Ore characterization of LSE gold deposit in “X” Pit, Toka Tindung Project, North Sulawesi

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Abstract. Toka Tindung Project is a low sulphidation epithermal gold deposit, which is located in North Sulawesi, Indonesia. To be able to maximize the production yield of the Toka Tindung Project, it is important to understand the characteristics of the ore along with its mineral associations. This paper discusses the ore characterization and its mineral associations in “X” pit using thin section analysis to define the rock characteristics and hydrothermal alteration, X-Ray Diffraction (XRD) to identify the hydrothermal alteration minerals, and ore microscopy to identify the type of ore minerals. The study area is occupied by three alteration zones, namely silicification, advanced argillic and intermediate argillic alteration. The silicification is characterized by quartz with accessory minerals such as kaolinite, smectite, and celadonite. The advanced argillic alteration is typified by kaolinite, with minor quartz. The intermediate argillic alteration is characterized by clay minerals such as illite, mixed illite/smectite, smectite, and minor quartz minerals. Mineralization in “X” pit is in the form of sheeted vein type quartz with colloform texture, and the ore minerals are found as sulfides such as pyrite and sphalerite.

1. Introduction
Each type of deposit has different characteristics with a wide variety of ore and associated minerals. Characterization of ore minerals, ore mineral texture, and its associated minerals are several things that need to be known so that the economic minerals of a deposit can be utilized properly and optimally. The mineralogical characteristics of ore and its mineral association in an ore deposit greatly influence the extraction process and the recovery value obtained [1]. Thus, knowing deposit’s ore characteristics and mineralogy and its variation is a part of exploration activities, which has a high risk in investment perspective. This variation of ore has a great impact on technical risks associated with project evaluation, mine plan, and metallurgical unit operations [1–3]. For this reason, it is necessary to conduct a study on the characterization of ore minerals and their associated minerals at the research location so that it can support ore mineral mining activities in the future.

The research area is one of the pits in the Toka Tindung Project gold mine, namely the “X” pit with area of about 500 m long and 400 m wide. Gold deposit of the Toka Tindung Project is included in the low-sulfidation epithermal gold deposit with a gold metal resource of 1.75Moz AuEq [4,5] with gold and silver as its main ore product and is deposited in the form of quartz-adularia vein system, with host rocks consisting of Pliocene-Pleistocene volcanic rocks [5–7]. The characteristics of ore are important factors of the gold recovery that can be obtained through a specific processing method [8]. Therefore,
ore characterization in the study area is important to be done as the preliminary study for the further research.

Literature studies, field observations and laboratory analysis were then carried out to identify the texture characteristics of the ore and gold-bearing ore mineralogy at the “X” pit in Toka Tindung Project. Identification of the texture and mineralogical characteristics of the ore in the study area was obtained through several analytical methods including thin section analysis, ore microscopic analysis and X-Ray Diffraction (XRD) analysis. It is hoped that this research can produce the overall characteristics of ore minerals including ore mineral types, ore mineral textures, alteration types and associated minerals, as well as mineralization characteristics in the study area.

2. Regional Geology

The research area is located in north part of Sulawesi Island, Indonesia[7]. The processes of tectonism and volcanism in northern Sulawesi are influenced by a double subduction process in the Maluku sea plate [9] which was formed due to collision between the Australian and Pacific plates in the Oligocene (25Ma). This process also takes effects on hydrothermal magmatic mineralization in north arm of Sulawesi, including the Toka Tindung gold project.

The Toka Tindung gold project is a low sulfidation epithermal deposit that is associated with volcanic rock. According to Effendi and Bawono [10], Toka Tindung Project is included in young volcanic rocks formation that are comprised of lava, lapilli, and volcanic ash formed by several young stratovolcanic in north Sulawesi. Van Leeuwen and Pieters [7] states that the lithologies of the Toka Tindung Gold Project consists of Pliocene-Pleistocene volcanic rock which is mainly composed of basaltic andesite flow and volcanic rock layers with varying compositions from basaltic andesite to rhyodacite, and in some places is associated with hydrothermal breccias and carbonaceous tuffaceous sediments. The thickest limestone beds are found in the northern part of the Toka Tindung area. These lithology are then intruded by domes and rhyodacite dykes (Figure 1).

![Figure 1. Geological map of the Toka Tindung Project, dominated by volcanic rocks (modified from Angeles 2001 in [7]).](image-url)
Mineralization in Toka Tindung is controlled dominantly by North North West (NNW) trending faults. Other major geological structures that were formed in plio-pleistocene rocks have the East North East (ENE), North North East (NNE), and North West (NW) trends. Gold deposits in Toka Tindung were mainly controlled by NNW and ENE trending faults and manifested in the form of veins, stockwork, and hydrothermal breccias [7].

3. Methodology

The data in this study are divided into two based on how they were collected: primary and secondary data. The primary data are the data that the author collected in the field such as samples, its further analysis, while the secondary data are the data given by the company of Toka Tindung Project, such as the pit map. The primary data were taken from field observations and laboratory analysis of the surface samples of “X” pit, which were divided into two types of samples, namely vein and wallrock. Several analyses were then conducted to identify the type of ore characteristics and mineralogy in “X” pit and its association minerals, which is thin section analysis, ore microscopy, and X-Ray Diffraction (XRD).

3.1. Thin section analysis

Thin section (petrography) analysis was done to observe the mineral association and the abundance of the types of minerals. This analysis was also used to describe the host rock type, textures, alteration, and mineralization in the research area. The thin section analysis was done using polarized-light microscope to observe 12 thin section samples that were taken from “X” pit. This observation was carried out in Optical Geology Laboratory, Geological Engineering Department, Faculty of Engineering, Universitas Gadjah Mada.

3.2. Ore microscopy analysis

Ore microscopy analysis was done to 11 samples taken from the “X” pit using the reflected-light microscope for identify the opaque mineral in the research area. These ore minerals can be in form of native element, oxide, or sulfide minerals. This analysis was also used to observe the ore texture and other characteristics of the ore that can be used to understand the mineralization in the research area, particularly the ore minerals in the “X” pit. This observation was carried out in GetIn Cicero Laboratory, Geological Engineering Department, Faculty of Engineering, Universitas Gadjah Mada.

3.3. X-Ray Diffraction

XRD analysis is used to identify the type of minerals in rocks. The data collected in the XRD analysis was used to identify minerals in the rock based on a diffraction pattern called a diffractogram and written as X-ray vs 2θ (theta). This analysis was done using the qualitative method and was divided into two types of analysis, namely bulk and clay analysis including air dried, ethylene glycol immersed, and heated in 550 °C. The XRD method aims to find out mineral association in the research area, be it in the form of gangue minerals or ore minerals, mainly those which was not observed using microscopy methods. There were 4 samples used for this analysis, and the analysis was carried out using XRD machine type Rigaku Multiflex in Main Laboratory of Geological Engineering Department, Faculty of Engineering, Universitas Gadjah Mada.

4. Results

4.1. Hydrothermal alteration

Field observation shows that the research area is included in near surface low sulfidation epithermal mineralization. This causes the characteristics of hydrothermal alteration minerals in the study area in the form of minerals formed in the surface zone such as kaolinite mineral [11]. The research area is divided into three types of hydrothermal alteration based on their mineral association, namely silicification, advanced argillic, and intermediate argillic (Figure 2). The silicification alteration has
the widest distribution in “X” pit, covering the center part and the east side of the pit, while the advanced argillic alteration type is scattered to a limited extent in the graben zone and the intermediate argillic alteration type is scattered on the western edge of the “X” Pit.

The determination of the alteration type was carried out based on company data, field observations, thin section analysis, and XRD analysis. In general, it is easy to distinguish silicified alteration using thin incision analysis, given the relatively high abundance of quartz in the sample (Figure 3). However, to distinguish the types of clay minerals present in advanced argillic (Figure 4) and intermediate argillic (Figure 5) alterations, thin slice analysis needs to be supported by XRD analysis. With XRD analysis, not only clay minerals in advanced argillic alteration and intermediate argillic alterations can be identified, but also some accessory minerals in silicification alteration and opaque minerals present in the sample (Figure 6).

![Hydrothermal Alteration Map](image)

**Figure 2.** Hydrothermal alteration map of the study area (“X” pit) which shows three hydrothermal alteration zones, namely silicification, advanced argillic, and intermediate argillic.

Based on the thin section analysis, it can be observed that the silicified alteration has the same texture and structure as the original rock but has a higher level of hardness due to the intensive
addition of silica in the form of secondary quartz (Figure 3). Advanced argillic alteration in the thin sections can be observed from the abundance of clay minerals which are quite high and the texture of the original rock that cannot be observed. Similar to advanced argillic alteration, intermediate argillic alteration also consists of a high abundance of clay minerals and an almost unidentified original rock texture. To differentiate between the two, XRD analysis needs to be carried out especially to identify kaolinite minerals which are the main features of advanced argillic alteration.

**Figure 3.** Thin section analysis of sample ANK_19 W’s lapilli tuff which has undergone silicified alteration in parallel-polarised (A) and cross-polarised (B). Mineral abbreviation: Qz=Quartz, Pl=Plagioclase, Cly=Clay.

**Figure 4.** Thin section analysis of sample ANK_FS 11’s tuff which has undergone advanced argillic alteration in parallel-polarised (A) and cross-polarised (B). Mineral abbreviation: Qz=Quartz, Cly=Clay, Oxd=Oxide.

**Figure 5.** Thin section analysis of sample ANK_01’s crystal tuff which has undergone intermediate argillic alteration in parallel-polarised (A) and cross-polarised (B). Mineral abbreviation: Qz=Quartz, Pl=Plagioclase, Cly=Clay, Opq=Opaque minerals.
After conducting the XRD analysis, it is known that the silification alteration in “X” pit is characterized by quartz minerals with accessory minerals such as kaolinite, smectite, and celadonite found at several points (Figure 6A). Other than that, it is also known that the advanced argillic alteration in “X” pit is characterized by kaolinite clay mineral, with quartz present as a minor mineral (Figure 6B). Another type of alteration is the intermediate argillic alteration type which is characterized by clay minerals such as illite, mixed illite/smectite, smectite, and minor quartz and pyrite minerals (Figure 6C).

Figure 6. Hydrothermal alteration mineral association characteristics of each alteration zone: (A) silification zone, (B) advanced argillic zone, (C) intermediate argillic zone. The abbreviations in clay analysis mean AD: Air Dried, EG: Ethylene Glycol, H550C: Heated in 550 °C.
4.2. Ore mineralogy and mineralization

The mineralization system formed in the study area is a low-sulfidation epithermal deposit in the form of veins with a sheeted vein structure that extends north-south following the geological fault structure found in “X” pit (Figure 2). Ore mineralization in the study area is deposited on quartz veins with the minor presence of chalcedony, adularia, and clay minerals as gangue minerals in the vein. Other minerals associated with the quartz vein are oxide minerals such as goethite, hematite, and manganese oxide. The vein texture formed in the study area is mainly in the form of banded texture with colloform banded texture as its main texture (Figure 7A, 7B, 7C), crustiform (Figure 7D), or mixed both (Figure 7C). Other minor textures in the form of open space filling textures are also present, namely as drusy cavities, cockade, and comb texture (Figure 7A, 7B, 7C).

![Figure 7. Vein textures on “X” pit: (A) quartz vein with colloform and cockade textures with yellow-black iron oxide on the surface, (B) Colloform and drusy cavity textures with manganese oxide on the surface, (C) veins with a colloform-crustiform texture, comb, and drusy cavities, (D) quartz veins with a crustiform texture.](image)

There are very few ore minerals found in the veins, and the minerals that can be detected using the ore microscopy method in the vein are mainly in the form of sulfide and oxide minerals such as pyrite, sphalerite, and hematite (Figure 8), with a manganese oxide found at several points formed on the surface of the veins. After observing 11 samples using the ore microscopy method, it can be said that the gold minerals in the study area cannot be observed using the ore microscopy method.

The ore microscopy samples of the “X” pit are then divided based on the texture of the ore and ore minerals contained in each of these textures and observed in Table 1. In the table we can see that
pyrite is present in all of the samples and hematite almost present in all of the samples, while sphalerite and goethite are present only in ANK_21V with colloform-cockade texture, and manganese oxide only present in ANK_FS 04V with colloform-drusy cavities texture.

Table 1. Summary of vein texture and ore minerals contained in pit "X".

| Sample Number | Vein texture                  | Ore minerals                  |
|---------------|-------------------------------|-------------------------------|
| ANK_10V       | Colloform                     | Pyrite                        |
| ANK_12V       | Colloform, drusy cavities     | Pyrite, hematite              |
| ANK_13V       | Crustiform                    | Pyrite, hematite              |
| ANK_18V       | Colloform-crustiform, comb    | Pyrite, hematite              |
| ANK_21V       | Colloform, cockade            | Pyrite, sphalerite, goethite  |
| ANK_25V       | Colloform, drusy cavities     | Pyrite, hematite              |
| ANK_FS 03V    | Colloform                     | Pyrite, hematite              |
| ANK_FS 04V    | Colloform, drusy cavities     | Pyrite, hematite, manganese oxide |
| ANK_FS 05V    | Colloform                     | Pyrite, hematite              |
| ANK_FS 08V    | Colloform, cockade            | Pyrite, hematite              |
| ANK_FS 13V    | Colloform                     | Pyrite                        |

Figure 8. Ore minerals formed in “X” pit quartz veins, consist of (A) pyrite (Py) and sphalerite (Sph) in sample ANK_21V, (B) hematite (Hem) with pyrite inclusions (Py) in sample ANK_FS 05V, (C) pyrite in sample ANK_25V, and (D) pyrite in sample ANK_FS 13V.
5. Discussion
The research area namely “X” pit is a part of the Toka Tindung Project which is characterized as a low-sulfidation epithermal gold deposit [4–6]. The "X" Pit is divided into three types of hydrothermal alteration based on their mineral association, namely silicification, advanced argillic, and intermediate argillic (Figure 2). The silicification alteration has the widest distribution covering the center part and the east side of the research area dominantly composed of quartz, with some clay minerals such as kaolinite, smectite, and celadonite formed as accessory minerals. The silicified wallrock is associated with banded quartz vein mineralization (Figure 7) showing that the low sulfidation epithermal deposit in the study area formed in a shallow environment (approximately 0-300 m) [11–13]. The second hydrothermal alteration formed limited on the western edge of the “X” Pit is intermediate argillic alteration characterized by clay minerals including illite, mixed illite/smectite, and smectite, and minor quartz, and pyrite minerals. The mineral association in the intermediate argillic alteration indicates that the alteration zone is located on the side of a low sulfidation epithermal system [11,14]. The third hydrothermal alteration type is advanced argillic located limited in the graben zone consisting of dominantly kaolinite, with quartz present as minor minerals. According to Hedenquist [11], advanced argillic alteration formed on the top of the low sulfidation epithermal system, which is defined as steam-heated alteration characterized by kaolinite blanket along with cristobalite, smectite, and locally alunite and native sulfur. Mineralization in the study area formed in banded textured quartz vein mainly colloform as its main texture (Figure 7A, 7B, and 7C), crustiform (Figure 7D), or both (Figure 7C), which was identified as typical low sulfidation epithermal deposit formed in a shallow environment (approximately 0-300 m) [4–6]. The sulfide minerals that can be observed through ore microscopy are pyrite (Figure 8) and sphalerite (Figure 8A) and the abundances of these minerals are very low. The gold minerals in the study area cannot be identified in ore microscopy method. Thus, this indicates that the gold in the study area falls in the invisible gold category [1].

6. Conclusion & Recommendation
Based on the results of the integration between the data analyses that have been carried out from samples taken from pit "X", the following conclusions can be drawn:

- Mineralization in pit "X" is a low sulfidation epithermal deposit in the form of sheeted vein and characterized by the presence of quartz, illite, smectite, and chalcedony as gangue minerals, and pyrite, sphalerite, hematite, goethite, and manganese oxide as its ore minerals.
- Some of the characteristic textures of low sulfidation epithermal deposits are also present, such as banded textures (colloform and crustiform), open space filling textures (drussy cavities and comb), and cockade.
- Three types of alteration are recognized including silicification, advanced argillic, and intermediate argillic. The silicification alteration has the widest distribution in “X” pit, covering the center part and the east side of the pit with the abundance of secondary quartz as its key mineral and kaolinite, smectite, and celadonite as its minor minerals. The advanced argillic alteration type is scattered to a limited extent in the graben zone with kaolinite clay mineral, with quartz present as a minor mineral. The intermediate argillic alteration type is scattered on the western edge of the “X” pit with clay minerals such as illite, mixed illite/smectite, and smectite, and minor quartz minerals.
- Given that there’s no gold observed in ore microscopy, it can be concluded that gold in the research area is in the form of invisible gold.

Recommendation for further study:
- Since gold at the research location cannot be identified by the ore microscopy method, it is recommended that geochemical analysis and mineral mapping be carried out to determine with certainty the characteristics of the gold mineralogy in the study area.
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References
[1] Zhou J and Gu Y 2016 Geometallurgical Characterization and Automated Mineralogy of Gold Ores *Gold Ore Processing: Project Development and Operations* ed M D Adams (Elsevier) pp 95–111
[2] Moon C J, Whateley M and Evans A M 2006 *Introduction to mineral exploration* (Oxford: Blackwell Publishing)
[3] Lipton I 2017 Using Geometallurgy to Improve Mine Profitability *MGEI Geometallurgy Convention 2017* vol 9th, ed Basuki N I and Idrus A. (Yogyakarta: Masyarakat Geologi Ekonomi Indonesia) pp 5–7
[4] Williamson A 2011 Discovery and Development of Toka Tindung Low Sulphidation Epithermal Gold Project *The Sulawesi Mineral Recources 2011 Seminar MGEI-IAGI* ed N . Basuki (Manado: Masyarakat Geologi Ekonomi Indonesia) pp 259–66
[5] Moyle A J, Wake B A, Tuckey S H and Ariti J 1997 The Toka Tindung Gold Project, Northern Sulawesi, Indonesia *World Gold ’97* (Singapore) pp 27–34
[6] Wake B A, Sinugroho I A and Kuswandi M D 1997 Epithermal Gold-Silver Mineralisation in a Fosil Hot Spring System, Toka Tindung, North Sulawesi *National Seminar of Human Resources of Indonesian Geologists* (Yogyakarta: Geological Engineering, Mineral Technology Faculty UPN “Veteran” Yogyakarta) pp 1–6
[7] Leeuwen T M Van and Pieters P E 2011 Mineral deposits of Sulawesi *The Sulawesi Mineral Recources 2011 Seminar MGEI-IAGI* ed N . Basuki (Manado: Masyarakat Geologi Ekonomi Indonesia) pp 1–130
[8] Marsden J . and House C . 2006 *The Chemistry of Gold Extraction* (Littleton, Colorado: Society for Mining, Metallurgy, and Exploration, Inc. (SME))
[9] Hamilton W 1979 *Tectonics of the Indonesian Region* (U.S. Geological Survey)
[10] Effendi A C and Bawono S S 1997 Peta Geologi Lembar Manado, Sulawesi Utara 2nd Ed
[11] Hedenquist J W, Arribas R A and Gonzalez-Urrien E 2000 Exploration of Epithermal Gold Deposits *SEG Rev.*13 245–77
[12] White N C and Hedenquist J W 1995 Epithermal Gold Deposits: Styles, Characteristics and Exploration *Publ. SEG Newsfl.*1 9–13
[13] Simmons S F, White N C and John D A 2005 Geological Characteristics of Epithermal Precious and Base Metal Deposits *Econ. Geol.*100th Anni 485–522
[14] Evans A M 1993 *Ore Geology and Industrial Minerals* (Oxford: Blackwell Publishing)