Geology, hydrothermal alteration and mineralization of the Carlin-type gold deposit at South Ratatotok, Southeast Minahasa Regency, North Sulawesi Province, Indonesia

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Abstract. South Ratatotok in North Sulawesi, Indonesia is one of the regions that was once a gold-producing region in North Sulawesi. Mesel gold deposit in this region is approved as Carlin type gold deposit with a total of resources of 12.25 Mt @ 5.21 g/t Au. Near the Mesel deposit, gold mineralization is currently discovered prospects such as Leon, Bulex Hill, Heind's Find and Monkey Forest. This study is aimed to elucidate the types and distribution of hydrothermal alteration and ore mineralization encountered in these four prospect areas. Research methods including field work (including geological and hydrothermal alteration mapping, rocks and ore sampling) and various laboratory works consisting of petrographic analysis, ore microscopy, X-Ray Diffraction (XRD) and fire assay were performed. As a result, the study area is composed of several lithological units including limestone, volcanic breccia, porphyritic andesitic intrusion units as well as colluvial deposit. The wall rocks have been suffered by various hydrothermal alteration as follows: silicification in limestone, carbonatization in volcanic breccia, argillic alteration in volcanic breccia and propylitic alteration developed in porphyritic andesitic intrusion, minor decarbonatization associated with limestone and minor oxidation in volcanic breccia. Gold mineralization is present as a replacement type in very fine size of sulphides and gold is closely associated with silicified limestone. Ore chemistry by fire assay analysis indicates that gold and silver contents vary from 0.012 g/t to 2.41 g/t Au, and <0.5 g/t to 2.1 g/t Ag, respectively. The increase of gold content is geochemically followed by high values of Ag, As, Sb, Cu, Pb, Zn and by low value of Hg because of oxidation. Supergene process was also the key factor in the enrichment of gold where the oxidized ore has relatively higher gold grade than in non-oxidized ore.

1. Introduction
Fifteen magmatic arcs are identified in Indonesia which have a total extent of over 15,000km². Of these arcs, only six arcs of Mid-Tertiary or younger age that contain the precious (gold and silver) and base metals (particularly copper) in Indonesia (Carlile and Mitchel, 1994). These six major Neogene mineralized magmatic arcs are the Sunda-Banda, Central Kalimantan, Sulawesi-East Mindanao, Halmahera, Irian Jaya Continental arc and Medial Irian Jaya arc. The Sulawesi-East Mindanao is well known arc that produces gold in different deposit types, particularly in the North Sulawesi.

South Ratatotok area is one of the regions that were once a gold-producing region in North Sulawesi (Garwin et al., 2005; Maryono, et al., 2014). Mesel gold deposit located in this area is approved as or similar to Carlin type gold deposits (Sillitoe, 1994; Hofstra and Christensen, 2002; van Leeuwen and Pieters, 2011), with a total of resources of 12.25 Mt @ 5.21 g/t Au (Turner et al., 1994).
and had been mined by PT. Newmont Minahasa Raya (PT NMR). Near the Mesel deposit, gold mineralization is also discovered in several prospects such as Leon, Bulex Hill, Heind's Find and Monkey Forest (Fig. 1). The Leon and Bulex Hill prospect are located in PT Sumber Energy Jaya (PT SEJ) concession. To conceive gold deposit characteristics in these four prospects, conducting detail scale (1:25.000) geological mapping regarding alteration and ore mineralization is required, therefore this study is aimed to elucidate the types and distribution of hydrothermal alteration and ore mineralization in this area. It is expected that the result would be important for a better understanding of the genesis of the gold mineralization especially hosted by sedimentary rock (limestone) and would be useful in designing future exploration strategies for gold deposits in Indonesia.

![Figure 1. Location map of research area and prospects](image)

2. Research Methods
This study is conducted in four stages including desk study, fieldwork, laboratory work, data processing and interpretation. Fieldwork stage consist of mapping of surface geology, hydrothermal alteration and ore mineralization, including sampling of representative rock types, altered rocks and gold-bearing ore. Laboratory works include analysis of mineralogy (petrography, ore microscopy and X-ray diffraction) and ore chemistry using fire assay. A total of 20 selected samples of fresh/least-altered and altered rocks was analysed by transmitted-light microscope. Ore microscopy was performed using reflected-light microscope for a total of 15 selected ore samples. X-ray diffraction both bulk and clay analysis were done for 5 argillic-altered samples. Mineralogical analysis was done at Department of Geological Engineering, Universitas Gadjah Mada, Yogyakarta, while ore chemistry was conducted using FA-AAS and ICP-MS at ALS laboratory, Canada.

3. Results and Discussion
3.1. Geology
The research area is composed of several rock units, which from relatively oldest to youngest are limestone, volcanic breccia and porphyritic andesitic intrusion units as well as colluvial deposit (Fig. 2). The limestone unit that had been silicified is the host of the gold mineralization in the research
area. This unit is a part of the Early Miocene to Middle Miocene Ratatotok limestone formation (Effendi and Bawono, 1997). In some places, volcanic breccia unit that is found near the silicified limestone is intensively altered to argillic style, while the porphyritic andesitic intrusion had been suffered by propylitic alteration.

There are two geological structures found in the study area, including shear joints and strike slip faults i.e., dextral strike slip fault and interpreted dextral strike slip fault (Fig. 2). Commonly, the fracture in shear joint structures has been filled by calcite vein. The direction of main stress forming the geological structures for both shear joints and NE-SW dextral slip fault is similar. That is relatively NW-SE direction (Fig. 3). Due to the existence of calcite in the fractures and the absence of ore body following these structures, so that both shear joints and dextral strike slip fault may not be a syn-mineralization structures, but they are interpreted as post-mineralization structures.

Figure 2. Geological map and geological profile (A-B and C-D) of the study area
Figure 3. Main stress analysis for shear joint structure filled by calcite vein (a) and main stress analysis for dextral strike slip fault (b)

3.2. Hydrothermal alteration

Four main alteration zones (Fig. 4) are identified including (a) silicification alteration typified by quartz (Fig.5a), (b) carbonatization characterized by the presence of calcite mineral and calcite vein/veinlet (Fig.5b), (c) propylitic alteration typically composed of chlorite – pyrite (Fig.5c) and argillic alteration represented by clay minerals such as illite-smectite mixed layer (Fig.5d),

Figure 4. Hydrothermal alteration map and cross section of the research area
Figure 5. (a-c) Photomicrograph of rock samples that experience silicification, carbonatization and propylitic alteration, respectively, in cross polarized light. (d) Typical volcanic breccia that undergo argillic alteration. Abbreviation= Cal: calcite, Cal vein: calcite vein, Chl: chlorite, Cly: clay minerals, Hb: hornblend, Hem: hematite, Opq: opaque minerals, Oxd: oxide minerals, Pl: plagioclase, Py: pyrite, Qz: quartz, Sec. Qz: secondary quartz,

On an outcrop scale, decalcification alteration is found in limestone that contact with volcanic breccia. This kind of alteration is characterized by the shortage of carbonate content in limestone and by the appearance of rhombic-shaped dolomite (Fig. 6). The small carbonate content in this alteration can be easily identified because it shows relatively weaker reaction as reacted to 0.1M HCl solution. Another minor alteration is oxidation which is typified by several oxide minerals such as hematite and goethite. Base on the alteration map, it indicates that alteration zones hosting ore mineralization in Monkey Forest, Leon and Bulex Hill prospects somehow follow the NE-SW, NW-SE, and N-S trending structures, respectively. Otherwise, these structures are considered as the controlling factor for ore mineralization in the research area along with lithology types.

Figure 6. (a) Decarbonatization alteration in limestone and (b) its photomicrograph in cross polarized light. Abbreviation= Cal: calcite, Cal-Dol vein: calcite-dolomite vein, Opq: opaque minerals, Crys. Foram: crystallized foraminifera.

3.3. Ore mineralization
The Mineralization style in the research area is unique. Quartz veins are rare. Quartz in vugs (Fig. 7a) are found in several places. Ore mineralization is associated with all types of alterations. Base on ore microscopic analysis, ore minerals encountered in research area are pyrite, marcasite and arsenopyrite
(Fig. 7b). Other ore minerals, such as realgar, stibnite, orpiment, hematite and goethite are also found. Gold mineralization is only situated in silicified limestone (silicification alteration) and is not observable through ore microscopic analysis. However, it appears in fire assay analysis results of 7 selected ore samples ranging from 0.012 g/t Au to 2.41 g/t Au, whereas the silver content varying from <0.5 g/t Ag to 2.1 g/t Ag (Table 1). High gold content is associated with silicification alteration and would be the highest if it is oxidized. The increase of gold content is geochemically followed by high values of Ag, As, Sb, Cu, Pb, Zn and by low value of Hg because of oxidation (Table 1 and Fig. 8). Late-stage realgar, orpiment and stibnite that are probably accompanied by calcite and gypsum occur closer to the center of mineralization as fracture and vug filling (Fig. 9).

![Figure 7](image-url) Quartz and arsenopyrite in vug (a) and typical ore minerals found in silicified limestone (b) under reflected microscope. Abbreviations: Qz = quartz, Apy = arsenopyrite, Mrc = marcasite, and Py = pyrite.

| Sample Code | Hydrothermal Alteration   | Metal (ppm) | Au  | Ag  | As   | Sb   | Cu  | Pb  | Zn  | Hg  |
|-------------|---------------------------|-------------|-----|-----|------|------|-----|-----|-----|-----|
| S85 BG      | Least altered             |             | 0.012 | <0.5 | 70   | 0.93 | 6   | <2  | 7   | 5.61 |
| S94E        | Decarbonisation           |             | 0.015 | <0.5 | 36   | 5.05 | 6   | <2  | 6   | >25.0 |
| GBGT*       | Silicification            |             | 1.784 | 2.025 | 1566 | 96.79 | 17.25 | 13.5 | 26.75 | 6.021 |
| S61 BGT OXD | Silicification and oxidation |         | 2.41 | 2.10 | 195  | 46.30 | 10  | 19  | 22  | 0.156 |

*average grade from samples of S41, S61 BGT, S94C and S123 BGT

![Figure 8](image-url) Correlation between gold grade and other metals ($R^2$ = correlation coefficient)
Figure 9. Typical mineralized outcrop in research area (a) and the occurrence of late stage stibnite, realgar and orpiment as vug filling (b and c)

Base on the mineral assemblages and occurrences as well as relative forming temperature of secondary minerals by Corbett (2017), four stages of ore mineralization in the research area are developed as shown in Table 2. The mineralization stages consist of (a) early stage (decarbonisation and minor gold mineralization), (b) main stage (silicification alteration and main gold mineralization), (c) late stage (argillic, carbonatisation and propylitic alteration), and (d) supergene (oxidation).

Table 2. Ore and gangue mineral paragenetic sequences of alteration and mineralization in the research area

| Hydrothermal Alteration | Mineralization Stages |
|-------------------------|------------------------|
|                         | Early | Main | Late | Supergene |
|                         | Decarbonisation | Silisification | Argillic Carbonatisation | Propylitic | Oxidation |
| Ore Minerals             |        |      |      |           |
| Gold                    |        |      |      |           |
| Pyrrt                   |        |      |      |           |
| Arsenopyrite             |        |      |      |           |
| Marcasite               |        |      |      |           |
| Stibnite                |        |      |      |           |
| Realgar                 |        |      |      |           |
| Orpiment                |        |      |      |           |
| Hemsitite               |        |      |      |           |
| Goethite                |        |      |      |           |
| Gangue Minerals          |        |      |      |           |
| Quartz                  |        |      |      |           |
| Calcite                 |        |      |      |           |
| Dolomite                |        |      |      |           |
| Gypsum                  |        |      |      |           |
| Chlorit                 |        |      |      |           |
| Kaolinite               |        |      |      |           |
| Mix illite/smectite     |        |      |      |           |
| Mix chloride/smectite   |        |      |      |           |
| Corrensite              |        |      |      |           |

| Abundant | Moderate | Less Abundant |
|-----------|----------|---------------|
|           |          |               |
4. Implication for exploration
The Carlin-type gold mineralization in South Ratatotok region hosted by sedimentary rock (limestone) of the Early – Middle Miocene Ratatotok limestone formation is one of the known gold deposits in Ratatotok District, which was previously mined by small-scale miners in the region. Lithology and geological structure have become the main geological factors controlling the formation of gold mineralization. Due to the difficulties in finding quartz vein on the surface and the presence of gold in very fine size, identifying the silicified limestone have to be the main priority for the future exploration in this area. Moreover, a careful study on the deposit geology, hydrothermal alteration, and ore characterization is crucial for an economic evaluation of the deposit since resulted maps and ore deposit characteristics are needed for designing an effective exploration program of this gold deposit type as a new primary gold resource in Indonesia.

5. Conclusions
Two significant factors controlling the formation of hydrothermal alteration and ore mineralization are NE-SW, NW-SE, and N-S trend structures and lithology such as limestone and volcanic breccia. Hydrothermal alteration and ore mineralisation types including decarbonatisation (early stage), silicification alteration and gold mineralization (main stage), as well as argillic, carbonatisation and propylitic alteration (late stage), and the latest supergene (oxidation) are identified. The sedimentary rock (limestone) that host gold mineralization in the research area could be a new target for gold exploration in Indonesia, particularly in another area of the region that have similar geologic and structural setting.

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