rate (3) selective flotation- using respective depressant during flotation can reduce dilution of concentrate and (4) ore blending-addition of clay, mica , or chlorite rich-ore with clean ores reduce the effects.

Carbonaceous materials: Carbonaceous materials, such as elemental carbon or activated carbon, can hinder gold recovery in two ways: either by trapping gold within the carbonaceous matrix and preventing its release, or by adsorbing gold that has already dissolved into the leach solution (Osseo-Asare et al., 1984b).

Carbonaceous materials (e.g., graphitic schist) can adsorb gold from solution, a phenomenon known as preg-robbing effect. Organic carbon being one of the complex ore categories is a preg-robbing material that adsorb dissolved gold from pregnant solution and can reduce gold recovery.

According to Mohamode L. Diakite et al., 2023; ore containing carbonaceous materials less than 1% is classified under lowly and mildly preg-robbing ores from which gold extraction is possible by using CIL process and pre-treatment of the ore with blinding agents to minimize the gold losses is essential. Organic content of Okote gold ore deposit averaged to 0.85% and can be classified under lowly and mildly preg-robbing ores that can be extracted using CIL. Studies on relationship between total organic carbon content and preg-robbing capacity indicated that for less than 0.05% total carbon content of feed, there is no preg-robbing effect. The processing of these ores includes roasting, the addition of kerosene or heavy oils, flotation, and aqueous chlorination.

Okote gold deposit chemical analysis showed that medium level of organic carbon. Therefore, the carbonaceous matter content of Okote gold deposit assumed to have an effect on gold recovery. The use of CIL circuit and addition of kerosene or heavy oils may reduce the effect.

Oxides (Fe, Mn): Iron oxides (e.g. hematite, magnetite, goethite) and manganese oxides (pyrolusite) have an effect on gold processing as follow:

Both iron and manganese oxides are denser than silicates and can be concentrated together with gold in gravity separation processes. This can be result in reduced concentrate grade. Gold can be found in Fe/Mn oxides as dissemination or locked form that is difficult to concentrate using gravity separation.

Iron oxides lower gold recovery by flotation as they coat gold bearing sulphide minerals like pyrite/arsenopyrite. Manganese oxide-pyrolusite can disturb flotation behavior by reacting with collectors or oxidizing reagents.

Fe-oxides have a property of hosting invisible/sub-microscopic gold in their structure and may adsorb gold from solution during cyanidation and Mn-oxides are strong oxidants that can consume cyanide through oxidation.

Okote gold deposit contains Fe-oxides such as goethite, heamatite, magnetite and limonite which need proper management during gravity separation, flotation and cyanidation.

Carbonates: Carbonate minerals, such as calcite ($CaCO_3$), dolomite ($Ca,Mg(CO_3)_2$), and ankerite ($Ca(Fe,Mg,Mn)(CO_3)_2$), can have a substantial impact on gold processing. Regarding calcium ions, Barsky et al. (1935) observed that raising the pH above 11 with lime reduced the cyanidation rate, and at pH 12.2, gold leaching was nearly negligible. Additionally, in the presence of carbonaceous material, calcium ions can enhance the adsorption of gold onto elemental carbon (Davidson, 1974).

Carbonate minerals like dolomite and calcite can physically encapsulate fine gold particles, preventing the leaching agent (e.g., cyanide or thiosulfate) from contacting and dissolving the gold, leading to low gold recovery rates.

During oxidation pretreatment, carbonate minerals can decompose and the resulting products may react with other elements (like iron oxides) to form new, insoluble mineral phases (e.g., iron silicates); these new layers can coat the gold or other sulfide minerals, creating a passivation barrier that significantly reduces gold leaching efficiency.

Okote gold deposit contain substantial amount of carbonate minerals and may enhance adsorption of gold by elemental carbon and encapsulate fine gold particles and prevent leaching agents.

The effects of carbonates may be mitigated through blending of ore, PH control, using alternative leachants less affected by carbonates like thiosulfate and selective flotation.

4.2.3. Comparison with other deposits in Ethiopia

Mechanized and known gold production in Ethiopia are the Lega Dembi and Sakaro gold deposit and the Akobo gold deposit. There are also gold deposits on development stage such as Okote gold deposit, Kurmuk Dish and Ashashire gold deposit, Tulu Kapi gold deposit and Metekel-Bulen-Jelaye gold deposit.

a. Lega Dembi and Sakaro gold deposit

Geological Setting: Situated within late-Proterozoic meta-volcanosedimentary Megado belt of the Adola granite-greenstone terrane

Host rock: Host rock: graphite-bearing-biotite-sericite schist

Ore mineralogy: gold ores-native gold, electrum, petzite, hessite. Gold associated/host minerals-galena, chalcopyrite, pyrite and others like sphalerite, pyrrrhotite, arsenopyrite

Gangue mineralogy: Quartz, muscovite, biotite, phylogopite, anorthite, albite, hornblende

Gold processing implications and routes: Processing of gold in quartz-sulphide ores result in low recovery due to fine-grained (native gold, electrum, tellurides) locked in mainly pyrite and possibly invisible gold in arsenopyrite (Cook and Ciobanu, 2001).

Process route: Communition→ screening and hydrocyclone classification→thickening→cyanide leaching→CIP→ elution→electrowinning→smelting→dore gold bar

b. Akobo gold deposit

Geological Setting: Metavolcano-sedimentary rock sequence. The Akobo Gold is located within the “Surma Shear Zone” of the Akobo Greenstone Belt.

Host rock: Altered ultramafics, Metagabbro, carbonate-talc-mangnetite schist, chlorite schist

Mineral resource: 78,000t of ore at an average gold grade of 20.5g/t from only one site named as Segel deposit

Ore mineralogy: Gold mineralogy identified in the area include krennerite, montbrayite, buckhornite, aurostobite, calaverite, nagyagite and gold phosphorus thallium selenide.

Gangue mineralogy: Among the gangue minerals commonly associated with the gold deposit are quartz, actinolite, and chlorite

Grain size distribution: fine to coarse grained, 2/3 being >100µm.

Gold processing implications and routes: The gold is unusually pure, with no silver or other metals with little sulphides in the mineralization, but where found it is generally Cubanite ($CuFe_2S_3$) and pyrrhotite.

Temporal process routes: gold recovery flow sheet was configured as a gravity recovery circuit to target the coarse gold mineralogy followed by a CIL circuit for the full gravity tails to recover the finer gold mineralization.

c. Kurmuk-Dish and Ashashire

Geological Setting: lies within the Neoproterozoic volcano-sedimentary Tulu Dimtu shear belt at the northern end of the East African Orogen

Host rock: Include granitoid lenses and the margins of mafic bodies

Ore reserve: 52.759Mt at1.53g/t Au.

Ore mineralogy: native gold, tellurides, pyrite, chalcopyrite

Gangue mineralogy: quartz, ankerite-dolomite carbonates, muscovite, chlorite, albite

Grain size distribution: gold grain size ranges from very fine-grained (< 2 µm) to coarse-grained (75µm) and more.

Gold processing implications and routes: telluride composition of the deposit shows refractoriness which needs high lime addition to raise gold recovery. No preg-robbers,

The process selected for the recovery of gold is a conventional CIL circuit consisting of crushing (using jaw crusher), grinding (using SAG and Ball mill to 75µm, gravity recovery, cyanidation, followed by elution, electrowinning and smelting to produce gold doré. Proposed process routes on definitive feasibility study are Communition→ gravity separation →cyanide leaching→CIL→elution→electrowinning→smelting→dore gold. Gold from gravity concentrate

is recovered through intensive cyanide leaching in separate unit and gravity tailing gold recovery is in line with primary cyanide leaching.

d. Tulu Kapi gold deposit

Geological Setting: Tulu Kapi is located within the Arabian-Nubian Shield which consists of Archean (Upper Proterozoic rocks more than 800 Ma) gneiss making up a granite-greenstone terrain as well as weakly metamorphosed volcano-sedimentary succession of late Proterozoic.

Host rock: The host rocks are syanite and diorite plutons

Ore Reserve: The ore reserve of Tulu Kapi is 15.4Mt at 2.12g/t Au

Ore mineralogy: Ore and associated minerals: free gold, native silver, sulfides (pyrite, sphalerite, galena, chalcopyrite, bornite, arsenopyrite, tetrahedrite, tennanite), tellurides (calaverite, sylvanite)

Gangue mineralogy: feldspars, quartz, biotite, muscovite, carbonate, epidote.

Grain size distribution: gold occurs on the grain boundaries and fractures fill within sulphides. The gold grains vary from 1μm to 300μm with an average of about 11μm. Visible gold is occasionally seen in core

Gold processing implications and routes: gold in the deposit present chiefly as free gold. The absence of gold in arsenic, tellurium and antimony sulphide minerals was encouraging with respect to the gold metallurgy.

Proposed process routes on definitive feasibility study are Communition→cyanide leaching→CIL→elution→electrowinning→smelting→dore gold; i.e. ROM cyanidation was the selected process route.

e. Metekel-Bulen-Jilaye Gold deposit

Geological settings: Consists of meta-volcanic and meta-sedimentary sequences, mafic-ultramafic mega lenses and minor intrusions, as well as composite mafic to felsic plutonic complexes of bathoilithic dimensions.

Host rock: Skarn related?(greenstone hosted quartz-carbonate vein deposit), mafic-intermediate intrusives.

f. Okote gold deposit

Geological Setting: within late-Proterozoic meta-volcanosedimentary Megado belt of the Adola granite-greenstone terrain

Host rock: Meta-gabbro, Meta-volcanics, Meta-granodiorite and chlorite-carbonate-amphibole schist

Gold Resource: The Okote gold deposit resource is estimated to be 300.95Mt at 1.54g/t Au.

Ore mineralogy: native gold, electrum, petzite and sulfides hosting gold (eg., pyrite)

Gangue mineralogy: quartz, carbonates (calcite, dolomite, ankerite), chlorite, amphibole-hornblende, mica, clay minerals, feldspars and etc.

Grain size distribution: gold grain size vary from fine grain <10µm (15.98%), -37µm+10µm (68.08%) and over 74µm (15.59%).

Gold processing implications and routes: even though the majority of gold is free gold; there are some fine to very fine gold inclusions within sulfides and gangue minerals which are refractory. There are similarities in geological settings, mineralogical composition with other deposits in Ethiopia, especially Lega Dembi gold deposit which is in the same Megado greenstone belt of Meta volcano-sedimentary assemblage.

4.2.4. Possible process routes for Okote gold ore deposit

Depending on ore types (free-milling, complex, and refractory), gold grain size, associated minerals and grade/tonnage; gold process/metallurgy involves several different process routes. The main gold process routes include: gravity concentration, flotation, cyanidation(cyanide leaching), alternative leaching technology (thiosulfate leaching, halide leaching,..), pretreatment, smelting and refining.

Based on mineralogical composition of Okote gold deposit identified so far different processing routes can be suggested for appropriate gold recovery. The deposit contain gold minerals (such as native gold, electrum, petzite), gangue minerals (quartz, carbonates (calcite, dolomite, ankerite), chlorite, plagioclase, hornblende, mica, clay (llite, kaolinite)), associated ore minerals (pyrite, pyrrhotite, magnetite, rutile, ilmenite, limonite, galena, chalcopyrite, sphalerite, arsenopyrite, tennantite), and others. Gold grain size vary from fine grain <10µm (15.98%), -37µm+10µm (68.08%) and over 74µm (15.59%).

Gravity separation as process route: Utilizing the density difference between gold and other materials, methods like panning, shaking tables, and centrifugal concentrators are used. The gold minerals of Okote deposit such as native gold, electrum and telluride-petzite are denser than the associated gangue minerals and some gold grains are medium and few are coarse so that pre concentration using gravity separation can be considered as an option process route. Recovery of coarse gold particles using cyanide leaching is difficult as it require more time to be dissolve by cyanide. In this case process routes involving both gravity pre-concentration followed by cyanidation can result in optimum gold recovery.

Flotation concentration route: uses chemicals and air bubbles to attach to gold particles and separate them from the slurry. Flotation concentration which is governed by surface chemistry of minerals is best process route for sulfide minerals. Concentration of gold by flotation is carried out using different collectors (xanthate and dithiophosphate) and modifiers (PH, depressants and activators). Gold particles are found as physically or chemically locked in sulfide minerals. These fine grained gold inclusions can be concentrated by flotation which is later pre-treated and recovered using cyanidation.

Cyanidation process route: cyanidation which is the most common and known gold process route for century is best suited for free-milling ores or refractory ores after concentration and pre-treatments. In the case of Okote gold deposit, cyanide leaching can be used to recover gold after pre-concentration using gravity or flotation.

CIP/CIL gold recovery: In the CIL (carbon-in-leach) gold is leached and adsorbed on activated carbon in the same tank and in CIP (carbon-in-pulp) leaching and adsorption is in separate stages. In case of Okote gold deposit based on mineralogy CIL circuit can be applied as the carbonaceous content is classified under mildly preg-robbing ores.

Pretreatment route: Used when gold is locked in sulfide minerals or silicate matrices, making it inaccessible to direct cyanidation. Common pretreatment routes include fine to ultrafine grinding, roasting to oxidize sulfides and release gold; Pressure oxidation:-uses high pressure and temperature in autoclaves; Bio-oxidation-uses bacteria to oxidize sulfides (e.g., acidthiobacillus ferro-oxidans). Pressure oxidation/fine to ultrafine grinding can be applied to free Okote gold locked in sulfides.

Possible process route for Okote gold deposit: The process routes for Okote gold recovery can be a combination of gravity separation and cyanidation/cyanide leaching methods incorporating CIL circuit.

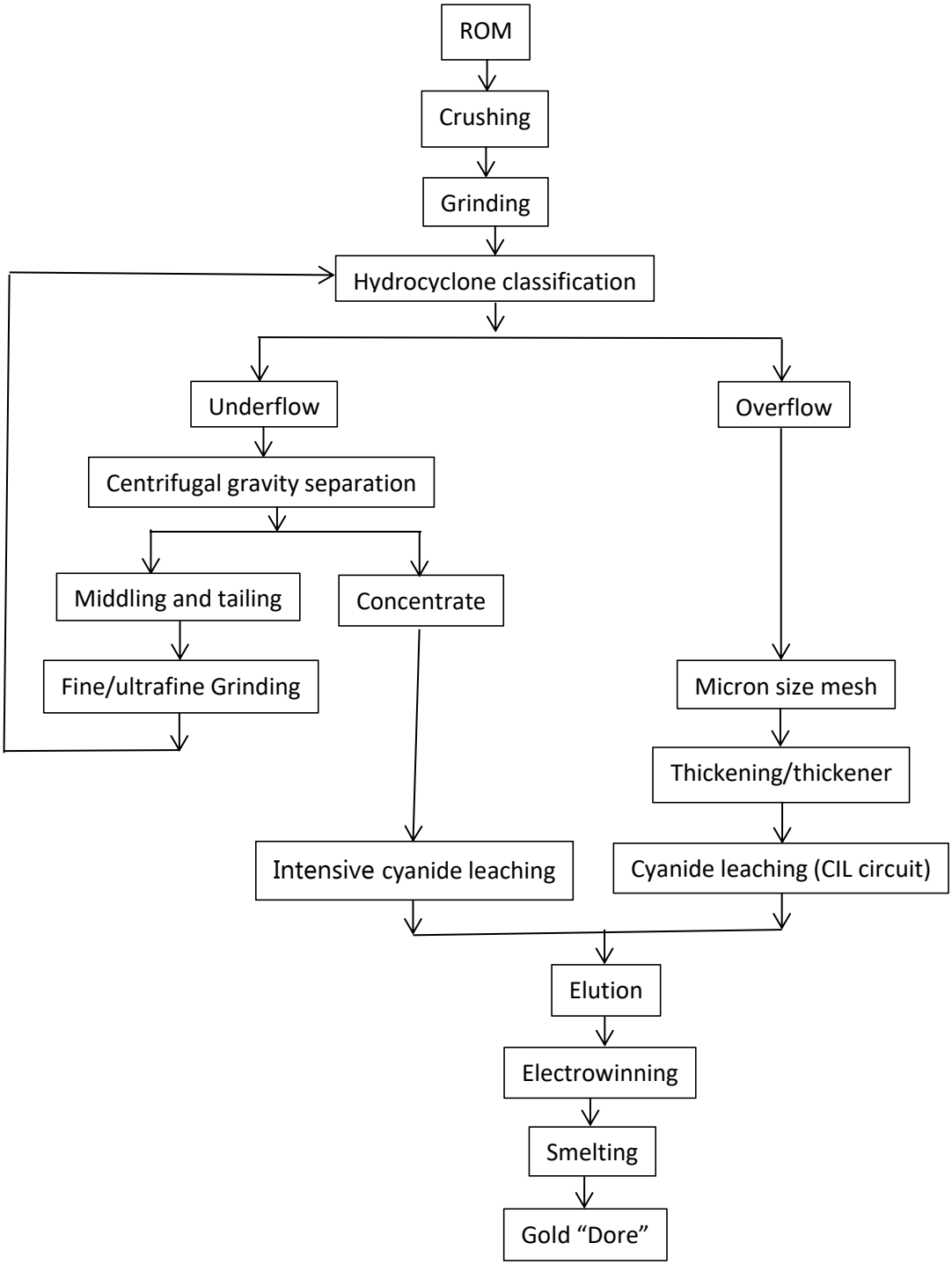


Figure 23 Possible flow sheet/chart of Okote gold processing

5. Conclusion and Recommendations

5.2. Conclusion

Okote gold deposit is found within Neoproterozoic greenstone terrains of southern Ethiopia, in the late-proterozoic Meta volcano-sedimentary Megado belt of the Adola granite-greenstone terrain. Okote gold deposit is situated in the southern extension of the Megado greenstone belt(comprising of Meta-ultramafics, amphibolites, amphibolite schist, graphite/quartz-graphite schist, sulfide bearing siliceous meta-pellites, and meta-granitoides).

Okote gold deposit area is underline by different lithologies such as amphibole-and biotite quartzo-feldspathic gneiss, amphibolite, Meta-ultramafic rocks (talc-tremolite-actinolite schist), Meta-gabbro, Meta-volcanics, chlorite-carbonate-amphibole schist, Meta-tonalite, Meta-granodiorite, and meta-sedimentary rocks (graphitic quartzite and graphite schist).

The host rocks for Okote gold include Meta-gabbro, Meta-volcanics, chlorite-carbonate-amphibole schist, Meta-ultramafics and Meta-granodiorite. Gold mineralization in these rock units are related to quartz and quartz-carbonate/tourmaline veins, veinlets and wall rock alterations.

Mineralogical characterization was accomplished through chemical and mineralogical analysis in that chemical analysis is employed in support for mineralogy study. Samples were collected over different lithologies from mineralized quartz veins and rocks. Chemical analyses of the samples were done using AAs and ICP-OES analytical techniques for major and minor oxides as well as gold and silver. Chemical analysis for trace elements and both carbon and sulfur were done using ICP-MS and Gravimeter analytical techniques respectively. Mineralogical composition analysis was done using optical microscopy, XRD and electron microprobe analyzer.

Chemical analysis for major and minor oxides result showed that SiO_2 and CaO are the highest components in the Meta-gabbro, chlorinate-carbonate-amphibole schist and Meta-ultramafics mineralization parts. Overall silicon, aluminum, iron, calcium and magnesium are the dominant elements/oxides in the deposit. Gold and trace elements as well as sulfur and carbon analysis shows that the Okote gold deposit contain low level of Ag, Cu, Zn, Pb, moderate total sulfur, sulphate sulfur, low level of As, Te, Se, and Sb and medium level of total carbon and organic carbon. This indicates that the gold ore deposit processing may be affected oxygen and cyanide consumers and refractory iron sulfide minerals as well as preg-robbing minerals.

The dominant gold ore in the deposit is native gold comprising 99.51% followed by electrum (0.48%), and gold bearing-tellurium ore –petzite (0.01%). Native gold is found as intergranular, fracture fill and enclosed form in sulfides (pyrite, pyrrhotite, chalcopyrite) and other gangue minerals such as quartz, chlorite, plagioclase, calcite, biotite, rutile and ilmenite.

Native gold in the deposit is found as intergranular (60.4%), fissure/fracture fill (33.7%), and enclosed (6.18%). All of the enclosed gold grains have a grain size below 37µm, most of them are below 5µm, which are difficult to liberate.

The grain size distribution of Okote gold is found to be 15.59% over 74µm, 40.07% (-74µm+37µm), 28.01% (-37µm+10µm), 10.39% (-10µm+5µm) and 5.59% below 5µm. There are also erratic coarse gold grains.

Average diagnostic leach test on two samples (HG-SC1 and HG-SC2) of particle size 80% passing 100µm resulted in Au distribution as 85% cyanide recoverable, 9.4% gold enclosed in sulfides, and 5.6% encapsulated gold. Another chemical phase analysis with composite sample on particle size 95% passing 38µm resulted in gold distribution to be 93.39% exposed gold, 1.26% enclosed gold in sulfide and 5.35% enclosed gold in other minerals. This indicates that further grinding exposed some of gold hosted by sulfides however; still gold hosted by silicate minerals remains unexposed. Therefor, 6.6% of gold hosted both by sulfides and silicate minerals which are a refractory ores, need further finer to ultrafine grinding or oxidative pre-treatment

Microprobe gold point analysis for sample GOK-TC-731 in average weight percent indicate 99.683% Au, 0.38975% Ag, 0.0625%Cu, 0.00725% Zn, 0.00025%Fe, 0.00325% Ni, 0.00725% As, 0.004% Se, 0% Sb, 0.00575% Pb, and 0% Bi. Even though As is found in small amount it is a toxic substance to the environment and need proper management.

From OM, XRD and EMPA mineralogical analyses, the gangue and associated ore minerals identified in the Okote gold deposit include quartz, carbonates (calcite and dolomite), chlorite, clay minerals (illite, kaolinite), amphibole-hornblende, plagioclase feldspar-albite, k-feldspar, mica (muscovite, biotite), tourmaline and pyrite, pyrrhotite, chalcopyrite, ilmenite, rutile, and iron oxides (magnetite, hematite, goethite, limonite) respectively. There are also other minerals like chalcocite, covellite, galena, sphalerite, walfermite, melonite, sheelite, and molybdenite in the deposit

Quartz being the dominant followed by calcite, chlorite, clay minerals and mica accounts 86.05% gangue mineral composition in the overall Okote gold deposit.

Pyrite is the most dominant associated ore mineral in the deposit followed by pyrrhotite and chalcopyrite. Its grain size is unevenly distributed and range from 50µm-500µm. The pyrites are generally fine to coarse in grain size, relict, randomly distributed and some forming veinlets and fracture fill, idomorphic-hpidiomorphic in texture. Chalcopyrite and gangue minerals as well as trace amount of gold inclusions are found in the pyrite.

Pyrrhotite mainly found distributed among gangue minerals and it is found as well enclosing micro-grained gangue minerals, chalcopyrite, pyrite, magnetite and ilmenite, its size is relatively coarse and unevenly distributed that range from 150µm-850µm.

Understanding the mineralogical composition (ore minerals and gangue minerals) and their grain size distribution as well as their effect on processing is an important prime request in the feasibility study and process plant design.

Native gold: comprises almost exclusively gold ore mineralogy of the deposit. From diagnostic leach test, chemical phase analysis and gold grain size distribution, it can be concluded that recovery of native gold can be increased through fine grinding or oxidative pretreatment.

Electrum: silver is more reactive than gold and can consume cyanide when found in large amount over gold. In case of Okote gold deposit the electrum content (0.48%) is very small and hardly affects gold recovery.

Copper ores are cyanide consumers except for chalcopyrite. Other gold minerals such as chalcocite and covellite are cyanide consumers which are found in trace amount in the deposit and have little effect on gold recovery.

Gold in tellurides (eg. Petzite) is chemically combined in tellurium mineral, requires oxidative pretreatment for efficient recovery. However, telluride composition (0.01%) is very low in the ore deposit and do not need oxidative pretreatments.

Gold in iron sulfides (pyrite, pyrrhotite)- pyrite and pyrrhotite may possess both enclosed and encapsulated gold that need fine/ultrafine grinding and oxidative pretreatment.

Gold in silicates-locked within quartz in micron sizes are difficult to recovery by conventional leaching and need fine grinding.

Some part of the Okote gold deposit contain significant level of clay minerals-illite, chlorite and mica, which may result in increased solution viscosity and pose difficulties in filtration during dewatering. This need proper handling of ROM (blending), pre-desliming-removal of fines using hydrocyclones or screens, use of dispersants/modifiers- addition of flocculants can improve filtration rate.

Okote gold deposit mineralogical study generally indicate nearly free milling and some refractory types of gold ores and can be recovered by gravity separation and cyanide leaching that incorporate CIL circuit with little modification in reagents and application of pretreatments (ultrafine grinding, oxidative pretreatments).

In conclusion based on the mineralogical analyses results; that the gold ore of Okote deposit is almost entirely native gold, and can be best recovered by using gravity separation, and cyanidation processing methods supported by ultra-fine grinding or oxidative pre-treatments.

5.2. Recommendations

Mineralogical characterization of Okote gold deposit in this study mainly based on chemical analysis using AAS, ICP-OES and ICP-Ms and mineralogical analyses through optical microscopy, XRD and EMPA. These mineralogical analytical techniques are not enough for detailed mineralogical characterization of the deposit and additionally the following techniques are required.

- Detailed mineralogical study employing quantitative evaluation of materials by scanning electron microscopy (QEMSCAN) to determine the proportions of gangue, gold ores and host minerals at low concentration in the deposit as well as gold grain size distribution down to 2µm.
- Liberation test:
  - 1st at 80% particles size passing 74 µm
  - 2nd at 80% particle size passing 20 µm
  - 3rd at 80% particle size passing 10 µm
- Mineralogical investigation using laser ablation microprobe inductively coupled mass spectrometry (LAM-ICP-MS) to know the concentration of gold in each sulfide minerals, silicates and oxides.
- From gold grain size distribution analysis of Okote gold, gold grain size below 10 µm accounts for about 15.98%. Very fine (normally <10 µm in size) particulate gold locked in sulphides or other gangue, may not be exposed to cyanide solution at "normal" grinds, 80% passing 75µm and may require finer to ultra-fine grinding, 80% passing 20µm that has to be supported by proper metallurgical tests.
  - ✓ Proper metallurgical test employing head ore cyanidation at grain size range of 80% passing 75µm, 45µm and 25µm at defined reagent consumptions and leaching kinetics.
- Ore blending procedure is important during run off mine to reduce the effect of slime production by chlorite, clay minerals and micas.

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Appendix

Table 24 Chemical analysis results Using ICP-OES and ICP-MS Techniques

Chemical composition	Sample ID					Chemical composition				
	GOK-RK-007	GOK-RK-010	GOK-TC-731	GOK-TC-1054			GOK-RK-007	GOK-RK-010	GOK-TC-731	GOK-TC-1054
SiO_2 (%)	51.98	53.01	91.76	87.88		Ga (ppm)	1.6	2.2	4.3	3
Al_2O_3 (%)	2.17	2.67	4.17	3.6		Hf (ppm)	0.2	0.4	1.1	1
Fe_2O_3 (%)	3.77	1.88	1.15	1.82		Nb (ppm)	0.6	0.9	2.5	1.1
MgO (%)	0.9	0.94	0.85	0.38		Sn (ppm)	<1	<1	1	<1
CaO (%)	21.45	21.5	0.16	2.33		Sr (ppm)	35.7	17.8	10.6	100.9
Na_2O (%)	0.06	0.04	0.21	1.05		Ta (ppm)	0.1	0.1	0.1	0.2
K_2O (%)	0.15	0.1	0.03	0.14		Th (ppm)	<0.2	0.4	0.5	0.2
TiO_2 (%)	0.03	0.08	0.38	0.08		U (ppm)	<0.1	<0.1	0.1	<0.1
P_2O_5 (%)	<0.01	0.02	<0.01	0.02		V (ppm)	67	56	108	25
MnO (%)	0.09	0.03	0.01	0.03		W (ppm)	42.3	42.1	24.4	127.5
Cr_2O_3 (%)	0.022	0.007	0.025	0.003		Zr (ppm)	6.9	15	45.2	34.2
LOI (%)	19.3	19.7	1.2	2.6		Y (ppm)	3.4	3	1.1	9.6
Au (ppb)	8.4	15.1	>100,000	415.5		La (ppm)	2.3	6.9	1.5	4.4
Ag (ppm)	<0.1	<0.1	0.6	<0.1		Ce (ppm)	1.6	6.9	4.2	6.3
Cu(ppm)	16.6	13.9	6.4	18.3		Pr (ppm)	0.66	1.34	0.4	1.34
Zn(ppm)	18	10	2	4		Nd (ppm)	2.8	5.3	1.6	6.1
Pb(ppm)	2.4	1.1	0.3	0.7		Sm (ppm)	0.64	0.85	0.28	1.35
Ni(ppm)	56.8	20.4	10.8	7.3		Eu (ppm)	0.26	0.24	0.09	0.35
As (ppm)	2.2	0.8	3.5	1.9		Gd (ppm)	0.78	0.74	0.3	1.65
C_{TOT} (%)	4.69	4.7	0.02	0.45		Tb (ppm)	0.11	0.09	0.04	0.26
S_{TOT} (%)	<0.02	<0.02	<0.02	<0.02		Dy (ppm)	0.65	0.5	0.25	0.37
Sb (ppm)	0.3	<0.1	0.3	<0.1		Ho (ppm)	0.12	0.1	0.05	0.37
Hg (ppm)	<0.01	<0.01	<0.01	<0.01		Er (ppm)	0.32	0.29	0.13	1.1
Se (ppm)	<0.5	<0.5	<0.5	<0.5		Tm (ppm)	0.04	0.04	0.02	0.15
Ba (ppm)	175	109	10	83		Yb (ppm)	0.28	0.28	0.16	1.06

Chemical composition	Sample ID					Chemical composition				
	GOK-RK-007	GOK-RK-010	GOK-TC-731	GOK-TC-1054			GOK-RK-007	GOK-RK-010	GOK-TC-731	GOK-TC-1054
Sc (ppm)	11	8	7	4		Lu (ppm)	0.04	0.04	0.03	0.16
Be (ppm)	<1	<1	<1	<1		Mo (ppm)	0.4	<0.1	0.5	0.2
Co (ppm)	22.2	15.6	10.7	27.7		Cd (ppm)	<0.1	<0.1	<0.1	<0.1
Cs (ppm)	<0.1	<0.1	<0.1	<0.1		Bi (ppm)	<0.1	<0.1	<0.1	<0.1
						TI (ppm)	<0.1	<0.1	<0.1	<0.1

Table 25 Elemental analysis using ICP techniques

Element	HG-SC1	LG-SC2	Element	HG-SC1	LG-SC2	Element	HG-SC1	LG-SC2
Ag(ppm)	0.16	0.08	K (%)	0.6	0.75	Ta (ppm)	0.11	0.09
Al (%)	6.9	8.61	La (ppm)	3.4	4	Te (ppm)	0.2	0.18
As (ppm)	25.1	6.4	Li (ppm)	3.4	5.4	Th (ppm)	0.3	0.5
Ba (ppm)	210	250	Mg (%)	1.9	2.55	Ti (%)	0.364	0.237
Be (ppm)	0.52	0.53	Mn (ppm)	951	1240	TI (ppm)	0.07	0.06
Bi (ppm)	0.11	0.08	Mo (ppm)	2.77	3.23	U (ppm)	0.1	0.2
Ca (%)	5.2	6.12	Na (%)	1.48	1.71	V (ppm)	134	170
Cd (ppm)	0.08	0.07	Nb (ppm)	1.5	1.2	W (ppm)	178.5	4.7
Ce (ppm)	9	9.16	Ni (ppm)	36.4	48.2	Y (ppm)	27	13.8
Co (ppm)	33.3	26.6	P (ppm)	810	490	Zn (ppm)	74	67
Cr (ppm)	95	122	Pb (ppm)	12.1	9.7	Zr (ppm)	4.2	10.6
Cs (ppm)	0.14	0.13	Rb (ppm)	13.3	11.9	C_{ORG}(%)	0.01	0.03
Cu (ppm)	92.1	65.8	Re (ppm)	0.003	<0.002	C_{TOT}(%)	1.46	1.14
Fe (%)	6.74	5.86	S (%)	1.62	0.52			
Ga (ppm)	13.4	15.6	Sb (ppm)	0.92	0.39			
Ge (ppm)	0.15	0.14	Sc (ppm)	26	28.9			
Hf (ppm)	0.2	0.4	Se (ppm)	2	1			
Hg (ppm)	<0.01	<0.01	Sn (ppm)	0.7	0.0			
In (ppm)	0.068	0.044	Sr (ppm)	282	369			