Addis Ababa University

Addis Ababa Institute of Technology

Center for Ethio-mines Development

CHARACTERIZATION OF ORE AND GANGUE MINERALOGY AT THE ASHASHIRE GOLD DEPOSIT, BENISHANGUL- GUMZ REGION, WESTERN ETHIOPIA

A project submitted to Center for Ethio-mines Development for the partial fulfilment of the degree of Master of Engineering in Mineral Engineering

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Declaration

I hereby declare that this project is my original work and has not been presented for a degree in any other university, and that all sources of material used for the project have been duly acknowledged.

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Abstract

Gold is a precious metal that is highly prized and has been significant throughout human history. It has been used as money and for ornamental purposes. It is a crucial component in electronics, medical equipment, and other industrial uses. Around the world, mining operations have sprung up in response to the demand for gold, and efficient extraction and processing depend on an understanding of the mineralogy of gold deposits. This study aimed to characterize the mineralogy of the Ashashire gold deposit located in the Benishangul Gumuz Regional State, Western Ethiopia. Six representative mineralized core samples were analyzed using fire assay with atomic absorption spectroscopy (AAS), inductively coupled plasma (ICP), quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) and X-ray diffraction (XRD). The study found that the gold in the deposit occurs primarily as native gold and gold-telluride, with a strong association with tellurium and often found as free particles or in association with gangue minerals such as quartz and pyrite. Pyrite is the dominant sulfide mineral detected in all core samples, with only trace amounts of chalcopyrite detected. The gangue minerals present in the deposit are mainly quartz, ankerite-dolomite, muscovite, chlorite, and albite, with lower levels of paragonite, rutile, magnetite, and calcite. The presence of tellurium suggests that specialized processing techniques may be required to liberate the gold from the tellurides. The degree of liberation, liberation sizes, and recovery of gold are all impacted by the texture of the ore. The gangue mineral composition of the ore can also impact gold processing in several ways, including cyanide consumption, clay coating and gold adsorption, ore hardness, mineralogical complexity, and processing costs. The mineralogical data can be used to develop a suitable processing route, taking into account the ore texture, gold mineralogy, and gangue mineral composition. A combination of techniques such as gravity separation, flotation, cyanide leaching, pressure oxidation, and CIL/CIP could be employed to maximize gold recovery and minimize environmental impact. Further metallurgical testing and optimization are necessary to fully understand and optimize gold recovery from this deposit.

Key words: Gold, mineralogy, Ashashire gold deposit, gangue minerals, processing techniques.

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List of Acronyms

AAS	Atomic Absorption Spectrometry
ALS	Australia Laboratories Service
EIGS	Ethiopian Institute of Geological Survey
EMRDC	Ethiopian Mineral Resource Development Corporation
GSE	Geological Survey of Ethiopia
GSR	Golden Star Resource
ICP	Inductively Coupled Plasma
MMAJ	Metal Mining Agency of Japan
ppm	Parts Per Million
QEMSCAN	quantitative evaluation of material by scanning electron microscope
SEM	Scanning Electron Microscope
wt%	Weight in percent

CHAPTER ONE

INTRODUCTION

1.1. Background

Gold is a valuable metal and has added to the creative, social and monetary improvement of humanity. Gold was used for special decorative ornaments and jewelry because of its lustrous color and resistance to tarnishing. It was probably the first metal used by humans because of its occurrence as a free metal in placer deposits, enabling its recovery without the requirement of complex separation techniques.

Gold ores are generally arranged into two major classes: refractory and free-milling. Typically, free-milling ores are defined as those where over 90% of gold can be recovered by conventional cyanide leaching (Marsden and House, 2006; Zhou et al., 2004). Refractory ores are defined as those that yield low gold recoveries or result in acceptable gold recoveries only with significantly higher reagent consumptions or more complex pretreatment processes (La Brooy et al., 1994; Zhou et al., 2004; Marsden and House, 2006).

Gold can be divided into three categories depending on how it occurs: submicroscopic, surface-bound, and microscopic gold. Microscopic gold, also known as visible gold, comprises native gold, electrum, gold amalgams, gold tellurides, gold antimonide, gold bismuthite, gold sulfides, gold selenides, gold sulfotellurides and gold sulfoselenides and so forth((Boyle, 1979; Healy and other, 1990; Wang et al., 1994). Submicroscopic gold, also known as invisible gold, is gold that cannot be seen with an optical or scanning electron microscope. Submicroscopic gold, commonly occurs as discrete particulate within sulfide minerals (mainly in pyrite and arsenoppyrite), is the major form of gold in the Carlin-type gold deposits and other refractory gold ores (Radtke, 1985; Cabri et al., 1989; Wang et al., 1994). Submicroscopic gold can be found in two main forms: solid solution gold and colloidal gold. Laser ion mass spectrometry (LIMS) is the only method that can detect surface gold, which cannot be seen with an electron or optical microscope. The ore's primary surface gold carriers are carbonaceous matter, stained quartz, FeOx, and clay minerals. Principal surface gold carriers in the ore include FeOx, stained quartz, carbonaceous matter and clay minerals.

Processing any gold ore requires detailed mineralogical investigations. There are six mineralogical factors determining the recovery processes of gold: The gold-containing minerals, the grain size of the gold-bearing minerals, the nature of the gangue minerals, the associated sulphide minerals, coatings on gold, and chemically bound or "invisible" gold (Henley, 1975; Cabri, 1988). The techniques commonly used in gold process mineralogical studies can be classified into two categories: conventional and advanced instrumental techniques. Conventional techniques include fire assay, cyanide leaching, gravity concentration, acid diagnostic leaching, quadruple-tonne FA-AA assay, and optical microscopy. Advanced instrumental techniques include scanning electron microscopy (SEM), 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), etc. These techniques can be used individually, but most often, several techniques will be used collectively in a process mineralogical study due to the complexity of the issue being studied (Zhou et al., 2004).

Ashashire is the location of the study in Western Ethiopia's Kurmuk Woreda Benishangul Gumuz Regional State. It is about 750 km west of the capital, Addis Ababa and90 km north-west of Asosa, the regional administrative center, in Benishangul-Gumuz National Regional State. The Ashashire gold deposit is primarily hosted within a sequence of Neoproterozoic metasedimentary and metavolcanic rocks, which are part of the Asosa greenstone belt (Abdelnasser et al., 2020). The mineralization is primarily associated with quartz veins and shear zones that are hosted within a major fault system that runs through the area (Abdelnasser et al., 2020). According to Abdelnasser et al., Ashashire's gold grades range from 2 to 20 grams per tonne, with a high-grade core surrounded by lower-grade mineralization. 2020). According to Abdelnasser et al., the gold mineralization at Ashashire is linked to arsenopyrite, pyrite, and chalcopyrite, as well as small amounts of sphalerite and galena. 2020). Tellurides, which are rare and extremely valuable gold-bearing minerals, are another characteristic of the deposit (Abdelnasser et al., 2020).

The aim of the present study is to characterize the mineralogy of the Ashashire gold deposit to better understand the properties of the ore and associated gangue minerals for efficient gold processing. While it's important to know the grade of a metal in a mineral deposit, understanding the in situ properties of the minerals of interest and the associated gangue minerals is also crucial for successful processing. Mineralogical characterization is an important aspect of this understanding, as the direct gold mineralogy can significantly impact the processing of the ore. The Ashashire gold deposit is approaching the production stages, and obtaining detailed information on the mineralogy of gold and the associated gangue minerals is critical for the gold recovery process. Therefore, this project work can contribute to the understanding of the mineralogy of ore and gangue minerals in Ashashire for processing of gold.

1.2. Description of the study area

1.2.1. Location, accessibility and physiography

In the Kurmuk Woreda Benishangul Gumuz Regional State of Western Ethiopia, the study area is called Ashashire. It is about 750 km west of the capital, Addis Ababa and 90 km north-west of Asosa, the regional administrative center, in Benishangul-Gumuz National Regional State (Fig.1). Access to the area is via the main paved road from Addis Ababa- Gimbi-Bambasi-Asosa-Kamashi then to Kurmuk or by flying from Addis Ababa to Assosa. From Assosa, one paved road leads to

Kurmuk town via the Assosa-Komosha-Kurmuk route and Sudan.

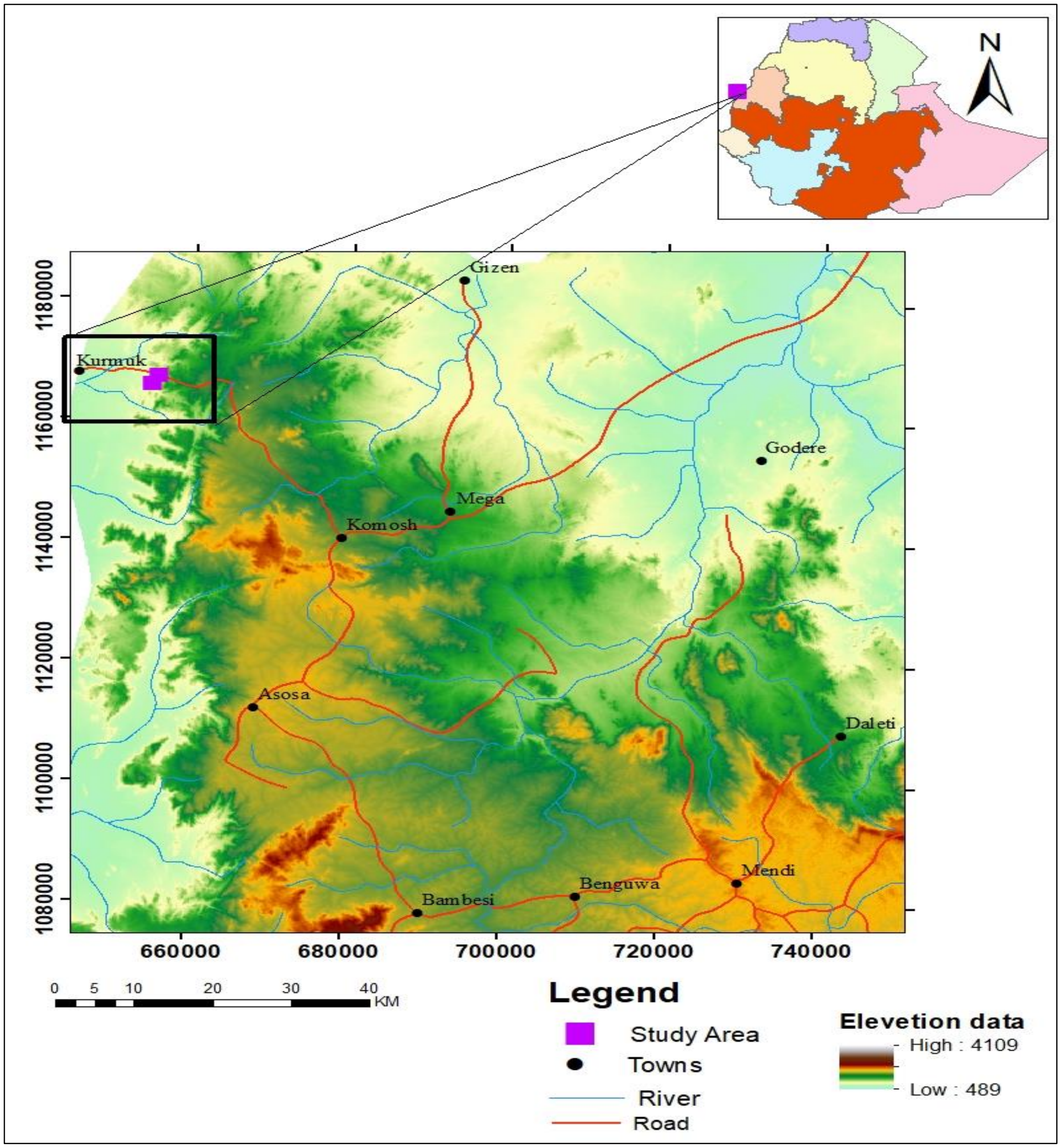


Figure 1. Location and accessibility map of the study area

Topographically the study area ranges from approximately ~700m to 1200m above sea level. The center of the Ashashire is situated at approximately Universal Transverse Mercator (UTM) zone (36N). There are rugged valleys, mountainous ridges, and steep slopes to flat land in this region. Low lands dominate in the west portion, while the eastern part forms hills and mountain ridges.

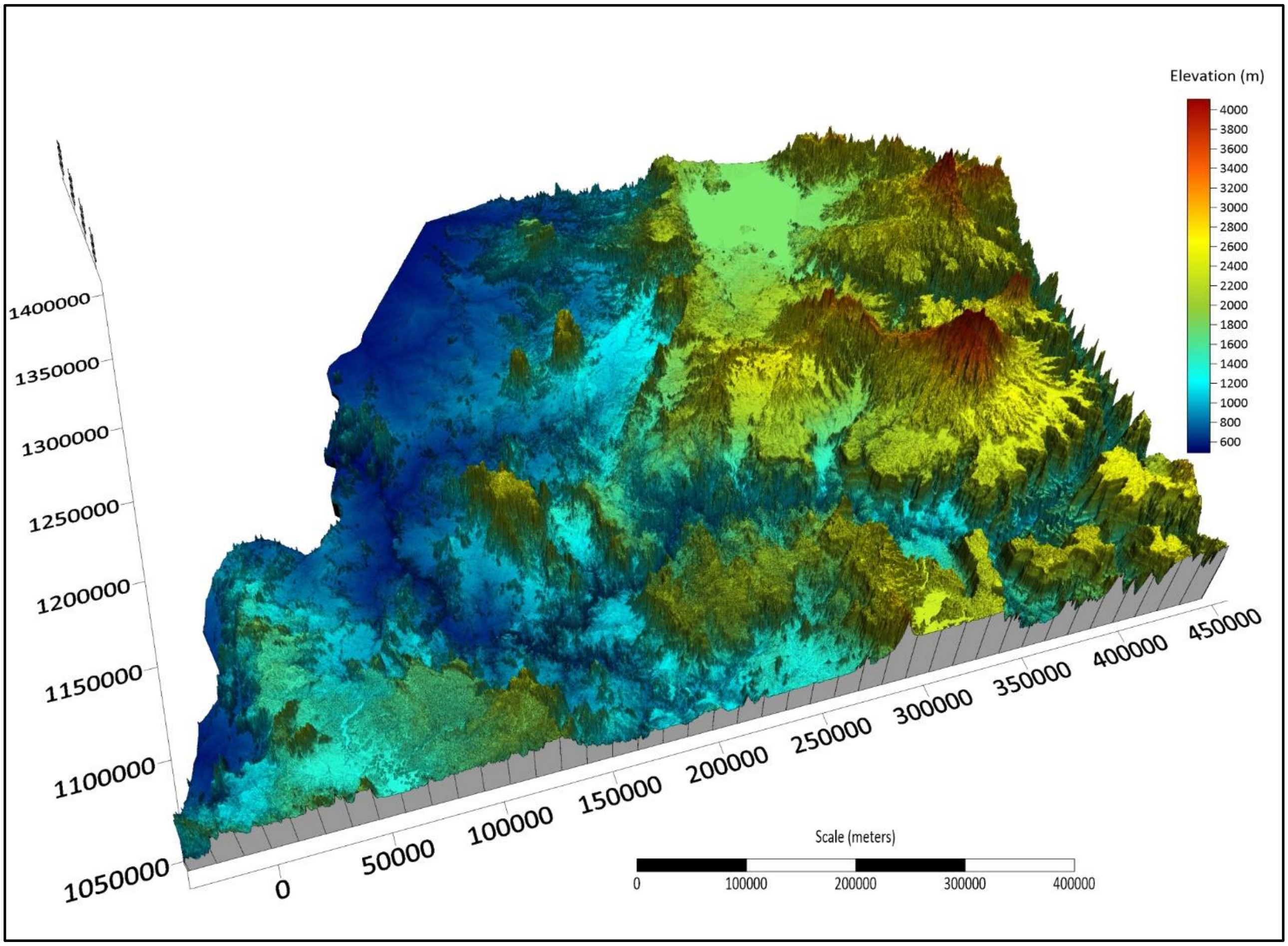


Figure 2. Physiographic map of the study area

1.3. Statement of the problem

A significant number of occurrences of primary gold and base metal in western Ethiopia, including Ashashire, have been documented by a number of organizations, including the Ethiopian Mineral Resource Development Committee (EMRDC) in 1982, Golden Star Resources Limited (GSR) in 1997, the Metal Mining Agency of Japan (MMAJ) in 1974, the Geological Survey of Ethiopia (GSE) in 1991 and 1995, and Benzu Gold Mining Ethiopia (BGME) in 2013. These reports consist of geological, geochemical, structural, and geophysical data from the analysis of stream sediments, surface samples, and borehole samples. Kurmuk Gold Mine PLC currently holds an exploration and mining license at Benishangul Gumuz, including Ashashire. However, most exploration companies in the region have focused on grade and tonnage rather than examining the ore and gangue mineralogy of the deposits. While knowing the grades of a metal in a deposit is essential, understanding the in-situ properties of the minerals of interest and their associated gangue minerals is crucial for developing an effective processing strategy. Mineralogical characterization is an important aspect of this understanding, as the direct gold mineralogy can significantly impact the processing of the ore. The Ashashire gold deposit is approaching the production stages, and obtaining detailed information on the mineralogy of gold and the associated gangue minerals is critical for the gold recovery process. However, no previous study has focused specifically on the mineralogical characterization of gold processing in the Ashashire area. As a result, there has been limited scientific work in the region to date. This project aims to contribute to the understanding of the mineralogy of the ore and gangue minerals in Ashashire for the processing of gold.

1.4. Objectives

1.4.1. General objective

The main objective of this project work is to characterize the mineralogy of the ore and associated gangue minerals in the Ashashire gold deposit.

1.4.2. Specific objectives

The specific objectives of the study are;

- Determining the concentration of the gold and associated elements in the ore
- Identifying and quantifying the gold-carrying minerals and associated gangue minerals that present in ore deposit.
- Determining the liberation characteristic of the ore
- To evaluate the mineralogical and chemical features that may impact the processing of the ores and
- To identify the possible processing techniques for the extraction of gold from the ore based on the mineralogical and chemical data obtained.

1.5. Scope of the study

The purpose of the study is to acquire a comprehensive understanding of the Ashashire gold deposit's mineralogy, which is necessary for developing gold processing techniques that are both effective and efficient. Among the specific objectives are determining the liberation characteristics of the ore, evaluating the mineralogical and chemical features that may impact the processing of the ores, and identifying the possible processing techniques for the extraction of gold from the ore based on the obtained mineralogical and chemical data. Other specific objectives include identifying and quantifying the gold-carrying minerals and associated gangue minerals that are present in the ore. An atomic absorption spectrometer (AAS), an inductively coupled plasma (ICP), a quantitative evaluation of material by scanning electron microscope (QEMSCAN), and fine powder X-ray diffraction (XRD) are among the analytical methods that will be utilized. Additionally, the study will include a literature review to locate pertinent articles and scientific journals that are related to the process mineralogy of gold deposits. The integration and interpretation of the mineralogical and geochemical data obtained from the analysis will provide a detailed understanding of the ore and gangue mineralogy and its impact on gold processing. Based on the mineralogical data, various processing routes can be considered to optimize gold recovery.

1.6. Expected outcomes and Project relevance

The expected outcome of the study will be the identification and quantification of the gold-carrying minerals and the gangue minerals that are present in the ore deposit. The project will also determine the concentration of gold and associated elemental concentration in the ore and the liberation characteristics of the ore. These features will be interpreted for processing implications, providing valuable information for future gold ore processing to be conducted in the study area. The beneficiaries of the project are Kurmuk Gold Mine PLC, which can use the preliminary information obtained from the study for future gold ore processing in the study area. Other companies that practice gold and sulphide deposit exploration and mining can also use the study as a guide for identifying additional prospective areas of gold mineralization. Furthermore, the researcher working on the project will gain logical concepts and deep knowledge in the field of mineralogy and gold processing.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Gold has been a highly valued metal for at least 5000 years due to its unique properties, rarity, and cultural significance, and it has contributed to the artistic, cultural, and economic development of mankind (Marsden and House, 2006). As a transition metal with atomic number 79, gold is very dense and malleable, and it occurs as a single stable isotope ^{197}Au, with a most common oxidation state of zero (0), but varying from (-I) at (+V), with (+I) and (+III) predominating (Encyclopedia Britannica). Gold is also a relatively chemically stable metal that does not form oxides or ions in aqueous solution but can form complexes with CN, Cl, OH, or HS (Marsden and House, 2006). Gold is a siderophile element, which means it has an affinity for iron and is part of the highly siderophile elements (HSE). These elements migrated to the Earth's core during the differentiation of the various crustal layers (Marsden and House, 2006). A comparison of the concentrations of gold in the silicate crust and chondrites, the core contains 98% of terrestrial gold. According to Hofmann et al., this, along with the fact that gold is scarce in the chondritic earth, explains why gold is only found in trace amounts in the Earth's crust. 2021). The typical grouping of gold in the covering is just 4 sections for each billion (ppb), with the mainland hull having 1.3 ppb (Marsden and House, 2006).Gold, on the other hand, may occasionally concentrate locally in ore bodies, indicating a spike that can be up to 10^4 times the background concentration in the crust. This is because gold is chemically stable. The factors that control its concentration at certain sites to deposit level in the Earth's crust and the ultimate source of the gold in the various deposits remain topics of debate (Hofmann et al., 2021).

2.2. Types of gold ore deposits

Gold deposits are formed by geologic processes that concentrate gold into minable ore deposits, with all gold deposits except placer deposits formed by hydrothermal processes. Hydrothermal systems can form in various geologic environments, ranging from dynamic systems associated with magmatic intrusive to low-energy systems associated with deep fluid circulation heated by geothermal heat flow. The various types of hydrothermal systems in different host rocks create variations in deposit morphology, grade ranges (variation in gold content), and wall rock alteration (Groves et al., 2018).

Gold deposits exhibit different characteristics depending on the nature of the host rock, the genetic model, and the mineral associations related to mineralization. Placer and orogenic gold stores are the most useful regarding world gold creation, followed by porphyry and epithermal stores, as indicated by Groves et al. (2018). Placer stores are regularly tracked down in riverbeds or along the coast and are framed by the enduring and disintegration of gold-bearing rocks. As indicated by Simmons et al. (2005), epithermal deposits are associated with volcanic rocks, porphyry deposits are associated with igneous intrusions, and orogenic gold deposits are typically found in metamorphic rocks and originate from processes of mountain formation.

Groves and others 2018), three primary geological settings for gold deposits are distinguished by the mineralization process: hydrothermal, magmatic-hydrothermal, and sedimentation processes. Hydrothermal systems are formed when magmas enter the crust and interact with the surrounding rock to form magmatic-hydrothermal deposits. Hydrothermal deposits, on the other hand, are made when hot fluids move through the crust, usually along faults or fractures. Lastly, sedimentation deposits form when gold precipitates from fluids in sedimentary basins.

2.3. Classification of gold ores and minerals

2.3.1. Gold ore types

Gold ores are divided into two main categories based on the methods needed for gold recovery and mineral processing: refractory and free-milling. In brief, free-milling ores are those that can be conventionally leached using cyanide to recover over 90% of gold, according to Marsden and House (2006) and Zhou et al. (2004). On the other hand, refractory ores produce low gold recoveries and require higher reagent consumption or more complex pretreatment processes to achieve acceptable gold recoveries, as noted by La Brooy et al. (1994), Zhou et al. (2004), and Marsden and House (2006). Refractory ores can be classified based on their gold recovery rates, with non-refractory ores having a recovery rate of over 95%, mildly refractory ores having a recovery rate of 80-95%, moderately refractory ores having a recovery rate of 50-80%, and highly refractory ores having a recovery rate of less than 50%, according to Vaughan (2004).The classification of gold ores into free-milling and refractory categories is important because it informs the selection of appropriate processing methods. Free-milling ores can be processed using conventional cyanide leaching methods, while refractory ores require more complex processing methods, such as pressure oxidation, bioleaching, or roasting, to recover the gold. Understanding the refractory nature of a gold deposit is critical to the economic viability of a mining project, as refractory ores require more advanced processing methods, which can significantly increase the cost of gold production (Marsden and House, 2006; Zhou et al., 2004).

2.3.2. Gold mineral types

Based on where it occurs, gold can be divided into three categories: surface-bound, submicroscopic, and microscopic gold. Microscopic gold is also known as visible gold. Native gold (Au) and electrum (Au, Ag) are the most plentiful and critical gold minerals, which are tracked down in different gold deposits. Other gold minerals, such as kustelite (Ag, Au), auricupride (Cu3Au), tetraauricupride (CuAu), calaverite (AuTe2), krennerite ((Au, Ag) Te2), aurostibite (AuSb2), and maldonite (Au2Bi), also have economic importance in some gold deposits (Boyle, 1979; Healy et al., 1990; Wang et al., 1994).

Submicroscopic gold, otherwise called undetectable gold, will be gold that shouldn't be visible with an optical or or scanning electron microscope. The majority of gold in Carlin-type gold deposits and other refractory gold ores is submicroscopic gold, which is typically found as discrete particulate within sulfide minerals like pyrite and arsenopyrite (Radtke, 1985; Cabri et al., 1989; Wang et al., 1994).

Surface-bound gold refers to gold that is adsorbed onto the surface of other minerals during mineralization and subsequent oxidation or metallurgical processing. This type of gold cannot be seen under optical or electron microscopes and can only be detected using laser ion mass spectrometry (LIMS) (Liu et al., 2019). The principal carriers of surface gold in ore deposits include FeOx, stained quartz, carbonaceous matter, and clay minerals (Liu et al., 2019).

2.4. Mineralogical factors affecting gold processing

The efficiency of gold processing can be influenced by several mineralogical factors. Firstly, the mineralogy of the ore is significant as gold may be combined with sulfide minerals like pyrite, which can consume oxygen and cyanide during leaching, resulting in reduced gold recovery (Marsden and House, 2006). Additionally, particle size can also impact gold processing, with fine-grained ores requiring more grinding to release the gold particles, leading to elevated processing costs (Deschênes et al., 2015). Mineral liberation is also crucial as gold encapsulated within other minerals may be challenging to extract and require further processing steps (Muir et al., 2016). Gold may also be associated with other minerals such as silver, copper, or lead, which can compete for adsorption sites on activated carbon during leaching, thereby decreasing gold recovery (Fleming et al., 2011). The surface chemistry of minerals can also impact gold processing, with some minerals having a high affinity for cyanide, which reduces the availability of free cyanide for gold leaching (Habashi, 2005). Lastly, mineral impurities like arsenic, antimony, or mercury can form stable complexes with gold and reduce gold recovery or interfere with downstream processing (Marsden and House, 2006).

Table 1 identifies some typical mineralogical problems and the processing techniques that might be impacted in gold ore processing (Zhou et al., 2004; Henley, 1975; Cabri, 1988). Among the factors listed in Table 1, liberation, grain size, and association are considered the most important and must be evaluated in a gold processing program. Liberation refers to the ability to separate gold from the host mineral and is influenced by particle size, mineralogy, and ore texture. Grain size is another crucial factor that influences gold processing, affecting the efficiency of gold recovery and the choice of processing method. Association refers to the relationship between gold and other minerals in the ore, such as sulfides, oxides, and carbonates, and impacts the efficiency of gold extraction and recovery rates. Other mineralogical factors, such as the presence of refractory gold minerals and the locking of submicroscopic gold in sulfide and sulfarsenide mineral structures, can also impact the efficiency of gold extraction and recovery rates. Refractory gold minerals are those that are resistant to standard cyanidation and require additional processing steps, such as pressure oxidation or bioleaching, to recover the gold. The locking of submicroscopic gold in sulfide and sulfarsenide mineral structures makes it difficult to extract the gold and requires specialized processing methods, such as roasting or pressure oxidation.

Table 1: Common mineralogical issues affecting gold extraction

No.	Mineralogical Issue	Affected Processes	Reference
1	Liberation/locking	Gravity, flotation, and leaching	(Zhou et al., 2004).
2	Grain size	Gravity, flotation, and leaching	(Marsden et al., 2006; Zhou et al., 2004).
3	Association	Gravity, flotation, and leaching	(Zhou et al., 2004).

4	Surface chemistry	Gravity, flotation, and leaching	(Zhou et al., 2004).
5	Coating and rimming	Gravity, flotation, and leaching	(Fink et al., 1950; Zhou et al., 2004).
6	Dissolution kinetics	Leaching	(Cabri, 1988; Zhou et al., 2004).
7	Cyanicides and oxygen consumers (secondary copper minerals, pyrrhotite)	Leaching	(Fleming, 1998; Zhou et al., 2004).
8	Refractoriness (submicroscopic gold)	Gravity, leaching	(Radtke, 1985; Wang et al. 1994; Simon et al., 1999).
9	Preg-robbing (C-matter, iron oxide, etc.)	Leaching	(Fleming, 1998; Zhou et al., 2004).
10	Deleterious minerals/toxic elements (As, Hg, Se, Sb, Te, etc.)	Flotation, leaching, solution purification, and tails disposal	(Zhou et al., 2004).
11	Gangue mineralogy (clays, acid-forming and acid-consuming minerals)	Flotation, leaching, and tails disposal	(Marsden et al., 2006; Zhou et al., 2004).

2.5. Techniques used for gold process mineralogical study

To develop an effective gold ore processing strategy, a comprehensive understanding of the mineralogical properties of the ore is crucial. According to Marsden and House (2006), several key parameters need to be determined, including the gold ore grade, ore composition (both elemental and mineralogical), concentrations of other valuable minerals, nature and concentrations of minerals detrimental to processing, gold grain size distribution, gold mineral type, and liberation characteristics of all valuable minerals.

The amount of gold in the ore is referred to as the "gold ore grade," and it is typically expressed in grams per tonne (g/t). This parameter is important because it determines the ore's economic viability and the processing method. The higher the gold mineral grade, the lower the handling costs, and the more beneficial the mining activity.

The ore's mineral and elemental composition provides crucial information about the variety and abundance of minerals present. A processing strategy that is tailored to the particular mineralogy of the ore is created using this information. Because they may have an effect on the method of processing, it is also necessary to determine the presence of other valuable minerals like silver, copper, or zinc. The nature and concentrations of minerals that consume cyanide or interfere with the processing of gold, such as clays, can significantly impact the efficiency of the processing method used. Therefore, it is essential to identify these minerals to develop an appropriate processing strategy.

The distribution of gold particle sizes in the ore can impact the efficiency of the processing method used. Fine-grained ores may require additional grinding to release the gold particles, which can increase processing costs. Therefore, understanding the gold grain size distribution is critical to developing an effective processing strategy. Different types of gold minerals, such as native gold, tellurides, and refractory gold minerals, require different processing methods. Determining the type of gold mineral present in the ore is, therefore, critical to developing an effective processing strategy.

Finally, the liberation characteristics of all valuable minerals, including gold, determine the efficiency of the processing method used. The degree of liberation of the minerals is influenced by factors such as mineralogy, grain size, and texture. Therefore, understanding these parameters is crucial to developing an effective processing strategy that maximizes gold recovery while minimizing processing costs and environmental impacts.

The techniques commonly used in gold process mineralogical studies can be classified into two categories: conventional and advanced instrumental techniques. Conventional techniques include fire assay, cyanide leaching, gravity concentration, acid diagnostic leaching, quadruple ton one FA-AA assay, and optical microscopy (Chryssoulis and Cabri, 1990; Wang et al., 1992; Zhou et al., 2004). These techniques are relatively simple and widely used in the mineralogical analysis of gold ores. On the other hand, more complex advanced instrumental techniques call for sophisticated equipment and expertise. Secondary ion mass spectrometry (SIMS), particle-induced x-ray emission (PIXE), laser ablation microprobe inductively coupled plasma mass spectrometry (LAM-ICP-MS), and others are among these methods (Chryssoulis and Cabri, 1990; Wang et al., 1992; Zhou and co., 2004). The distribution, association, and mineralogical form of gold in ores can be better understood with the help of these methods than with more conventional methods.

In practice, a combination of conventional and advanced instrumental techniques is often used in a process mineralogical study to obtain a comprehensive understanding of the mineralogy of gold ores.

2.6. Gold processing methods

The methods and procedures used to extract gold from its ores are referred to as gold processing methods. The grade and type of ore, the processing capacity of the plant, the cost of the process, and environmental regulations are all important considerations when selecting a gold processing method (Marsden and House, 2006). Most present day gold handling plants utilize a mix of a few strategies to upgrade gold recovery rates and limit handling costs. Four main techniques are commonly used in the beneficiation of gold ore: gravity concentration, amalgamation, cyanide leaching, and flotation. Gold can be recovered from its ores using one or a combination of the above methods.

2.6.1. Gravity concentration

Gold can be recovered from a wide range of ores, including alluvial deposits, hard rock ores, and refractory ores, using gravity concentration. To separate the gold from the gangue minerals, this method makes use of the high specific gravity of gold and the differences in specific gravity between gold and other minerals. There are several gravity concentration methods that can be used for the concentration of gold, including jigging, Falcon concentrators, Knelson concentrators, shaking tables, and spirals.

Jigging is a gravity concentration method that has been widely used for the concentration of gold ores. According to Laplante et al. (1995), jigging is effective for the recovery of coarse and fine gold particles. Falcon concentrators, on the other hand, are high G-force gravity concentration devices that can be used for the recovery of fine gold particles. McLeavy et al. (2011) found that Falcon concentrators are effective for the recovery of gold particles smaller than 50 microns. Similarly, Knelson concentrators are centrifugal gravity concentrators that can be used for the recovery of gold particles from alluvial and hard rock deposits. Laplante et al. (1995) reported that Knelson concentrators are effective for the recovery of gold particles smaller than 20 microns.

Shaking tables are widely used for the concentration of gold ores. According to Li et al. (2020), shaking tables are effective for the concentration of fine-grained gold particles. Spirals are also effective for the concentration of fine-grained gold particles. They use a combination of gravity and centrifugal force to separate gold particles from gangue minerals. According to Burt (1984), spirals are effective for the recovery of gold particles smaller than 100 microns.

Overall, gravity concentration methods remain an important and widely used technique for gold recovery. The selection of the appropriate gravity concentration method depends on several factors, including the particle size distribution of the gold particles, the specific gravity of the gold and gangue minerals, and the mineralogy of the ore. Placers, quartz vein gold ores, and oxidized ores are generally considered free-milling, meaning that the gold can be easily liberated from the surrounding rock and recovered by gravity concentration methods.

2.6.2. Amalgamation

The mixture cycle includes the utilization of mercury to frame a combination with gold particles, which is compelling on free or free coarse gold particles with clean surfaces (Youlton et al., 2021) On the other hand, mercury's high surface tension prevents it from getting into small crevices in ore particles, so the ore must be finely ground to expose the gold. Due to its high costs, inefficiency in large-scale operations, and a lack of ores that can be treated using this method, its use has become limited. Amalgamation is typically used in combination with other beneficiation methods such as cyanidation, flotation, and gravity concentration.

2.6.3. Leaching processes

Cyanidation is one of the primary methods used for the beneficiation of gold ores. This technique involves the use of solutions of sodium or potassium cyanide as lixiviants or leaching agents to extract precious metals from the ore. The cyanide leaching process can be conducted under different technical conditions, and for well-leachable high-grade gold ores, **agitation leaching** is an effective technique. In agitation leaching, an ore pulp with grain sizes of less than 100 microns is continuously agitated during its leaching in special tanks, such as Pachuca tanks. The leaching period typically lasts less than 24 hours, and the gold recovery rate is usually above 90%. (Habashi, 2017).

Vat leaching is another technique used in the beneficiation of gold ores, which also requires well-leachable ores. In this technique, the grain sizes required are much coarser than those used in agitation leaching, with a maximum size of less than 1 cm. This is because the ore is not agitated in the leaching tanks, and only coarse material warrants good permeability. The leaching period for vat leaching is generally 2-4 days, and the gold recovery rate is typically in the range of 70-80%. **Heap leaching**, on the other hand, is a slow and inexpensive process that is usually applied to low-grade gold ore. A sprinkler system provides a continuous spray of alkaline cyanide solution that percolates through the ore, dissolving the gold, and the ore is piled on an inclined impermeable surface. The gold-bearing solution is then collected and pumped to a gold recovery plant. However, the gold recovery rate in heap leaching is typically no more than 70%. (Marsden & House, 2006).

Cyanidation techniques used in the gold industry today include heap or valley fill leaching followed by carbon adsorption (carbon-in-column adsorption), agitation leaching followed by carbon-in-pulp (CIP), or agitated carbon-in-leach (CIL).Not all ores yield to high recovery by cyanide process. Arsenic and antimonial ores require a preliminary low-temperature roast, while gold ores containing copper or other constituents that are readily soluble in cyanide solution consume excessive amounts of cyanide and make the process inapplicable. In these cases, the flotation process has found wide application. Cyanicides are species that interfere with gold cyanidation in various ways, including forming stronger cyanide complexes than gold, forming new radicals, adsorbing CN radicals, and consuming dissolved oxygen. Identifying these species early is important to take appropriate corrective measures. Cyanidation is best suited for fine-grain gold in disseminated deposits, while encapsulation of visible gold in sulfide and silicate minerals is a common cause of gold losses. (Marsden & House, 2006).

2.6.4. Flotation

Flotation is a physicochemical separation technique that is based on the differences in the surface properties of minerals. The process involves the addition of reagents to the ore slurry, which selectively adsorb onto the surface of the target mineral particles, making them hydrophobic and allowing them to attach to air bubbles. The mineral particles then rise to the surface of the flotation cell, forming a froth that is separated from the ore slurry (Rao & Finch, 1987).

The efficiency and selectivity of gold mineral flotation can be impacted by various parameters. Some of the key parameters include the size of gold grains outside normal floatable size classes, the silver content of native gold, the composition of the gold mineral, activators and depressants, collector loading, and the shape of gold grains (Liu et al., 2018). The size of the gold grains can affect the efficiency of the flotation process, with fine particles requiring additional processing steps and large particles potentially being less efficiently recovered. The silver content of native gold can impact the surface properties of the gold particles, while the composition of the gold mineral can affect its interaction with flotation reagents. Activators and depressants are reagents that can modify the surface properties of minerals and improve the selectivity of the flotation process, while collectors selectively adsorb onto the surface of gold particles. The shape of gold grains can also impact their interaction with flotation reagents and their floatability. Optimizing these parameters can enhance the efficiency and selectivity of gold mineral flotation (Liu et al., 2018).

2.7. Previous works

The Ashashire gold deposit has been extensively studied for its geology, mineralization, and structural controls (Alemu et al., 2021). In comparison to the Lega Dembi gold deposit in southern Ethiopia, previous works have focused on the geology, mineralization, and processing characteristics of the deposit (Tadesse et al., 2021). The Lega Dembi deposit's Neoproterozoic metavolcanic rocks contain gold mineralization linked to sulfides like pyrite, arsenopyrite, and sphalerite. Since the 1990s, this deposit, which is one of Ethiopia's largest gold deposits, has been operating.

Research on the geology, mineralization, and structural controls of the Ezana gold deposit has been conducted in northern Ethiopia, as documented by Mulugeta et al. (2015).The deposit is hosted by Precambrian metamorphic rocks and is characterized by quartz veins and veinlets with associated sulfides such as pyrite and arsenopyrite. The gold mineralization is associated with shear zones and faults that crosscut the host rocks.

In western Ethiopia, the Wollega gold deposit has been studied for its geology, mineralization, and geochemistry (Kassa et al., 2018). The deposit is hosted by Neoproterozoic volcanic rocks and is characterized by disseminated and vein-style gold mineralization associated with quartz veins and hydrothermal alteration zones. The gold mineralization is associated with sulfides such as pyrite, arsenopyrite, and sphalerite.

Overall, the gold deposits in Ethiopia have similarities in terms of their host rocks, mineralization styles, and associated sulfides, but also have distinct characteristics that reflect their unique geologic and structural settings. The Lega Dembi deposit, for example, is known for its refractory gold mineralization, which requires more complex processing methods than other deposits

(Tadesse et al., 2021). This includes oxidative and pressure oxidation processes that can be used to extract gold from sulfide minerals.

In comparison, the Ashashire gold deposit contains both native gold and gold-telluride minerals, which can be pre-concentrated using gravity separation methods before further processing using cyanide leaching or other techniques (Alemu et al., 2021). The Wollega gold deposit contains primarily disseminated gold associated with sulfide minerals, which may require a combination of flotation and cyanide leaching methods for recovery (Kassa et al., 2018). The Ezana gold deposit is associated with shear zones and faults that are related to the East African Orogeny (Mulugeta et al., 2015).

In addition to their differences in mineralization and processing characteristics, the gold deposits in Ethiopia also have differences in their tectonic setting and age. The Lega Dembi gold deposit is hosted by metavolcanic rocks of the Neoproterozoic Arabian-Nubian Shield, which were formed in a volcanic arc setting (Tadesse et al., 2021). This is in contrast to the Ashashire gold deposit, which is hosted by Precambrian rocks and has been interpreted to be related to a late-stage deformation event associated with the Pan-African Orogeny (Alemu et al., 2021). The Wollega gold deposit is also hosted by Neoproterozoic volcanic rocks, but these were formed in a rift-related setting (Kassa et al., 2018). The Ezana gold deposit, in comparison, is hosted by Precambrian metamorphic rocks that were affected by the East African Orogeny (Mulugeta et al., 2015).

Understanding the unique characteristics of each gold deposit is important for exploration and mining. This requires detailed geological and mineralogical studies, as well as research and innovation to develop new processing methods that are more efficient and sustainable.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1. Materials

Starting with the underlying preparation of this project, various materials and instruments have been utilized to achieve it. The samples' elemental gold concentration was determined by fire assay with atomic absorption spectroscopy (AAS).Inductively coupled plasma (("ICP") was used to conduct multi-elemental head assay analysis of the samples. This method involves creating a plasma by ionizing a gas using an electric current and then introducing the samples into the plasma. The resulting emission spectra are then analyzed to determine the elemental composition of the samples.

Quantitative evaluation of material by scanning electron microscope and X-ray diffractometer (QEMSCAN and XRD) were used for mineralogical analysis, which includes ore mineral identification and quantification; liberation studies; and gangue mineral identification and quantification. QEMSCAN utilizes a filtering electron magnifying lens to get high-resolution pictures of the examples and afterward dissects the pictures to distinguish and evaluate the minerals present in the examples. The crystal structure of the minerals in the samples is examined using X-rays in XRD.

In this study, various computation facilities were used to manage and process the data obtained from the different analytical techniques used. The facilities included computers, required software, printing facilities, and other computer peripherals. To store and manage the data obtained from the different analytical techniques, laptops, hard discs, and flash drives were used. These storage devices gave a helpful and secure method for putting away the enormous measure of information created during the review. Software was likewise used to process and decipher the information acquired from the different logical strategies. ArcGIS and Microsoft software were two pieces of software that were utilized in this study. ArcGIS is a powerful geographic data framework (GIS) programming that was utilized to make maps. On the other hand, Microsoft ware includes a variety of software tools that were utilized for data analysis, presentation, and report writing, such as Microsoft Excel and Microsoft Word.

3.2. Methodology

To accomplish the above mentioned objectives the following methods and activities are used and accomplished.

3.2.1 Literature review and secondary data collection

To identify the research problem or gap detail literature review and data collection has been conducted. For this project, the literature review focused on identifying relevant articles, scientific journals, and books related to the process mineralogy of gold deposits. Different databases, including Google Researcher, Science Direct, and Web of Science, were utilized in the in the literature review. Keywords related to the project's topic were used in the search. Secondary data were gathered in addition to the literature review to find relevant information about the subject matter. This included information on the geology, geochemistry, and genesis of gold mineralization in the target area. The secondary data was obtained from various sources, such as government geological surveys, mining companies, and academic publications. The collected data was then organized and analyzed to identify potential project gaps and to develop a project framework for the current study.

3.2.2. Sample preparation and Data analysis

In this study, all sample preparation and data analysis were conducted by Kurmuk Gold Mine PLC. The company selected six representative samples from the mineralized zone of the core section for mineralogical characterization.

Sample preparation for the analyses was undertaken at the ALS sample preparation facility in Addis Ababa. The samples were first reduced to -3 mm using a jaw crusher coupled to a Terminator. The samples were then riffle split, and 1 kg of sub-samples were put into an LM2 pulverizer to generate 120 g of samples at a nominal 75 µm.

Inductively coupled plasma (ICP) for multi-elemental analysis and fire assay with atomic absorption spectroscopy (AAS) finishing were used to analyze the samples at the ALS Johannesburg laboratory.

After being ground to a P80 of 75 m, the remaining subsamples were sent for mineralogical analysis. Quantitative assessment of minerals by checking electron microscopy (QEMSCAN) and X-beam diffraction (XRD) were utilized to identify and evaluate the minerals present in the examples.

The mineralogical characterization of the deposit utilizing the above scientific procedures took into account the assurance of a few significant mineralogical highlights. One of the key features that could be determined was the gold and associated element concentration. The use of fire assay with AAS and ICP techniques allowed for the quantification of gold and other elements present in the samples. This information is crucial in determining the potential economic viability of the deposit. Additionally, the results provided insight into the concentration of other elements that may be present, which can impact the extraction and processing of gold.

Another significant mineralogical include that could be resolved was the gold grain size and distribution. The use of QEMSCAN and XRD techniques allowed for the identification of the size and distribution of gold grains in the samples. This data is fundamental in choosing the appropriate mineral handling procedures for the extraction of gold. The extraction process's efficiency can be affected by the size and distribution of the gold grains, and choosing the right processing method can help maximize gold recovery.

The liberation characteristics of the ore were another feature that could be determined using QEMSCAN. This technique allowed for the identification of the minerals present in the ore and their association with gold. This information is crucial in selecting appropriate comminution and mineral processing techniques. The liberation characteristics of the ore can impact the efficiency of the extraction process, and selecting the appropriate processing technique can help ensure maximum recovery of gold.

Identification of gold minerals and gangue minerals was another critical feature that could be determined using XRD and QEMSCAN. Identifying the gold minerals and gangue minerals is crucial in selecting appropriate mineral processing techniques and reagents for the extraction of gold. The selection of appropriate processing techniques and reagents can help maximize the recovery of gold while minimizing the impact on the environment.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. Result

4.1.1. AAS gold analysis

The AAS gold analysis is a method used to determine the amount of gold in a mineral sample .In this study, the six representative samples were examined utilizing the fire measure strategy, which includes dissolving the example at high temperature to isolate the gold from different minerals, followed by examination utilizing AAS. The AAS method measures the amount of gold in the sample by passing a light beam through it and measuring the amount of light absorbed by the gold atoms.

The aftereffects of the AAS assessment are presented in Table 2, which shows the gold content of all of the six examples. The gold content is expressed in grams per ton (g/t), which shows the amount of gold contained in a tonne of ore. The consequences of the three-fold gold tests are additionally revealed, which gives a sign of the accuracy of the examination. The average gold content of the representative samples is displayed in Figure 3, which gives a graphical portrayal of the gold content of the samples.

Table 2: Gold head assays of the representative samples

Sample No.	Rock Type	Assay 1 (Au g/t)	Assay 2 (Au g/t)	Assay 3 (Au g/t)	Average (Au g/t)
AS1	Granite	2.25	2.26	2.24	2.25
AS2	Granite	1.62	1.92	1.84	1.79
AS3	Pelite	1.47	1.92	1.75	1.71
AS4	Pelite	2.33	2.03	2.22	2.19
AS5	Mafic	4.07	3.64	3.53	3.75
AS6	Mafic	2.65	2.82	5.27	3.58
Average					2.54

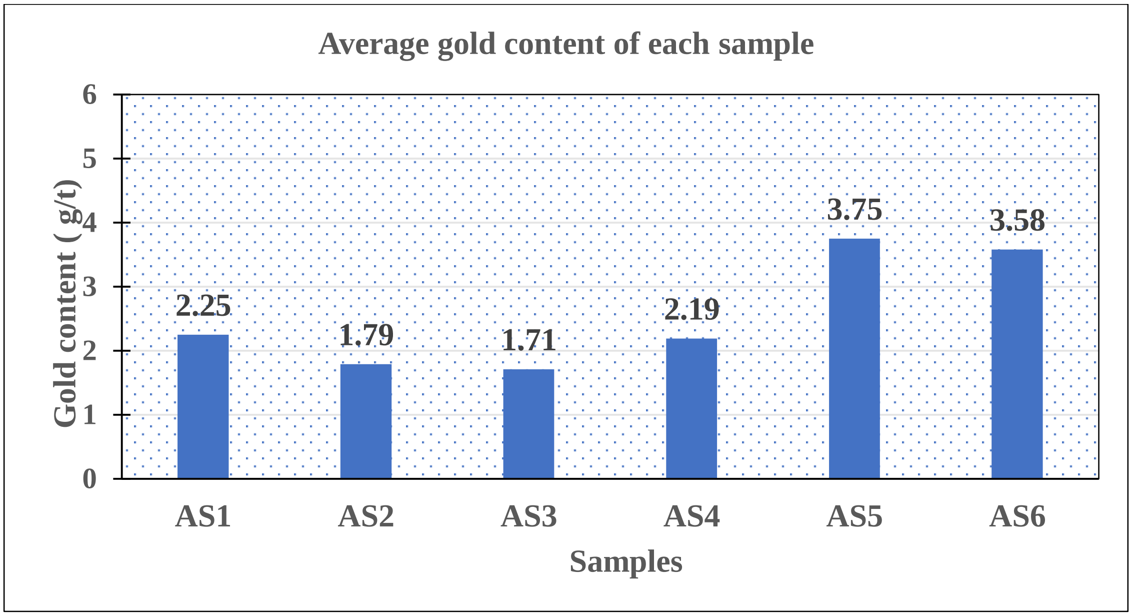


Figure 3. Average gold content of the representative samples

The samples tested had gold assays ranging from 1.47 to 5.27 g/t, and an average of 2.54 g/t of gold was calculated for the six representative samples.

The three sets of gold head assays for the representative samples presented in Table 2 show considerable variation for some samples, in particular AS6. A greater variation is shown for this data, which indicates the presence of a coarse gold particle component.

Gravity separation is a process that utilizes the difference in density between the gold particles and the surrounding rock to separate them. The process involves passing the ore through a series of screens or classifiers to separate the material into different size fractions. The coarse gold particles are then separated from the rest of the ore using various gravity separation methods, such as jigging, shaking tables, or centrifugal concentrators.

4.1.2. ICP gold analysis

The ICP gold analysis is a method used to determine the content of various elements associated with gold in the ore samples. The presence of elements like Ag, As, S sulfide, organic C, Te, and base metals can be detected and quantified using this method, which makes use of ICP (Inductively Coupled Plasma). The levels of these elements can inform the development of processing strategies and provide valuable information about the ore deposit's characteristics.

The presence of minerals like arsenopyrite, pyrite, stibnite, and copper sulphides, for instance, can be indicated by the levels of S sulfide and base metals in the ore. These minerals can essentially affect the handling strategies and can influence the recovery of gold from the ore. This method can also detect the presence of organic carbon. This is important because carbonaceous material can interfere with Cyanidation, which is a common method used to extract gold from the ore. Moreover, the presence of gold tellurides can be identified utilizing ICP investigation. Gold tellurides are a kind of gold mineral that can be harder to extricate utilizing regular handling techniques, and their presence can influence the decision of processing methods used.

Table 3 shows the results of the selected elemental analysis carried out on the Ashashire deposit using ICP, including the levels of Ag, As, S sulphide, organic C, Te, and base metals. These results give critical information on the attributes of the ore deposit and can be utilized to advise the improvement regarding handling systems for the store. The mineralogy and geochemistry of the store can be better perceived with the assistance of the top to bottom examinations in Appendix 1.

Table 3: Selected elemental assays of core samples

Element	**Unit**	**AS1**	**AS2**	**AS3**	**AS4**	**AS5**	**AS6**
Ag	ppm	0.3	0.3	0.6	0.6	2.1	0.6
Te	ppm	2.4	2.4	1.2	1.8	3.4	1.6
C Organic	%	0.03	<0.03	<0.03	<0.03	<0.03	<0.03
S sulphide	%	1.02	0.52	0.98	2.28	2.1	3.02
Cu	ppm	74	52	260	214	258	120
Zn	ppm	62	34	108	118	104	92
Hg	ppm	0	0	0	0.5	0.5	0.5
Ni	ppm	20	20	50	45	45	45
Pb	ppm	3	5	10	15	20	2.5
As	ppm	<10	<10	<10	<10	<10	<10

Table 3 presents the selected elemental assays of core samples from the Ashashire deposit. The table shows the levels of various elements associated with gold, including Ag, Te, C Organic, S sulphide, Cu, Zn, Hg, Ni, Pb, and As for six representative samples (AS1 to AS6).

The results show that the levels of Ag are generally low, with Ag ranging from 0.3 to 2.1 ppm. This suggests that the gold in the deposit is not strongly associated with this element. Tellurium occurred in all samples, ranging from 1.2 to 3.4 ppm. The levels of organic carbon (C Organic) are all below the detection limit of 0.03%, indicating that carbonaceous material is not likely to interfere with cyanidation. The ore's S sulfide content is notably high, ranging from 0.52 to 3.02 percent, which implies the presence of sulfide minerals such as pyrite, arsenopyrite, or stibnite,that may impact gold extraction from the ore. Additionally, Cu and Zn levels are also high, ranging from 34 to 260 ppm and 62 to 118 ppm, respectively. These elements may require extra steps to be eliminated from the ore and may affect the processes used to treat it.

Ni, Pb, As, and Hg levels are generally low, with Ni, Pb, and As below 50 ppm and Hg ranging from 0 to 0.5 ppm. Nonetheless, it is crucial to consider that even low concentrations of these elements can have consequences on the environment and necessitate careful management during mining and processing operations.

4.1.3. Correlation of Au with Ag, As, S sulphide, organic C, Te, and base metals

The correlation between each element, as well as with gold is summarized in the Table 4 below, and also displayed by the scatter diagrams (Figure 4). The calculated correlation obtained using IBM SPSS statistics software version 20 for ICP and AAS gold analysis.

Table 4: The Pearson correlation coefficients between each element as well as with gold

Element	**Unit**	**Au**	**Ag**	**Te**	**C Organic**	**S sulphide**	**Cu**	**Zn**	**Hg**	**Ni**	**Pb**	**As**
Au	ppm	1.00	0.54	0.59	-0.03	0.39	0.72	0.40	0.18	0.55	0.19	0.38
Ag	ppm	0.54	1.00	0.53	-0.06	0.01	0.15	0.36	0.12	0.31	0.13	0.11
Te	ppm	0.59	0.53	1.00	-0.07	0.14	0.51	0.26	0.11	0.44	0.17	0.09
C Organic	%	-0.03	-0.06	-0.07	1.00	0.01	-0.07	-0.08	-0.01	-0.10	-0.09	-0.05
S sulphide	%	0.39	0.01	0.14	0.01	1.00	0.14	0.32	0.08	0.13	0.23	0.07
Cu	ppm	0.72	0.15	0.51	-0.07	0.14	1.00	0.64	0.31	0.57	0.33	0.25
Zn	ppm	0.40	0.36	0.26	-0.08	0.32	0.64	1.00	0.16	0.46	0.26	0.17
Hg	ppm	0.18	0.12	0.11	-0.01	0.08	0.31	0.16	1.00	0.28	-0.04	0.11

Ni	ppm	0.55	0.31	0.44	-0.10	0.13	0.57	0.46	0.28	1.00	0.39	0.23
Pb	ppm	0.19	0.13	0.17	-0.09	0.23	0.33	0.26	-0.04	0.39	1.00	0.15
As	ppm	0.38	0.11	0.09	-0.05	0.07	0.25	0.17	0.11	0.23	0.15	1.00

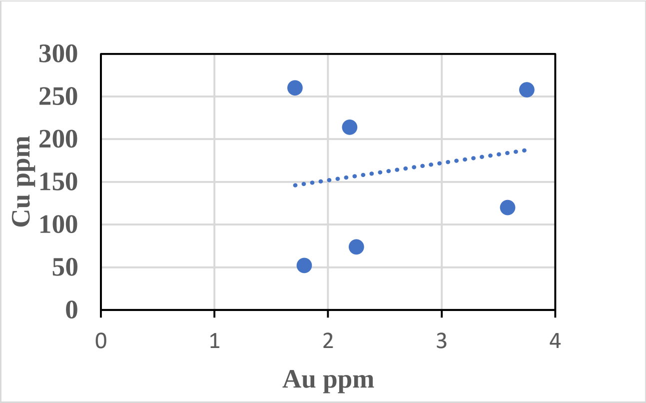
After examining the table, it can be seen that gold exhibits significant areas of strength in its relationship with copper (0.72), a moderate positive correlation with tellurium (0.59), and a weak positive correlation with silver (0.54), zinc (0.40), and nickel (0.55). Conversely, gold has a weak negative correlation of -0.03 with organic carbon. It is worth noting that some elements, such as lead (0.19), mercury (0.18), and arsenic (0.38), have very weak or negligible correlations with gold.

The solid positive connection among's gold and copper and the moderate positive relationship among's gold and zinc propose the potential for the presence of copper and zinc minerals related with gold in the store. In a similar vein, the moderately positive correlation that exists between tellurium and gold suggests that the deposit may contain telluride minerals like calaverite and sylvanite. These minerals can be refractory to cyanide leaching and may require specialized processing techniques such as pressure oxidation or roasting.

The weak to moderate positive correlations between gold and silver, nickel, lead, and arsenic indicating the potential for the presence of silver, nickel, lead and arsenic-bearing minerals in the deposit. Silver and nickel can be recovered as valuable byproducts in gold processing, while lead can also be recovered as a byproduct. However, arsenic can pose environmental and health risks during gold processing and requires careful management.

Gold has weak to no correlation with organic carbon and silver sulfide, indicating that these elements may not be significant mineralogical factors in gold processing. Finally, the weak to moderate positive correlation between gold and sulfur suggests the potential for the presence of sulfur-bearing minerals such as pyrite, which can generate acid rock drainage and affect the environmental and health risks of the process.

Overall, while the Pearson correlation coefficients provide a starting point for understanding the mineralogy and processing characteristics of the Ashashire Gold deposit, further mineralogical and geochemical analyses are necessary to fully characterize the deposit and optimize the processing conditions.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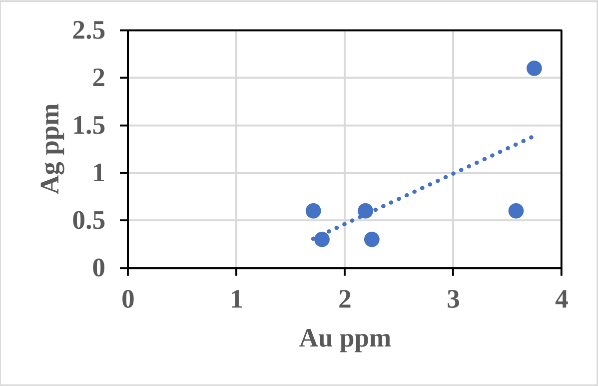
Au ppm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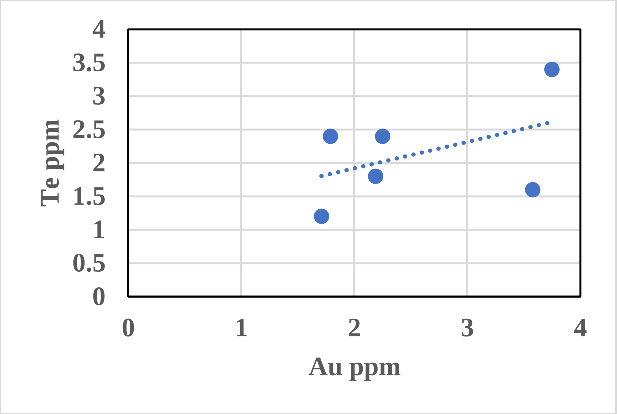
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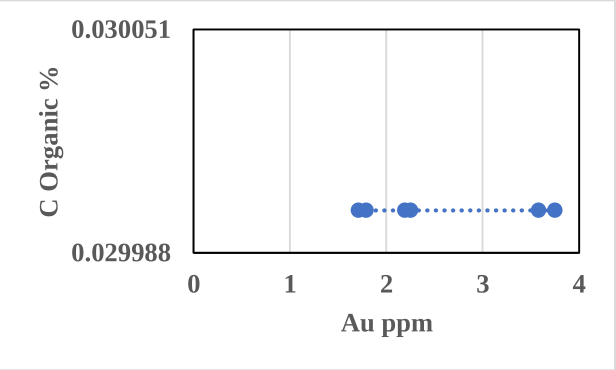
Au ppm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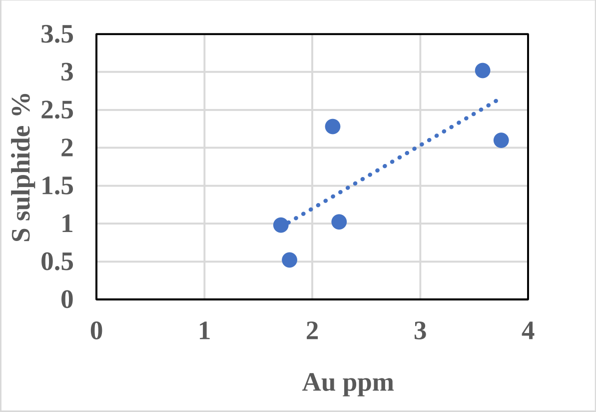
Au ppm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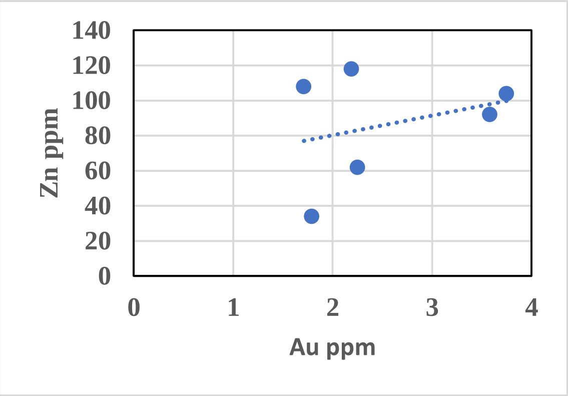
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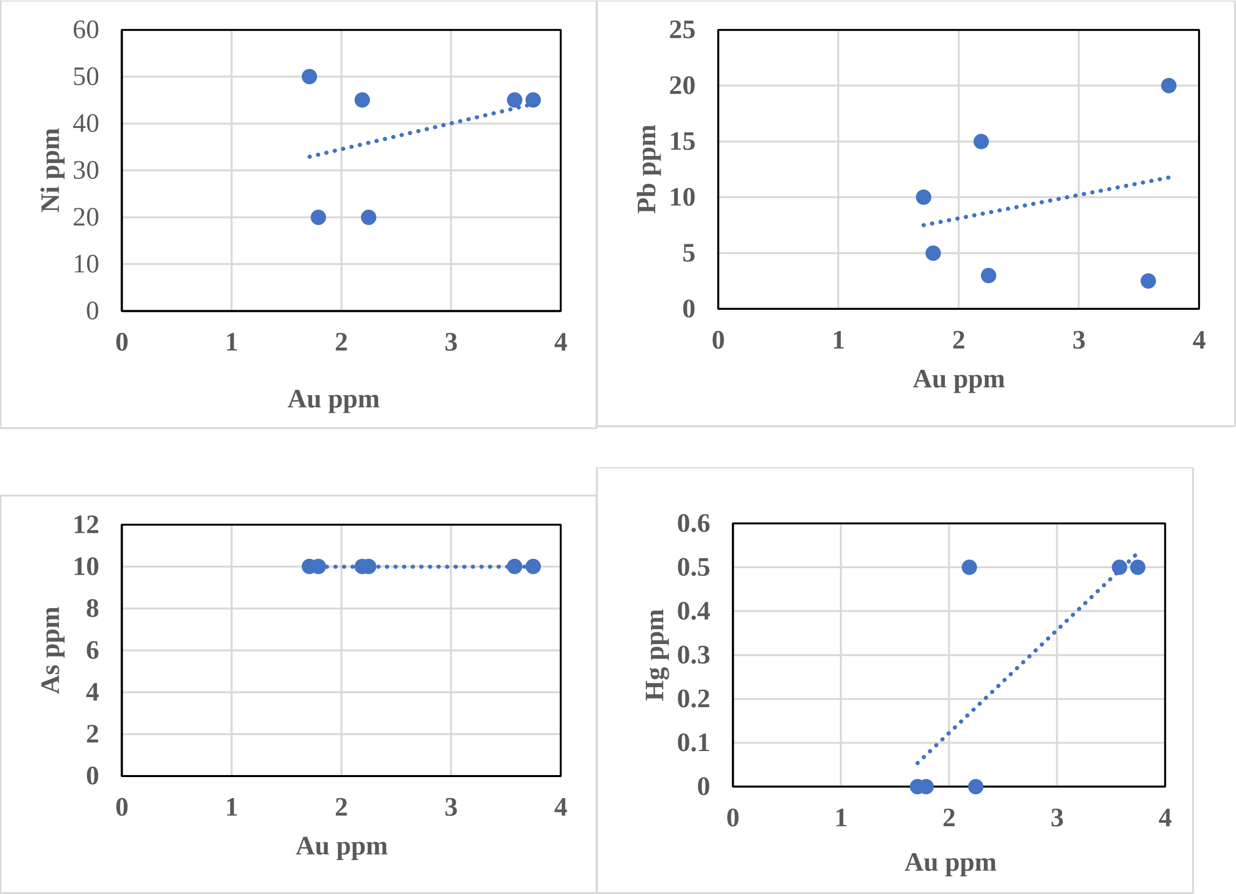


Figure 4. The scatter diagrams of Au with Ag, As, S sulphide, organic C, Te, and base metals

The scatter plot of Au with elements for the Ashashire Gold deposit shows significant gold mineralization with concentrations ranging from 1.71 to 3.75 ppm. The gold is positively correlated with silver, copper, and tellurium, which may indicate association with these metals. The deposit may also contain sulfide-related mineralization, including copper, zinc, and lead, which may affect gold processing and increase environmental risks. The deposit has low concentrations of organic carbon and arsenic. In summary, while the scatter plot provides some insights into the potential mineralogical and processing characteristics of the Ashashire Gold deposit, more specific information about the deposit would be required for definitive interpretations. Further mineralogical and geochemical analyses as well as specific metallurgical testing such as cyanide leach tests, gravity separation tests, and flotation tests, would be necessary to fully understand the deposit's characteristics, the potential for gold and other metal extraction from the deposit.

4.1.4. QEMSCAN and XRD analysis

The remaining sub-samples were ground to a P80 of 75 m before being submitted for quantitative mineral evaluation by X-ray diffraction (XRD) and scanning electron microscopy (QEMSCAN). Using automated scanning electron microscopy, QEMSCAN is a powerful tool for mineralogical analysis that can identify and quantify minerals in a sample. It can give detailed information on the mineralogy and texture of the example.

Table 5 provides the percentage composition of minerals present in the concentrated ore, as determined by QEMSCAN analysis. As shown in Figure 5, quartz comprises between 10.3% and 42.3% of the weight of all samples, followed by ankerite-dolomite (between 9.1% and 27.6%), muscovite (between 8% and 22.6%), chlorite (between 0.2% and 17.4%), albite (between 5.6% and 33.7%), and pyrite (between 1.9% and 6.73%). Other minerals with a minor presence include rutile (between 0.5% and 3.9%), magnetite (between 0.01% and 3.1%), calcite (between 0.3% and 5.0%), and paragonite (between 0.35% and 4.7%), as shown in Figure 6. Detailed analyses are presented in Appendix 2.

Table 5: Mineralogical composition of the representative samples (wt. %)

Mineral	**AS1**	**AS2**	**AS3**	**AS4**	**AS5**	**AS6**
Pyrite	3.5	2.1	3	5.9	5.1	6.73
Quartz	42.3	36.7	24.5	23.2	37.3	10.3
Ankerite-dolomite	11.7	9.1	21.7	27.6	15.4	24.9
Muscovite	22.6	15.8	8	9.4	11.6	8
Chlorite	4.1	0.2	17.4	13.9	15.2	15
Albite	8.6	33.7	11	6.2	5.6	23
Paragonite	Trace	0.8	2.7	4.7	0.35	1.8
Rutile	0.9	0.5	2.6	3.4	2.6	3.9
Magnetite	0.7	trace	2.8	1.8	1.5	3.1
Chalcopyrite	trace	trace	trace	trace	trace	Trace
Calcite	0.3	trace	5	2.1	3.9	3.9
Others	<5	<1	<2	<2	<2	<1

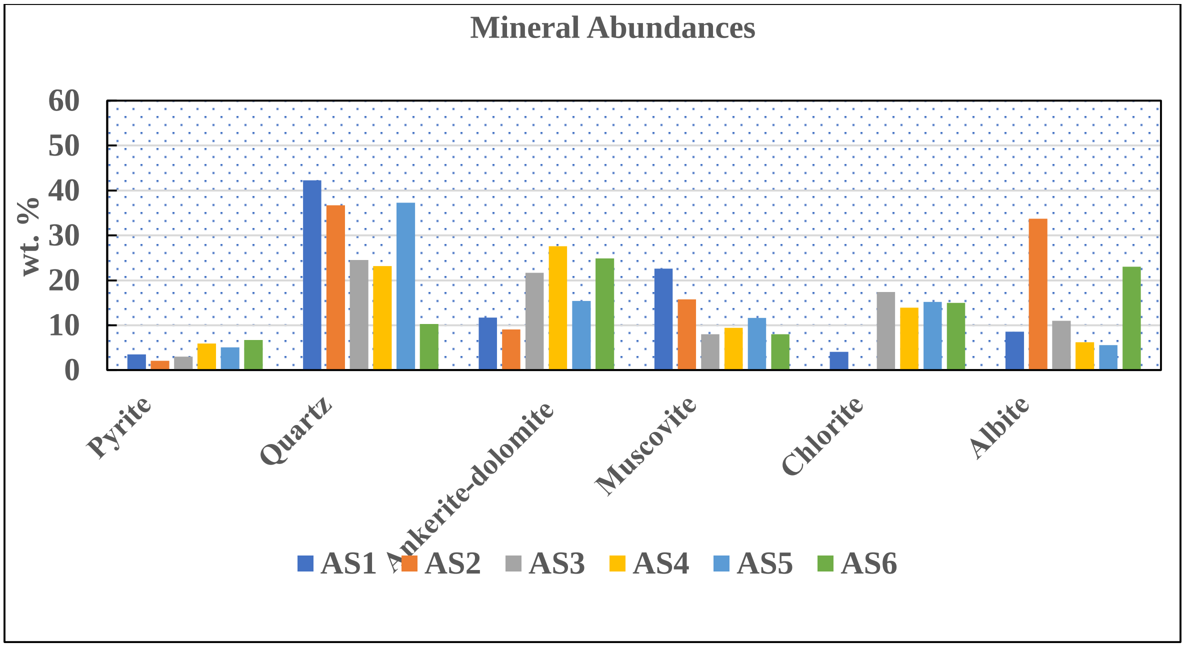


Figure 5. Mineral abundances for principal components for all samples

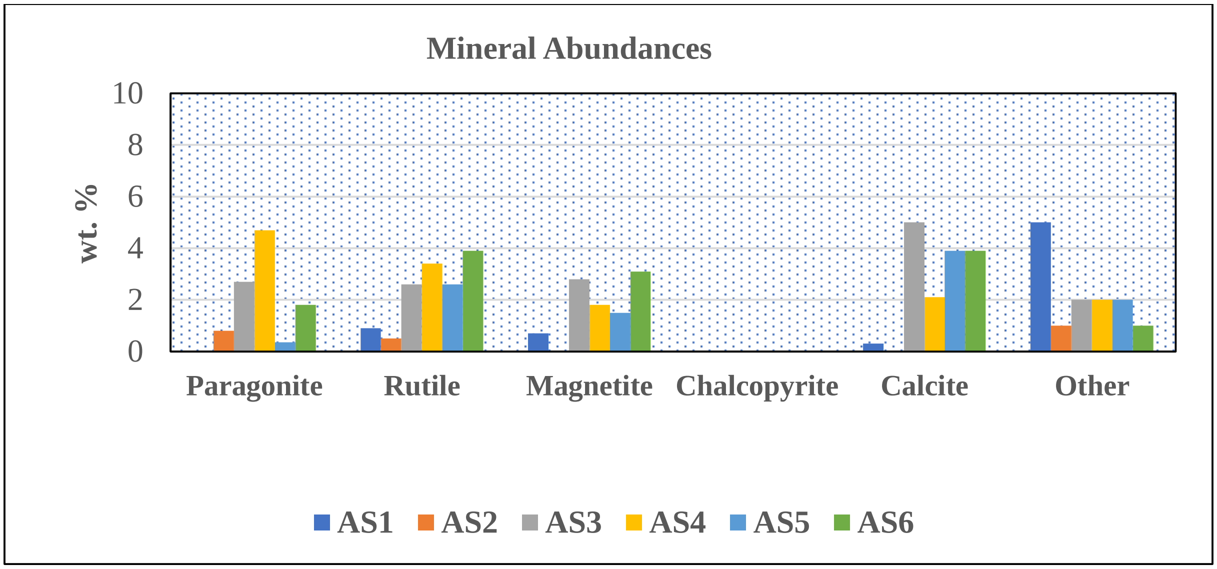
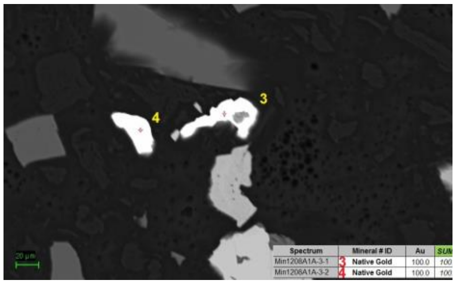


Figure 6. Mineral abundances for secondary components for all samples

From the above mineralogical data indicated, we can summarize the gangue mineralogy of the deposit as follows: Pyrite is the dominant sulphide mineral detected in all core samples, making up between 2 and 6.7% by mass, and only trace amounts of chalcopyrite were detected. The non-sulphide gangue species and their abundance varied between the six samples. The main gangue minerals were quartz, ankerite-dolomite, muscovite, chlorite, and albite, with lower levels of paragonite, rutile, magnetite, and calcite.

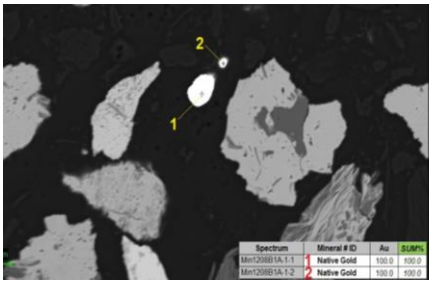
From QEMSCAN analysis, the two main types of gold detected are native gold and gold-telluride. In the six samples, gold occurred mainly in its native and minor gold-telluride forms. Gold mainly occurred as liberated or in association with gold-carrying gangue minerals (such as quartz and pyrite) along grain boundaries. The minor gold grains occurred in association with pyrite as inclusions or small grains in fractures.

The total number of gold grains identified in this study is 352. The overall gold grain size distribution shows an interval from very fine-grained (< 2 µm) to coarse-grained (75µm). The grain size distribution of the gold minerals is shown in Table 7. Backscattered electron (BSE) images of select gold grains are presented below.



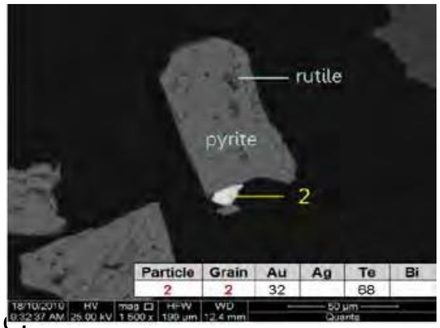
Spectrum	Mineral # ID	Au	SUM
Min1208A1A-3-1	3 Native Gold	100.0	100
Min1208A1A-3-2	4 Native Gold	100.0	100

a)



Spectrum	Mineral # ID	Au	SUM%
Min1208B1A-1-1	1 Native Gold	100.0	100.0
Min1208B1A-1-2	2 Native Gold	100.0	100.0

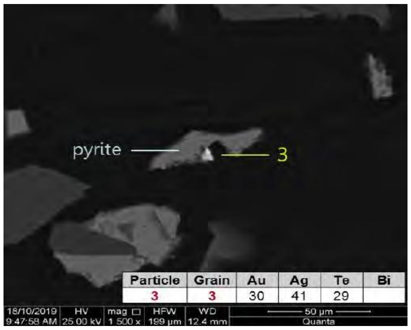
b)



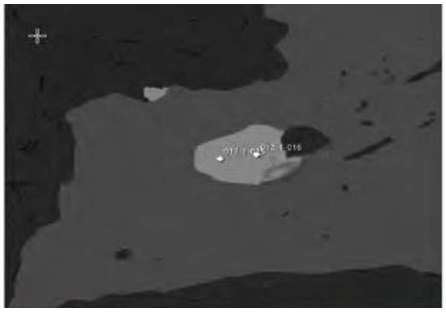
Particle	Grain	Au	Ag	Te	Bi
2	2	32		68	

c)

d



Particle	Grain	Au	Ag	Te	Bi
3	3	30	41	29	



e)

Figure 7. Backscattered electron (BSE) images of select gold grains. (a) (b) Liberated native gold (free-milling ore) ; (c)native gold (Au) in association with pyrite along grain boundaries ; (d)Native gold (Au) in association with pyrite and quartz; (E) pyrite contains small inclusions of gold-telluride, possibly calaverite ($AuTe_2$) (refractory ore)

Table 6. Grain size distribution of gold

Grain size range	**Proportion (%)**
< 2 µm	3.8
2 µm-20 µm	23.4
20 µm-40 µm	27.6
40 µm-60 µm	26
> 60µm	19.2
Total	100

A pie chart generated from this data is shown in Figure 9.

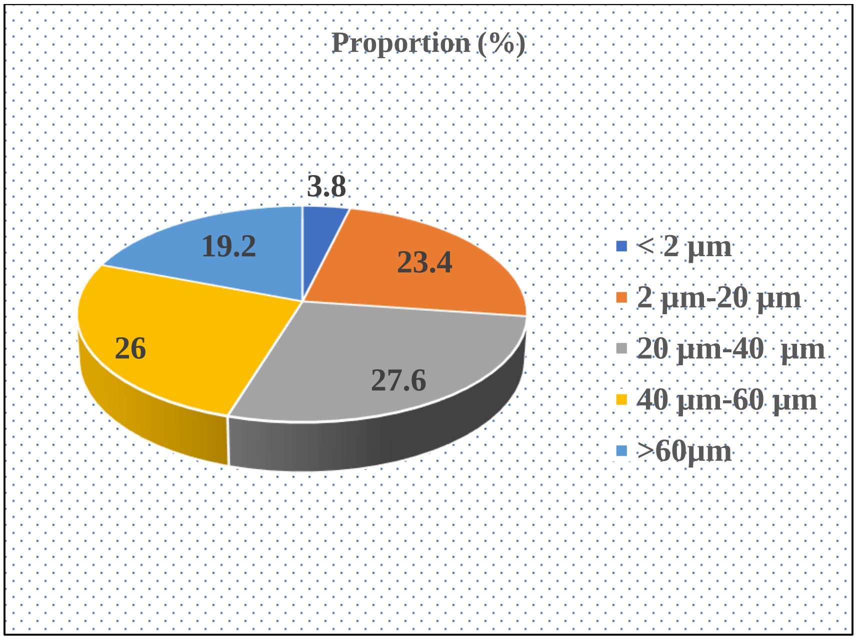


Figure 8. Pie chart showing the grain size distribution of gold

4.2. Discussion

4.2.1. Processing implications

Mineral processing prepares the ore for the extraction of valuable minerals by separating it from the gangue minerals. There are two fundamental operations involved in mineral processing: firstly, the release or liberation of the valuable minerals, and secondly, the separation of the valuable minerals from the gangue. To achieve the liberation of valuable minerals, a process called comminution is employed. This process involves crushing and, if needed, grinding the minerals to a particle size that results in a relatively pure combination of valuable minerals and gangue. The efficiency of the comminution process is essential for the efficient separation of the valuable minerals from the gangue. The separation of the valuable minerals from the unwanted gangue follows the comminution process. The efficiency of the separation process depends not only on the efficiency of the comminution process but also on the degree of difference in certain properties between the valuable minerals and the gangue. Separation can be achieved based on the difference in density, magnetic properties, electrical conductivity, surface properties, and optical properties between the valuable mineral and gangue.

Mineral processing's ultimate objective is the production of a concentrate, which is the enriched ore from which the valuable metal can be extracted. A thorough comprehension of the ore's mineralogy and texture is necessary for efficient mineral processing, which is crucial to the concentrate's quality. The mineralogy of the ore is important because it affects the grinding and concentration requirements, feasible concentrate grades, and potential difficulty of separation (Evans et al., 2011). Different mineralogical assemblages may require different concentration processes to achieve a feasible concentrate, and more than one concentration process may be needed to achieve the desired result. For example, in the processing of gold ores, a separation process such as gravity may be accompanied by flotation and subsequently by cyanidation or amalgamation to achieve the final concentrate grade. The texture of the ore is also important, as it affects the efficiency of the comminution process and the accessibility of the valuable minerals to the concentration process. The presence of fine-grained minerals, for example, can require additional processing steps to improve the liberation of the valuable minerals from the gangue.

Gold ores can be broadly classified into free-milling and refractory ores, based on the ease of extracting gold from the ore using conventional processing methods (La Brooy et al., 1994). Free-milling gold ores are those in which the gold can be easily liberated and extracted using conventional physical methods such as grinding, gravity separation, flotation, and cyanide leaching. In contrast, refractory gold ores are those in which the gold is locked within the mineral matrix and cannot be easily liberated using conventional processing methods, and may require additional processing steps such as roasting, pressure oxidation, or bioleaching to make the gold accessible to the leaching solution. The Ashashire gold deposit has exhibited some free-milling behavior due to the occurrence of gold mainly as liberated or in association with gold-carrying gangue minerals along grain boundaries. However, the detection of gold-telluride from SEM analysis suggests the presence of a minor gold fraction that can be considered refractory. Aspects of the ore mineralogy most likely to affect gold recoveries will be considered. Such aspects would include gold mineralogy, gangue minerals, and ore texture.

A) Effect of ore texture

The texture of the ore can have a significant impact on the degree of liberation and the liberation sizes of the gold particles. The degree of liberation refers to the amount of gold that is liberated from the gangue minerals, while the liberation sizes refer to the particle size at which the gold is liberated. Generally, it is easier to liberate gold that is situated between grain boundaries and cracks, compared to gold that is trapped within crystals.

Based on the SEM images of the gold grains in the Ashashire deposit, it was found that most of the gold particles are situated along micro fractures and grain boundaries. This fraction of gold is easier to liberate at fairly large particle sizes. However, a fraction of the gold is found as inclusions within the gangue minerals, mainly pyrite and quartz, and a small portion of the gold particles are very fine-grained, well below 2 microns. Liberating this fraction will require very fine grinding, which may have an adverse effect during the separation process. Concentrating very fine-grained gold particles can also be challenging and may require advanced concentration methods such as flotation, centrifugal gravity separation, or advanced leaching techniques (pressure oxidation, bioleaching, thiosulfate leaching or chloride leaching). Very fine grinding can cause the production of fine particles and slimes that can clog the downstream processing equipment, such as flotation cells or thickeners. Additionally, fine grinding can increase the amount of impurities in the concentrate, reducing the overall grade of the ore. Therefore, it is important to balance the need for liberation with the potential negative effects of fine grinding.

In addition to the impact on liberation and liberation sizes, the texture of the ore can also affect the recovery of gold. For example, if the gold is present in coarse particles, it may be more amenable to recovery by gravity separation methods, while if the gold is present in fine particles, it may be more amenable to recovery by flotation or leaching methods.

In summary, the texture of the ore is an important parameter that can significantly affect the processing of the Ashashire gold deposit. The degree of liberation, liberation sizes, and recovery of gold are all impacted by the texture of the ore. Therefore, it is important to carefully consider the ore texture when developing a processing strategy and selecting the appropriate processing methods.

B) Effect of gold mineralogy

The gold mineralogy of the Ashashire deposit can have a significant effect on the processing of the gold ore. The presence of a slow-dissolving gold mineral such as gold telluride can make a portion of the ore somewhat refractory, which can result in lower gold recoveries.

To overcome this challenge, different methodologies can be utilized. For instance, raising the pH of the leach solution to 12-12.5 can expand the recovery of gold tellurides. This is due to the fact that an increase in pH can make the gold tellurides more soluble and thus more readily available to the leachant. Notwithstanding, it is vital to take note of that raising the pH too high can bring about the precipitation of different minerals or the arrangement of cyanide-consuming species, which can diminish gold recovery rates. Notwithstanding pH change, different techniques like oxidation, cooking, or tension draining can likewise be utilized to work on the recovery of recalcitrant gold minerals. The gold can be made more readily available to the leachant by exposing the ore to high temperatures or pressures, which can break down the chemical bonds between the gold and other elements.

In outline, the gold mineralogy of the Ashashire deposit, especially the presence of refractory gold minerals like gold tellurides, can essentially affect the processing of the gold ore. Strategies such as adjusting the pH of the leach solution or using other methods such as oxidation or pressure leaching may be necessary to improve the recovery of gold from the ore.

C) Effect of gangue minerals

The existence of gangue minerals in gold ores is a significant factor to consider when choosing a suitable gold recovery method. Typically, gold ores are associated with various gangue minerals including but not limited to quartz, fluorite, calcite, pyrites, chalcopyrite, galena, and several others in small quantities, such as arsenopyrite, fluorites, carbonates, and chlorites (Hausen, 2000). As mentioned earlier, the QEMSCAN and XRD results show that the Ashashire Gold deposit is composed of several minerals, including quartz, ankerite-dolomite, muscovite, chlorite, albite, pyrite, and minor amounts of other minerals such as rutile, magnetite, calcite, and paragonite. The presence of these minerals can impact gold processing in various ways, such as reducing gold recovery by consuming cyanide, increasing the pH of the leach solution, or reducing the permeability of the ore.

Pyrite is the dominant sulphide mineral present in all core samples, ranging from 2.1-6.73% by mass. Sulphide minerals can consume reagents and oxygen, reducing their availability for gold recovery, and generate acid mine drainage, which can be harmful to the environment (Chryssoulis et al., 2009). However, the low amounts of sulphides present in the Ashashire gold deposit suggest that their impact on gold recovery rates may be minimal.

The abundance of quartz in the Ashashire gold deposit suggests that the ore may be hard and abrasive. Hard and abrasive ores can increase the wear and tear on processing equipment, leading to increased maintenance costs and downtime. To mitigate the impact of quartz on processing equipment, additional measures such as using wear-resistant materials and optimizing the grinding circuit may be required.

Carbonate minerals, such as ankerite-dolomite and calcite, can consume cyanide and affect the pH of the solution, which can impact the efficiency of gold recovery by cyanidation. This is because of carbonate minerals can react with cyanide to form metal-cyanide complexes, reducing the availability of cyanide for gold dissolution. This can result in low gold recovery rates and increased processing costs due to the need for additional cyanide. The high abundance of ankerite-dolomite in the Ashashire gold deposit suggests that cyanide consumption may be a significant issue during gold processing. Additional steps may be required to mitigate the impact of carbonate minerals on cyanide consumption, such as pH adjustment or neutralization.

Clay minerals, such as muscovite and chlorite, have high surface areas and can adsorb gold, reducing its availability for cyanide dissolution. The high abundance of muscovite and chlorite in the Ashashire gold deposit suggests that clay coating and gold adsorption may be significant issues during gold processing. Agglomeration or pre-leaching may be required to mitigate the impact of clay minerals on gold recovery. Albite and other minerals can impact gold processing by increasing processing costs. The high abundance of albite in the ore suggests that lime or other alkaline materials may be required for pH adjustment or neutralization. Additional processing steps such as pressure oxidation or roasting can also increase processing costs (Chryssoulis et al., 2009).

In summary, the gangue mineral composition of the Ashashire gold deposit can impact gold processing in several ways, including cyanide consumption, clay coating and gold adsorption, ore hardness, mineralogical complexity, and processing costs. Understanding the specific gangue minerals present in the ore and their potential impact on gold processing is critical for optimizing gold recovery rates and minimizing the environmental impact of mining operations.

4.2.2. Comparison with other deposits

The processing implications of a gold deposit are largely determined by its mineralogy, which can impact the degree of liberation, the liberation sizes, and the recovery of gold. The mineralogy of a gold deposit can also impact the selection of the processing method and the equipment that is used.

In terms of the Ashashire Gold deposit, as I mentioned earlier, the deposit contains gold in association with pyrite, quartz, and gold tellurides. A minor portion of the ore is somewhat refractory due to the presence of a slow-dissolving gold mineral (gold telluride), which can impact the processing of the ore and the recovery of gold. To extract the gold from the refractory ore, additional processing steps, such as pressure oxidation or bioleaching, may be required.

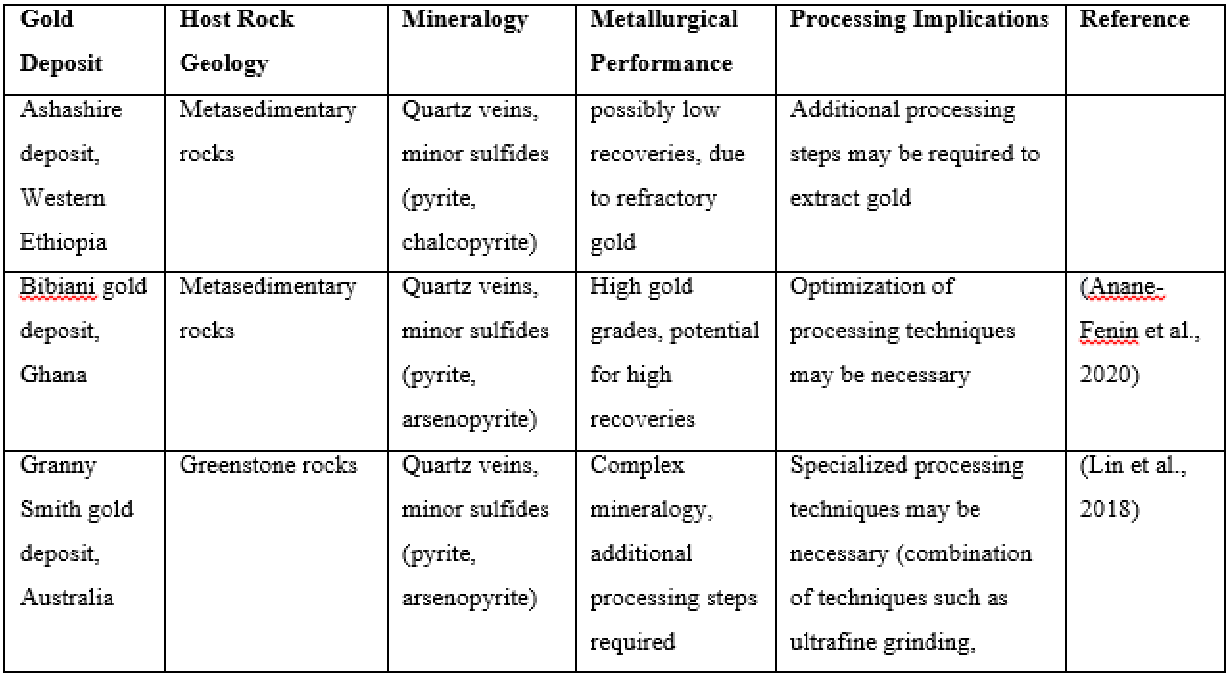
When compared to other gold deposits in Ethiopia, the mineralogy and metallurgical behavior of each deposit can differ significantly. As an illustration, the Lega Dembi gold deposit, which is among Ethiopia's largest gold deposits, contains gold linked with sulfide minerals like pyrite and arsenopyrite, alongside other minerals including quartz and carbonate. The gold is present as free gold and gold-silver alloys, making it amenable to conventional cyanide leaching (Asfaw et al., 2019). The Ezana deposit contains gold in association with sulfide minerals, such as pyrite and arsenopyrite. Additional processing steps, such as flotation and pressure oxidation, are recommended to extract the gold from the sulfide ores (Gebrehiwot et al., 2021).

Another gold deposit in Ethiopia, the Tulu Kapi gold deposit, contains gold in association with sulfide minerals such as pyrite and arsenopyrite, as well as other minerals such as quartz and carbonate. The gold at Tulu Kapi is also relatively free milling, and conventional cyanide leaching is expected to be used to extract the gold (Alemayehu et al., 2020). The Wollega gold deposit contains gold in association with sulfide minerals, such as pyrite and arsenopyrite. Additional processing steps, such as flotation and pressure oxidation, are recommended to extract the gold from the sulfide ores (Ayana et al., 2018).

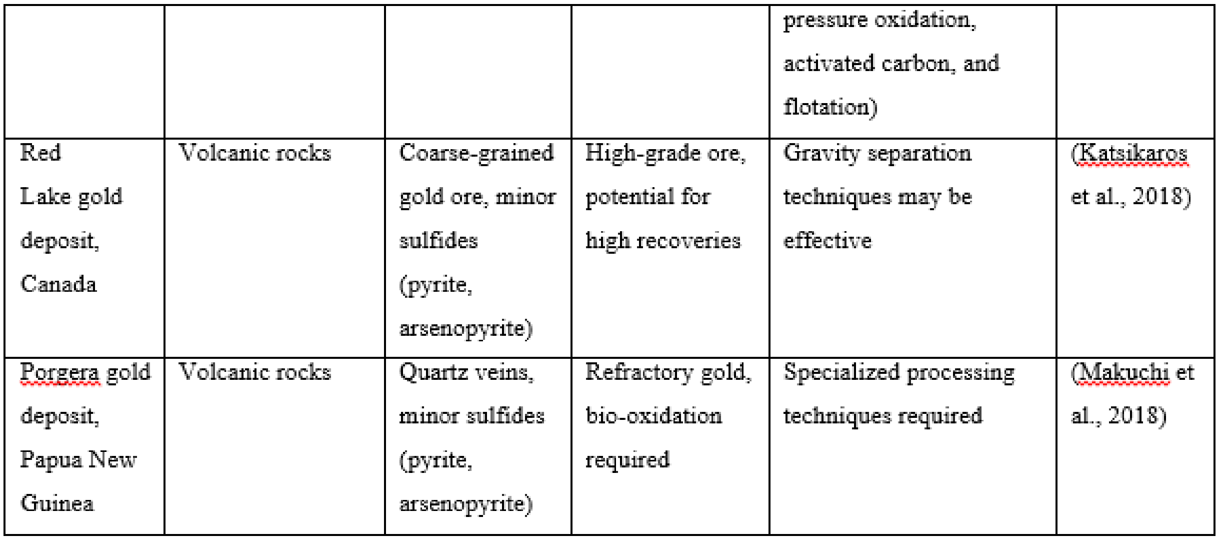
In terms of mineralogy, both the Ashashire and Wollega gold deposits contain gold in association with sulfide minerals, which require additional processing steps to extract the gold. The Ezana deposit is also associated with sulfide minerals, while the Lega Dembi and Tulu Kapi deposits contain free gold and are amenable to conventional cyanide leaching. In terms of metallurgical performance, the refractory nature of the Ashashire deposit due to the presence of gold tellurides requires additional processing steps, which is similar to the Wollega gold deposit. The Ezana deposit also requires additional processing steps due to its association with sulfide minerals. The Lega Dembi and Tulu Kapi deposits are relatively free-milling and require less processing compared to the other deposits.

Below here comparing the processing implications of the Ashashire deposit with the Bibiani, Granny Smith, Red Lake, and Porgera gold deposits, highlighting similarities and differences in mineralogy and metallurgical performance.

Table 8: Comparing the processing implications of the Ashashire deposit with other deposits



Gold Deposit	**Host Rock Geology**	**Mineralogy**	**Metallurgical Performance**	**Processing Implications**	**Reference**
Ashashire deposit, Western Ethiopia	Metasedimentary rocks	Quartz veins, minor sulfides (pyrite, chalcopyrite)	possibly low recoveries, due to refractory gold	Additional processing steps may be required to extract gold	
Bibiani gold deposit, Ghana	Metasedimentary rocks	Quartz veins, minor sulfides (pyrite, arsenopyrite)	High gold grades, potential for high recoveries	Optimization of processing techniques may be necessary	(Anane-Fenin et al., 2020)
Granny Smith gold deposit, Australia	Greenstone rocks	Quartz veins, minor sulfides (pyrite, arsenopyrite)	Complex mineralogy, additional processing steps required	Specialized processing techniques may be necessary (combination of techniques such as ultrafine grinding,	(Lin et al., 2018)



				pressure oxidation, activated carbon, and flotation)	
Red Lake gold deposit, Canada	Volcanic rocks	Coarse-grained gold ore, minor sulfides (pyrite, arsenopyrite)	High-grade ore, potential for high recoveries	Gravity separation techniques may be effective	(Katsikaros et al., 2018)
Porgera gold deposit, Papua New Guinea	Volcanic rocks	Quartz veins, minor sulfides (pyrite, arsenopyrite)	Refractory gold, bio-oxidation required	Specialized processing techniques required	(Makuchi et al., 2018)

4.2.3. The possible processing routes for the Ashashire deposit

Based on the mineralogy of the Ashashire deposit, there are several possible processing routes that could be considered to optimize gold recovery. The deposit contains a range of minerals, including quartz, ankerite-dolomite, muscovite, chlorite, albite, pyrite, rutile, magnetite, calcite, and paragonite, with the two main types of gold detected being native gold and gold-telluride.

One possible processing route is gravity separation. Since the deposit contains native gold and gold-telluride, which have a higher density than the gangue minerals, gravity separation techniques could be used to pre-concentrate the gold. The study also suggests the presence of coarse gold particles, particularly in sample AS6. Coarse gold particles are typically more difficult to recover using traditional cyanide leaching methods. In this case, gravity separation methods may be more effective than cyanide leaching for recovering the coarse gold particles. The pre-concentrated material can then be further processed using cyanide leaching or other techniques to extract the gold.

Another possible processing route is flotation. Flotation involves adding chemicals to the ore slurry to make the gold particles hydrophobic and the sulfide particles hydrophilic. The hydrophobic gold particles then attach to bubbles and rise to the surface, where they can be collected. Flotation can be used to separate the gold from the sulfides, making the subsequent cyanide leaching process more effective. Cyanide leaching is a widely used processing technique used to extract gold from ores. In the case of the Ashashire deposit, cyanide leaching can be used to extract the gold once it has been pre-concentrated using gravity separation or flotation. The ore is crushed and ground to a fine powder, and then mixed with a cyanide solution. The gold dissolves into the solution and can be recovered by adsorbing it onto activated carbon.

Pressure oxidation is another possible processing route. This involves treating the ore with oxygen and sulfuric acid under high pressure and temperature. This process can oxidize the sulfides and refractory gold, making it more amenable to cyanide leaching and increasing gold recovery. After oxidation, the gold can be extracted from the ore using various methods, including cyanide leaching or other suitable techniques.

Carbon-in-leach (CIL) or carbon-in-pulp (CIP) methods could be utilized as a final step. These techniques involve adding activated carbon to the ore slurry to adsorb the gold. The activated carbon is then separated from the slurry and the gold is recovered by stripping the carbon using a desorption process. CIL and CIP are commonly used for processing ores containing high-grade gold. A combination of gravity separation, flotation, cyanide leaching, pressure oxidation, and CIL/CIP could be employed to maximize gold recovery and minimize costs. By using a combination of techniques, it may be possible to optimize gold recovery while minimizing environmental impact.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In conclusion, this study provides valuable information on the mineralogical characteristics of the Ashashire gold deposit with processing implications. The study reveals that the gold in the deposit occurs primarily as native gold and gold-telluride, with a strong association with tellurium and often found as free particles or in association with gangue minerals such as quartz and pyrite. The gangue minerals present in the deposit are mainly quartz, ankerite-dolomite, muscovite, chlorite, and albite. Pyrite is the dominant sulfide mineral detected in all core samples, with only trace amounts of chalcopyrite detected.

The presence of tellurium suggests that the gold may be present in a refractory form, requiring specialized processing techniques rather than traditional cyanide leaching. The study also suggests the presence of coarse gold particles, particularly in sample AS6, indicating that gravity separation methods may be more effective than cyanide leaching for recovering the coarse gold particles.

The mineralogical data can be used to develop a suitable processing route, such as using flotation to separate sulfide minerals from the gold-bearing minerals. The grain size distribution of the gold is another important factor to consider when developing a processing strategy. Various processing routes can be used, such as gravity separation, flotation, cyanide leaching, pressure oxidation, or CIL/CIP. A combination of techniques may be required to optimize gold recovery while minimizing environmental impact, depending on the specific mineralogy of the deposit and desired recovery rates. However, further metallurgical testing and optimization are necessary to fully understand and optimize gold recovery from this deposit.

5.2. Recommendations

This study mainly covered the mineralogical characterization of the Ashashire gold deposit, particularly the ore and gangue minerals. It involved AAS, ICP, QEMSCAN, and XRD analysis for the representative core samples. Thus, the mineralogical characterization was based on these analyses, which may not be enough for a detailed characterization of each mineralogical feature of the deposit. Therefore, for more comprehensive mineralogical characterization of the deposit, visual ore and gangue mineral identification and characterization during drill-core logging, electron probe microanalysis (EPMA) of gold grains, specific metallurgical testing such as cyanide leach tests, gravity separation tests, and flotation tests have to be implemented in the further studies.

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Appendices

Appendix 1. Elemental assays of the representative samples

Element	**Unit**	**AS1**	**AS2**	**AS3**	**AS4**	**AS5**	**AS6**
Ag	ppm	0.3	0.3	0.6	0.6	2.1	0.6
Te	ppm	2.4	2.4	1.2	1.8	3.4	1.6
C Organic	%	0.03	<0.03	<0.03	<0.03	<0.03	<0.03
S sulphide	%	1.02	0.52	0.98	2.28	2.1	3.02
Cu	ppm	74	52	260	214	258	120
Zn	ppm	62	34	108	118	104	92
Hg	ppm	0	0	0	0.5	0.5	0.5
Ni	ppm	20	20	50	45	45	45
Pb	ppm	3	5	10	15	20	2.5
As	ppm	<10	<10	<10	<10	<10	<10
C	%	1.44	1.08	3.24	3.63	2.34	3.42
S	%	1.12	0.58	1.04	2.2	2.04	3.06
Al	%	6.6	7.16	5.48	5.64	4.36	6.32
Ba	ppm	510	660	105	115	185	125
Be	ppm	3	3	3	2.5	2.5	2.5
Bi	ppm	1	1	1	1.5	0.5	0.5
Ca	%	2.5	2.1	6.6	6.9	4.7	6.6
Cd	ppm	3	3	3	2.5	2.5	2.5
Co	ppm	10	5	35	40	40	35
Cr	ppm	50	20	80	50	60	30
Fe	%	3.54	1.64	8.32	9.4	7.52	9.12
K	%	1.37	0.96	0.61	0.7	1.04	0.64

Li	ppm	10	3	15	15	10	10
Mg	ppm	1.36	0.88	2.8	2.76	2.04	2.96
Mn	ppm	700	300	1500	1500	1100	1500
Mo	ppm	5	55	3	2.5	2.5	2.5
Na	%	1.49	3.39	1.28	1.18	0.64	2.44
P	ppm	500	300	700	900	700	700
Sb	ppm	0.5	0.7	0.8	0.6	1.2	2.1
Ti	%	0.26	0.18	0.9	1.14	0.84	1.2
V	ppm	110	60	240	260	234	272
Sio$_2$	%	62.8	67.2	44.6	41	51.4	37.2
Sr	ppm	440	440	280	280	200	240
Y	ppm	1	1	1	0.5	0.5	0.5

Appendix 1. Mineralogical composition of the representative samples (wt. %)

Mineral	**AS1**	**AS2**	**AS3**	**AS4**	**AS5**	**AS6**
Pyrite	3.5	2.1	3	5.9	5.1	6.73
Quartz	42.3	36.7	24.5	23.2	37.3	10.3
Ankerite-dolomite	11.7	9.1	21.7	27.6	15.4	24.9
Muscovite	22.6	15.8	8	9.4	11.6	82
Chlorite	4.1	0.2	17.4	13.9	15.2	15
Albite	8.6	33.7	11	6.2	5.6	23
Paragonite	trace	0.8	2.7	4.7	0.35	1.8
Rutile	0.9	0.5	2.6	3.4	2.6	3.9
Magnetite	0.7	trace	2.8	1.8	1.5	3.1
Chalcopyrite	trace	trace	trace	trace	trace	trace
Calcite	0.3	trace	5	2.1	3.9	3.9
Other	<5	<1	<2	<2	<2	<1