Hydrothermal Alteration Associated with Vein-Type Sulphide Mineralization at Lappadata Prospect, South Sulawesi, Indonesia: A Preliminary Study

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Abstract. In Lappadata area, Bone Regency, South Sulawesi Province, Indonesia, indication of vein-type sulphide mineralization is occurred. This paper describes a recent study of the prospect which focused on hydrothermal alteration associated with the mineralization. In this study, alteration and mineralization samples have been collected selectively and representatively from the field and then analyzed in laboratory using petrography, ore microscopy, and X-ray diffraction methods. The study resulted that host rocks of the mineralization are porphyritic basalt and limestone members of the Early Eocene to Late Oligocene Salo Kalupang Formation. Hydrothermal alteration mineral assemblages include quartz, chlorite, muscovite, sericite, calcite, actinolite, epidote, illite, kaolinite, and pyrite, which generally zoned from distal-propylitic mainly characterized by chlorite, calcite and epidote to proximal-argillic characterized by sericite and illite. The mineralization occurred in quartz vein and disseminated with identified hypogene ores of sphalerite, chalcopyrite, galena, and pyrite as well as supergene ores of covellite, chalcocite, and malachite. Study of the hydrothermal alteration stability temperatures suggested that the mineralization was formed in temperature range of about 200 to 300°C, from a near-neutral pH hydrothermal fluid. The whole characteristics of hydrothermal alteration, ore and gangue minerals, mineralization types, as well as range of formation temperature and composition of the responsible hydrothermal fluid indicated that the mineralization in Lappadata prospect is an epithermal type.

1. Introduction
In Lappadata area, Bone Regency, southern part of Sulawesi Island, Indonesia, indication of vein-type sulphide mineralization is occurred, where fine-grained sulphides observed in quartz veins hosted in volcanic and sedimentary rocks. The indication was previously reported and shown in the regional geologic map of the Pangkajene and western part of Watampone quadrangles, Sulawesi, which marked by Cu symbol in Salo Kalupang Formation [1] (Figure 1). Preliminary field observation resulted that around the outcrops of the mineralization, boulders of secondary manganiferous ironstones were found scattered in places. In the most southern part of Bone Regency, South Sulawesi, which famously known as the Biru area (e.g.,[2], [3], [4]), located not far south of Lappadata area, the similar association of vein-type sulphide mineralization with secondary manganiferous ironstones (hematite and manganese) was also reported. Quartz-sulphide veins in the Biru area penetrate limestone in the same direction with hematite ore zone. The veins are discontinuous and steeply
dipping with <5 m thickness, and composed of disseminations, small blebs and veinlets of argentiferous galena, pyrite, arsenopyrite, magnetite, and minor chalcopyrite and pyrrhotite. Galena also occurs as lenses and short veins. Quartz and carbonate are the dominant gangue minerals, and alteration in form of silicification only occurs around ore body [5-7]. Currently a domestic company, PT. Wijaya Eka Sakti, conducting an exploration program (including core drilling) to test the prospect.

This paper describes a preliminary study of hydrothermal alteration associated with the mineralization in Lappadata area, which includes alteration and ore mineral assemblages, alteration zones, and estimated formation temperature of the mineralization as well as its responsible hydrothermal fluid composition inferred from sensitive stability temperature of selective alteration minerals.

![Figure 1. Geological map of Lappadata area and surroundings (cropped and modified from Ref. [1]). The sampling points near Lappadata village is the study area, which is situated around the indication of Cu-mineralization occurred in the Salu Kalupang Formation (Teos).](image)

2. Geological Background

Regional geology of Lappadata area and surroundings is shown in Figure 1. The followings are description of each lithology units in the area, from the oldest to the youngest [1]:

a. Salu Kalupang Formation (Teos); arranged by sedimentary rocks interbedded with volcanics; composed of sandstone, shale, and claystone interbedded with volcanic conglomerate, breccia, tuff, with intercalations of lava, limestone and marl; the limestone and marl contain fossils of molluscs and foraminifera; calcite veins occurred in places; in the area south of Lappadata, members of the Salu Kalupang Formation (Teos) are bedded in nearly north-south strike which parallel to the bedding strike of its limestone member (Teol), the dips are 42° and 75° to the east, respectively (Figure 1); the foraminifera assemblages indicated age of Early Eocene to Late Oligocene; the thickness is not less than 4500 m.
b. Tonasa Formation (Temt); mostly composed by limestone which includes of massive coral-, crystalline-, and bioclastics- limestone, as well as calcarenite; well bedded and intercalated with marl; the bedded limestone and marl contain fossils of foraminifera, pelecypods and gastropods; the massive limestone is strongly jointed; fossils assemblages indicated age of Early Eocene to Middle Miocene; the thickness is not less than 3000 m; intruded by sill, dike, and stock of basalt, trachyte, and diorite; in the Biru area, the limestone member of this formation is the host rock of the quartz-sulphide veins described by Widi et al. [5] and Van Leeuwen and Pieters [6,7].

c. Kalamiseng Volcanics (Tmkv); composed by lava and breccia with intercalations of tuff, sandstone, claystone, and marl; mostly basaltic and partly andesitic; dark grey to black, generally altered, amygdaloid with secondary minerals of carbonate and silicate; parts of the lava showed pillow structure; intruded by stocks of basalt, andesite, and diorite; Early Miocene in age and not less than 4250 m in thickness.

d. Walanae Formation (Tmpw); consists of sandstone interbedded with siltstone, tuff, marl, claystone, conglomerate, and limestone; bedded in northwest-southeast strike and 25° dipping to northeast (Figure 1); fossils assemblage indicated age of Middle Miocene to Pliocene; the thickness is not less than 4500 m.

e. Diorite intrusive (d); intruded the Salo Kalupang and Tonasa Formation near Lappadata village (Figure 1); generally grey in fresh color, porphyritic with amphibole and biotite phenocrysts; based on K/Ar dating, the age is Late Miocene [1,8].

3. Methods
This study generally consists of two stages, field works and laboratory works. The field works were conducted along Lappadata river, where fresh and altered rocks as wells as mineralization samples were collected selectively at each representative outcrops. During the field work, 13 samples have been collected from 8 outcrops. The samples points are shown in Figure 1.

The laboratory works performed include petrography, ore microscopy, and X-Ray diffraction (XRD) analysis. Sample preparations for microscopic analyses i.e., thin sections for petrography and polished sections for ore microscopy, as well as their observations using transmitted and reflected light polarizing microscope were performed in Optical Mineral Laboratory, Department of Geological Engineering, Hasanuddin University. For the XRD analysis, alteration and mineralization samples were pulverized to form powder and then scanned using an X-Ray diffractometer machine of Shimadzu Maxima_X XRD-7000. The diffraction patterns were recorded with scanning stage of 5-70° 2-theta. Results of the XRD scanning then subsequently analyzed using PDX-2 software from the Mineral Data Institute (MDI) combined with Impact Match! Version-3, to identify mineral species contained in the samples. The whole stages of the XRD works, from sample preparation, scanning, analysis, interpretation and identification of minerals were conducted in Laboratory of Mineral Exploration, Department of Mining Engineering, Hasanuddin University.

4. Host Rocks and Mineralization
The study resulted that host rocks of the vein-type and less disseminated mineralization in Lappadata area are porphyritic basalt and limestone (Figure 2). Field observation showed that porphyritic basalt exhibited grey to black in fresh colors and greenish in altered, fine hypocrystalline texture, and mostly composed by mafic minerals. Whereas the limestone was light grey in color, crystalline texture, and mainly composed by carbonate minerals. Based on the lithological characteristics and geographical distribution, both host rocks are the lava and limestone members of the Salo Kalupang Formation (Teos and Teol, respectively (Figure 1)). In addition, disseminated sulphides were also recognized occurred in the Diorite Intrusive (d). This unit intruded Salo Kalupang Formation along the north-northwest fault zone near Lappadata (Figure 1), thus it can be interpreted that the diorite intrusion is the hydrothermal source of the mineralizations.
Figure 2. (A) Outcrop of altered porphyritic basalt lava in Lappadata river, contains 0.1 to 0.2 cm quartz veinlets. (B) Outcrop of altered bedded limestone in Lappadata river. Argillic alteration strongly develops next to the limestone. (C) Mineralized quartz vein hosted in altered limestone, the thickness is about 2 to 3 cm. (D) Strongly altered and mineralized volcanic rocks that contains disseminated fine-grained sulphides and vuggy quartz. The fine-grained sulphides were also observed disseminated in the vuggy.

During the field works, ore minerals identified in alteration and mineralization outcrops mostly include chalcopyrite and pyrite, as well as supergene mineral of malachite. Chalcopyrite and pyrite were identified both in altered volcanic rocks (porphyric basalt) including its vuggy quartz, as well as in altered limestone. In addition, malachite was also recognized in the field, stained particularly on surfaces of weathered limestone, indicating a supergene product. Outcrops of mineralization in the field are shown in Figures 2.C and 2.D.

Under the microscope, identified hypogene ore minerals include sphalerite, chalcopyrite, galena, and pyrite. Supergene mineral covellite was also recognized, mostly distributed at the fringe of chalcopyrite and some totally replaced chalcopyrite (Figure 3.A-D). In addition, chalcocite also identified through XRD analysis. Textural analysis resulted ore mineral paragenesis as follow: sphalerite and galena are the earliest minerals; followed by chalcopyrite and pyrite; and then covellite and chalcocite; and finally malachite that formed as supergene mineral stained on surfaces of weathered limestone host rock.
Figure 3. Photomicrographs of selected polished section samples from the study area, showing ore mineral assemblages and their textural relationships: (A) Chalcopyrite fringe replaced by covellite. (B) Euhedral cubic-prismatic crystals of pyrite. (C) Granular texture of anhedral chalcopyrite and sphalerite. (D) Intergrowth texture of sphalerite and galena; fine-grained chalcopyrite scattered on early sphalerite. Abbreviations: Ccp: chalcopyrite, Cv: covellite, Gn: galena, Py: pyrite, Sp: sphalerite

5. Hydrothermal Alteration

In the study area host rocks of the mineralization were intensively altered. The altered rock samples vary in colors such as grey, green, brownish yellow, orange and white. In weakly or selectively altered samples, the protolith still can be identified through field (macroscopic) observation, and under the microscope their primary minerals can be observed easily. Whereas in the strongly or pervasively altered samples, most of the primary minerals have changed or altered to secondary minerals, the composition of their primary minerals is minor, and some can not be identified anymore. Identification of the pervasively altered samples in this study was conducted by XRD analysis.

Figures 4.A and 4.B showing two altered porphyritic basalt samples where their original colors (dark grey to black) have changed to greenish grey (Figure 4.A) and light green with brownish red stains on its surface (Figure 4.B). The green color on both samples indicated presence of chlorite as an alteration product of ferromagnesian minerals of the porphyritic basalts, mainly pyroxene. Petrographic study on the sample in Figure 4.A showed that the primary minerals still present, such as subhedral to euhedral plagioclase and pyroxene, but most of the pyroxene phenocrysts have altered to chlorite and epidote, and the groundmass altered to sericite (Figure 4.C). While sample in Figure 4.B under the microscope showed domination of chlorite and quartz, with relics of anhedral plagioclase phenocrysts; the pyroxene crystals were not observed since they have totally altered to chlorite (Figure 4.D).
Figure 4. (A,B). Hand specimen samples of altered porphyritic basalt. (C,D). Photomicrographs of altered porphyritic basalt. (E,F) Photomicrographs and XRD diffractogram of altered limestone (sample BN.IN.06.A and BN.IN.04.B, respectively). Abbreviations: Cal: calcite, Chl: chlorite, Cly: clay, Ep: epidote, Fsl: fossil, Opq: opaque, Pl: plagioclase, Px: pyroxene, Qtz: quartz, Ser: sericite.
Limestone which hosts mineralized quartz veins are generally strongly altered as well. Minerals identified macroscopically in the limestone include calcite, aragonite, and malachite. Petrography and XRD analysis indicated that mineral assemblages in the altered limestone samples include calcite, siderite, chlorite, epidote, and clay which identified as illite (Figures 4.E and 4.F).

In this study, 13 alteration samples have been analyzed from 8 locations.Alteration mineral assemblages identified from the whole samples by petrography and XRD analyses include: quartz, chlorite, muscovite, sericite, calcite, actinolite, epidote, illite, kaolinite, and pyrite. Using the hydrothermal alteration classification and terminology which generally applied in mineral exploration, e.g., [9], [10], [11], and by considering the distances of each sample locations to the mineralization zones, it was concluded that the hydrothermal alteration which relatively distal to the mineralization is propylitic type, which mainly characterized by the occurrences of chlorite, calcite, and epidote; whereas alteration proximal to mineralization is argillic type which indicated by dominant occurrences of sericite (muscovite) and illite. Mineral assemblages and alteration types as well as their relative distances to mineralization are described in Table 1. In the table, alteration mineral assemblages is arranged in order to their abundances, and the key minerals of each alteration type are marked by bolded font (Table 1).

| Sample       | Alteration minerals | Alteration types and zones |
|--------------|---------------------|-----------------------------|
| BN.IN.01     | Quartz, chlorite, muscovite | Propylitic, distal          |
| BN.IN.02     | Sericite, quartz, chlorite, calcite, muscovite | Propylitic, distal          |
| BN.IN.03     | Calcite, quartz, chlorite, pyrite | Propylitic, distal          |
| BN.IN.04.A1  | Sericite, quartz, actinolite | Argillic (sericite-illite), proximal |
| BN.IN.04.A2  | Sericite, quartz | Argillic (sericite-illite), proximal |
| BN.IN.04.B   | Calcite, chlorite | Argillic (sericite-illite + chlorite), proximal |
| BN.IN.05     | Chlorite, epidote, sericite | Argillic (sericite-illite), proximal |
| BN.IN.05.C   | Calcite, chlorite, illite | Argillic (sericite-illite), proximal |
| BN.IN.06.A   | Calcite, epidote | Argillic (sericite-illite), proximal |
| BN.IN.06.B1  | Quartz, illite, kaolinite | Argillic (sericite-illite), proximal |
| BN.IN.07     | Calcite, quartz, chlorite, illite | Argillic (sericite-illite), proximal |
| BN.IN.08.A   | Quartz, chlorite, calcite | Propylitic, distal          |
| BN.IN.08.B   | Quartz, chlorite, calcite, epidote | Propylitic, distal          |

In epithermal environment, several epithermal minerals have a sensitive stability temperatures that can be used to estimate their formation temperature and interprete their responsible hydrothermal fluid composition (pH). In this study, chlorite, epidote, illite, sericite (fine-grained muscovite), and actinolite were selected to estimate and interprete the temperature and pH, since they are sensitive-temperature minerals. Quartz, calcite, and pyrite were not chosen since they formed in wide temperature ranges, from <100°C to >300°C [10, 11]. The presence of acid mineral kaolinite which not suitable to the other alteration minerals which are generally neutral to near-neutral pH, became a consideration why kaolinite was not used in the formation-temperature estimation in this study. The presence of kaolinite together with other neutral hydrothermal alteration minerals commonly formed by overprinting of acid and near-neutral fluids [12].

Studies on hydrothermal minerals stability in epithermal environment suggested that chlorite formed in temperatu range of about 200 to 300°C, epidote about 200 to 320°C, illite 200 to 300°C, sericite 200 to 250°C, and actinolite 280 to 300°C, all formed from near-neutral hydrothermal fluids [10, 11, 13, 14]. Thus, by combining formation-temperature ranges of the five minerals, it can be estimated that mineralization in Lappadata prospect was formed in a temperature range of about 200 to 320°C, from a near-neutral pH hydrothermal fluid.
6. Conclusions

Several conclusions defined from this study include, host rocks of the mineralization are porphyritic basalt and limestone members of the Early Eocene to Late Oligocene Salu Kalupang Formation. The mineralization also genetically related to Late Miocene diorite intrusion, which is inferred as the hydrothermal fluid source. The mineralization formed in quartz veins and disseminated, with hypogene ores of sphalerite, chalcocite, galena, and pyrite as well as supergene ores of covellite, chalcocite, and malachite. Hydrothermal alteration mineral assemblages include quartz, chlorite, muscovite, sericite, calcite, actinolite, epidote, illite, kaolinite, and pyrite, which are generally zoned from distal-propylitic mainly characterized by chlorite, calcite and epidote, to proximal-argillic characterized by sericite and illite. Based on study of stability temperature of the hydrothermal alteration minerals, it is concluded that the mineralization was formed in a temperature range of about 200 to 320°C, from a near-neutral pH hydrothermal fluid. The whole characteristics of hydrothermal alteration (mineral assemblage and its spatial distribution to the mineralization), ore mineral assemblage and gangue, mineralization types, as well as estimated formation temperature and pH of the responsible hydrothermal fluid, indicated that the mineralization in Lappadata area is epithermal type. The characteristics of hydrothermal alteration, mineralization types, and the formation environment can be used to develop the prospect to the next stage and more detailed exploration.

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