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Mineralogical and Geochemical Characteristics of the Volcanogenic Massive Sulphide Deposits in Sangkaropi District, North Toraja, Indonesia

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Abstract—This paper describes an update study of the Kuroko-type volcanogenic massive sulphide deposits in Sangkaropi mineralization district, North Toraja, South Sulawesi Province, Indonesia, which focused on their associated hydrothermal alteration, ore and gangue mineralogy, as well as ore grades. Rock and mineralization samples were collected from field work to be studied using petrography, ore microscopy, X-ray diffraction, and chemical analyses of Instrumental Neutron Activation Analysis and Total Digestion Inductively Coupled Plasma methods. The study resulted that host rocks of the mineralizations were altered tuff and dacitic volcanic breccia. The mineralizations mainly occurred as massive closely-spaced disseminated sulphides, with veins, vein stockworks, and sulphide stringers. Quartz and barite were identified as the main gangues. Ore mineral assemblages include chalcopyrite, galena, sphalerite, pyrite, bornite, pyrrhotite, and covellite, with azurite and malachite as supergene minerals. Hydrothermal alteration minerals identified in clay, silicification, and altered host rocks include quartz, muscovite, halloysite, anorthite, chlorite, paragonite, and calcite, which generally consistent to the inner zones of Kuroko-type volcanogenic massive sulphide deposits alteration zones. Chemical analysis of two selected mineralization samples resulted highest ore grades of 3.5 ppm Au, 159 ppm Ag, >1% Cu, 0.49% Pb, and >1% Zn. From three localities of Kuroko-type deposits in the district, based on their ore grade characteristics, Rumanga deposit is the most promising to be detailly investigated in the future.

Index Terms—volcanogenic massive sulphide, VMS, Kuroko, ore, Sangkaropi.

I. INTRODUCTION

Volcanogenic massive sulphide or volcanic-hosted massive sulphide deposits (VMS or VHMS) are typically massive-stratiform bodies of sulphides precipitated from magmatic-hydrothermal fluids that mixed with seawater, at or immediately below the seafloor, commonly associated with submarine volcanics [1,2,3,4]. A typical type of VMS deposits, the Kuroko-type deposit, has been known distributed and clustered at Sangkaropi district which consists of three adjacent localities of mineralized bodies around the border of North Toraja- and Luwu Regency, South Sulawesi Province, Indonesia, namely Sangkaropi, Rumanga, and Bilolo deposits. The district extended about 17 km, in southwest-northeast trend. The deposits were operated in small scale mining by the Japanese during World War II. In 1974 to 1979 PT. Aneka Tambang, an Indonesia mining company, carried out a major exploration program which involved detailed shallow drilling. Later, during 1987 to 1994, Aberfoyle Company investigated the area as a part of Contract of Work exploration program. Recently, since 2006, local companies PT. Makale Toraja Mining, PT. Sangkaropi Rumanga Mining, and PT. Integra Mining Nusantara detailly explored and mined base metals in the deposits [5,6,7,8].

Three types of ore mineralization have been recognized in the district: (1) yellow ore, consists of pyrrhotite, pyrite, chalcopyrite (abundant), with less sphalerite, tetrahedrite, and enargite; (2) black ore, consists of pyrite, sphalerite, tetrahedrite, with less chalcopyrite, chalcocite, and galena; and (3) impregnated ore in form of disseminated pyrite in silicified rocks [9]. Ranges of ore grade are: 0.18 to 21.16% Cu, 2.27 to 25.31% Pb, 0.41 to 37.30% Zn, and 0.51 to 10.61% Fe. The mineralization deposited in temperature about 280°C, at a sea depth of not less than 640 m; mainly developed in contact zones between rhyolitic tuff-lava unit and underlying andesite unit [5]. The Kuroko-type VMS deposits in Sangkaropi district was inferred to be formed in Oligocene, about 35 to 22.5 ma [10].

This paper describes an update study of the VMS deposits in Sangkaropi district which focused on their mineralogical and geochemical characteristics, by performing field and laboratory
works as well as analytical studies of altered host rocks and ore mineralization samples.

II. GEOLOGY OF THE SANGKAROPI DISTRICT

Regionally, the Sangkaropi district and surroundings were arranged by Tertiary rock units of: Oligocene to Early Miocene Lamasi Volcanics which consists of andesitic-dacitic tuff, lava and volcanic breccia intercalated by calcareous sandstone and shale (Toml), and its limestone and marl members (Tomc); Early to Middle Miocene Riu Formation composed by marl, limestone, shale, calcareous sandstone with intercalations of claystone and tuff (Tmr); and Late Miocene to Pliocene layers. (4) Acidic tuff; composed of acidic tuff, tuff breccia, breccia and clay; the breccia contains fragments of dacite, granite, andesite, and pumice. (5) Rhyolitic pyroclastics and lava; massive and mainly composed of rhyolitic to dacitic tuff, breccia and lava; altered and silicified; about 80 m in maximum thickness. (6) Basalt and clay; exposed only around Sangkaropi deposit; basalt is dark green to black in fresh, and dark brown in altered; claystone is grey to dark grey; in contact to ore deposit, silicification and brecciation were observed in claystone. (7) Calcareous shale; composed of shale and clay which contains foraminiferan fossils. (8) Andesitic lava and pyroclastics; andesite lava is green and massive; andesitic pyrolastic rocks consist of volcanic breccia and tuff breccia with small amounts of clay and silicified rocks [5] (Fig. 1).

Locally, there are eight units of Tertiary rocks distributed in the district, which from older to younger are as follow: (1) Granitic rock; exposed in the northern part of Sangkaropi deposit; massive and phaneritic; consists of quartz, alkali feldspar, plagioclase, and mafic minerals; cut by quartz veinlets and altered by argillichitization, sericitization and chloritization. (2) Andesitic tuff breccia; mainly consists of andesitic tuff breccia and lapilli tuff which intercalated by sandy tuff, fine tuff, claystone, and silicified rocks; graded bedding structure exposed near Rumanga deposit. (3) Dacite; green; altered; distributed on the top of the andesitic breccia as flow layers. (4) Acidic tuff; composed of acidic tuff, tuff breccia, breccia and clay; the breccia contains fragments of dacite, granite, andesite, and pumice. (5) Rhyolitic pyroclastics and lava; massive and mainly composed of rhyolitic to dacitic tuff, breccia and lava; altered and silicified; about 80 m in maximum thickness. (6) Basalt and clay; exposed only around Sangkaropi deposit; basalt is dark green to black in fresh, and dark brown in altered; claystone is grey to dark grey; in contact to ore deposit, silicification and brecciation were observed in claystone. (7) Calcareous shale; composed of shale and clay which contains foraminiferan fossils. (8) Andesitic lava and pyroclastics; andesite lava is green and massive; andesitic pyrolastic rocks consist of volcanic breccia and tuff breccia with small amounts of clay and silicified rocks [5] (Fig. 1).

III. METHODS

This study consists of two main stages, field works and laboratory works. The field works were carried-out in and around the Sangkaropi VMS deposit district, where altered rock, as well as alteration and mineralization samples were collected randomly, selectively, and systematically from outcrops, adits, and pits. The laboratory works included petrography, ore microscopy, X-ray diffraction (XRD) analysis, and chemical analysis. Sample preparations for the microscopic studies, i.e., thin sections for petrography and polished sections for ore microscopy, as well as their observations using transmitted- and reflected light microscope, were performed in Optical Mineral Laboratory, Department of Geological Engineering, Hasanuddin University. For the XRD analysis, 13 selected powdered alteration and mineralization samples were sent to be identified their mineral assemblages in Research and Development Centre of Mineral and Coal Technology (Puslitbang Tekmita) Bandung. The objective of the chemical analysis was to measure concentrations or ore grades of five selected metals: gold, silver, copper, lead, and zinc. For this, two selected mineralization samples were sent to be prepared and analyzed in a commercial research laboratory, PT. Intertek Utama Services, Jakarta. The gold grade was determined by INAA (Instrumental Neutron Activation Analysis) method, silver by combination of INAA and TD-ICP (Total Digestion Inductively Coupled Plasma) method, and the base metals by TD-ICP method.

IV. RESULTS AND DISCUSSIONS

A. Characteristics of Ore Bodies

As mentioned, there were three Kuroko-type VMS deposits clustered and distributed in southwest-northeast trend in the Sangkaropi district: Sangkaropi deposit at the southwest, Rumanga deposit at the centre, and Bilolo deposit at the northeast (Fig. 1). During the field work, a detailed field observation, measuring section and sampling has been carried out from the lower part (footwall) to the top of ore bodies of the three deposits.
The Sangkaropi main ore body was about 150 m wide and subhorizontally extended in east-west trend (N290°E strike), with 60 m thickness from bottom to the top (Fig. 2.A). The ore body was concordantly cuts stratigraphic units of the host rocks of mainly dacitic breccia. A basalt dike was found at the northern part of the ore body, intruded the dacitic breccia host rock. The host rocks were generally fragmented with dacite and rhyolite were the main fragments, and ore minerals distributed clusterly above the host rocks. At the lower part of the ore body (footwall), the fragmented volcanic host rocks were exposed; and in the upper part, from 15 m to the top, disseminated chalcopyrite, galena, sphalerite, pyrite, and barite in altered massive and fragmented host rocks were observed (Fig. 2.B and 2.C) accompanied by quartz and barite veins and stockworks. Spots of supergene minerals azurite and malachite were abundantly found on surface of the ore body, indicating weathering of copper-bearing minerals (Fig. 2.B). Sulphide stockworks and stringers were found developed in altered dacitic tuff in a stream northeast of the Sangkaropi ore body, which indicating the altered lower part of the ore body [12,13,14]. Under the microscope, intergrowth and replacement textures were recognized in samples from Sangkaropi. Fig. 2.D shows the intergrowth of sphalerite, galena, chalcopyrite and pyrite.

The Rumanga main ore body was about 8 m wide and subhorizontally extended in east-west trend (N85°E strike), with 6 m thickness from bottom to the top. The ore body was concordantly cuts stratigraphic units of the host rocks of dacitic breccia, tuff, and marl. The volcanic breccia host rocks were generally fragmented with dacite was the main fragments, and ore minerals distributed clusterly in the host rocks. In Rumanga deposit, dacitic breccia fragments, and ore minerals distributed clusterly in the host rocks west trend (N290°E strike). The ore body was concordantly cuts stratigraphic units of the host rocks of dacitic volcanic rocks and marl. The lower part of Bilolo ore body was arranged by tuff. The central and particularly top parts of the ore body were dominated by barite and quartz gange associated with massive disseminated sulphides of pyrite, chalcopyrite, sphalerite, galena, pyrrhotite, and covellite; vein stockworks identified as well. Under the microscope, indications of galena, pyrrhotite, and covellite formed as late-stage minerals were observed, where some galena occurred as open-space filling (veinlets), pyrrhotite replaced chalcopyrite, and secondary covellite replaced chalcopyrite fringes (Fig. 2.F).

Fig. 2. (A) Morphology of Sangkaropi ore body, looking northeast. (B) Outcrop of Sangkaropi ore body, showing fragmented dacitic breccia host rock on the footwall, and massive sulphide ore on the upper part; supergene products of bluish azurite and greenish malachite are shown on the left-upper part of the outcrop. (C) A boulder of Sangkaropi “black ore” (“kuroko”) which consists of disseminated fine- to medium grained sphalerite, galena, chalcopyrite, and pyrite. (D) Photomicrograph of Sangkaropi mineralization sample, showing ore mineral assemblage of sphalerite (Sp), galena (Gn), chalcopyrite (Ccp), and pyrite (Py). (E) Photomicrograph of Rumanga sample, showing fine-grained disseminated chalcopyrite and bornite (Bn). At the left side, bluish covellite (Cv) replaced surfaces of chalcopyrite. (F) Photomicrograph of Bilolo sample, showing chalcopyrite, galena, and pyrite scarcely disseminated in barite (Brt) gangue. A chalcopyrite grain replaced by pyrrhotite (Po) in its central part and covellite at the fringe, is shown on the left side of the picture.
B. Hydrothermal Alteration and Gangue

Based on field and microscopic observations, the VMS ore mineralizations in Sangkaropi district were mostly found associated with quartz and barite gangues. Quartz occurred either as crystalline disseminated grains associated with ore minerals, and as veins and vein stockworks which irregularly distributed in the mineralized bodies. While barite formed as disseminated grains and veins which closely associated with ore minerals (Fig. 3.A), and as a layer on top of ore bodies. During field work, numbers of hydrothermal alteration outcrop were found around or adjacent to ore bodies of the Sangkaropi district (Fig. 3.B and 3.C). For identification of hydrothermal alteration and gangue mineral assemblages, thirteen selected altered host rocks as well as pervasive alteration (clay) and mineralization samples were collected from the three deposits and surroundings during the field work, to be analyzed using XRD method. List of the samples and their mineral assemblages are shown in Table I.

![Fig. 3.](image)

**TABLE I. ALTERATION AND GANGLUE MINERAL ASSEMBLAGES IDENTIFIED BY XRD**

<table>
<thead>
<tr>
<th>No</th>
<th>Sample code</th>
<th>Sample source</th>
<th>Mineral assemblages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S.01.SKR.G</td>
<td>Clay, Sangkaropi</td>
<td>Quartz, muscovite, halloysite</td>
</tr>
<tr>
<td>2</td>
<td>K.S.01.UL.E</td>
<td>Clay, Sangkaropi</td>
<td>Quartz, chlorite, paragonite</td>
</tr>
<tr>
<td>3</td>
<td>Z.S.01.UL.A</td>
<td>Clay, Sangkaropi</td>
<td>Quartz, muscovite, anorthite</td>
</tr>
<tr>
<td>4</td>
<td>K.S.02.UL.M</td>
<td>Clay, Rumanga</td>
<td>Quartz, halloysite, anorthite</td>
</tr>
<tr>
<td>5</td>
<td>S.11.WLN.K</td>
<td>Clay, Bilolo</td>
<td>Quartz, muscovite, anorthite</td>
</tr>
<tr>
<td>6</td>
<td>S.21.WLN.I</td>
<td>Clay, Bilolo</td>
<td>Quartz, calcite</td>
</tr>
<tr>
<td>7</td>
<td>S.06.SKR.C</td>
<td>Altered tuff, Sangkaropi</td>
<td>Quartz, muscovite, halloysite</td>
</tr>
<tr>
<td>8</td>
<td>Z.S.02.HL.H</td>
<td>Altered tuff, Sangkaropi</td>
<td>Quartz, halloysite</td>
</tr>
<tr>
<td>9</td>
<td>S.13.WLN.B</td>
<td>Altered dacitic breccia, Bilolo</td>
<td>Quartz, muscovite, anorthite</td>
</tr>
<tr>
<td>10</td>
<td>S.19.WLN.D</td>
<td>Altered tuff, Bilolo</td>
<td>Quartz, anorthite</td>
</tr>
<tr>
<td>11</td>
<td>S.31.WLN.J</td>
<td>Silicification, Bilolo</td>
<td>Quartz</td>
</tr>
<tr>
<td>12</td>
<td>TOP.RMG.MTS.L</td>
<td>Barite layer on top of ore body, Rumanga</td>
<td>Barite</td>
</tr>
<tr>
<td>13</td>
<td>TOP.ORE.RMG.F</td>
<td>Top of ore body, Rumanga</td>
<td>Quartz, pyrite</td>
</tr>
</tbody>
</table>

In general, the mineral assemblages identified from all samples include quartz, muscovite, halloysite, chlorite, paragonite, anorthite, calcite, pyrite, and barite (Table I). Based on the sample locations relative to ore bodies and the mineral assemblages they contained, generally the distribution of the hydrothermal alteration is consistent to the inner zones of the typical Kuroko-type VMS alteration zones [15]. There are four main zones of alteration in and around Kuroko-type deposit, which from the margins towards the core of the mineralization, are as follow: Zone I, characterized by assemblage of montmorillonite + zeolite + cristobalite; Zone II, consists of sericite + sericite-montmorillonite + Fe-Mg chlorite + albite + K-feldspar + quartz; Zone III, characterized by clay alteration within and around the mineralization, and contains sericite + interstratified montmorillonite + sericite + Mg-chlorite and quartz; Zone IV, surrounds the central part of the mineralized body and it displays strong silicification, with quartz + sericite + Mg-rich chlorite [15]. The alteration zoning was illustrated in Fig. 4 [16].

![Fig. 4.](image)
Montmorillonite, zeolite, cristobalite, albite and Kfeldspar, the main minerals of zones I and II, were not recognized from the samples analyzed (Table I). Most of the clay samples were collected around the ore bodies in the district (samples number 1 to 6 in Table I), where the mineral assemblages generally represent the zone III. Quartz and chlorite, two of the main minerals of the zone, were identified; while sericite, the fine-grained mica, was represented by muscovite and paragonite. In shallow environment, halloysite occurs mainly as a supergene weathering product [17], thus it is possible that halloysite in the area was formed by weathering. The presence of anorthite and calcite may indicates the Ca-bearing minerals, mainly feldspar, in the pre-altered host rocks. Thus, in general, the clay samples represent zone III alteration which distributed around the periphery of the ore bodies, as illustrated in Fig. 4.

The other seven samples were collected in the ore bodies (samples number 7 to 13 in Table I). The first five samples which were taken from strongly altered host rocks and silicification zone in Sangkaropi and Bilolo mineralizations, mainly consist of quartz accompanied by muscovite, halloysite, and anorthite. This is typical for zone IV, where silicification (quartz) and sericite (muscovite) are the main characteristics. The rest two samples were taken on the top of Rumanga ore body, from barite layer (sample code TOP.RMG.MTS.L), and from ore mineralization (sample code TOP.ORE.RMG.F.), which indicates the gangue quartz and pyrite ore (Table I). The distribution of this alteration zone, zone IV, which surrounds the central part of the mineralized body, can be seen in Fig. 4.

C. Ore Grade Characteristics

Two mineralization samples were chemically analyzed by methods described in Chapter III, to measure their ore (Au, Ag, Cu, Pb, and Zn) grades, one sample from Sangkaropi and one sample from Rumanga ore bodies. The detection limits of the analysis for each elements are as follow: Au 5 ppb, Ag 0.5 ppm, Cu 1 ppm, Pb 5 ppm, and Zn 1 ppm. The results are (respectively for Sangkaropi and Rumanga): 0.23 and 3.5 ppm Au, 3.2 and 159 ppm Ag, 0.23 and > 1 % Cu, 0.49 and 0.44 % Pb, and > 1 and 0.85 % Zn. This figure shows that Rumanga deposit contains a significant concentration of gold (3.5 ppm). This is not a common feature for VMS deposits world wide, which are generally dominated by base metals, and less contain gold and silver [3]. The Kuroko deposits in Hokuroku district (Japan) also not characterized by significant concentrations of gold and silver, all the eight large deposits were only mined for their base metals, particularly copper [18]. For the base metals, Rumanga deposit is also characterized by higher concentration of copper with respect to Sangkaropi deposit, while the concentrations of lead and zinc are averagely similar. This ore grade characteristics suggests that Rumanga deposit is more promising to be detailly investigated in the future.

V. CONCLUSIONS

The study revealed that host rocks of the kuroko-type VMS deposits in Sangkaropi district were mainly altered tuff and daitic volcanic breccia. Individual ore bodies were generally extended in east-west trend, where the ore zone overlying the volcanic-hosts footwall. Mineralizations in the ore zone mainly occurred as massive closely-spaced disseminated sulphides, which generally consist of sulphides ore of chalcopyrite, galena, sphalerite, pyrite, bornite, pyrrhotite, and covellite, with supergene minerals of azurite and malachite, in quartz and barite gangues. Hydrothermal alteration minerals identified in clay, silicification, and altered host rocks include quartz, muscovite, halloysite, anorthite, chlorite, paragonite, and calcite, which generally consistent to the inner zones of the Kuroko-type volcanogenic massive sulphide deposits alteration zones. From three localities of Kuroko-type deposits in the district, based on their ore grade characteristics, Rumanga deposit is the most promising to be detailly investigated in the future, considering its significant grade of gold and copper.

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