Spatial and temporal constraints of leached Cu-Au porphyry shoulder high-sulfidation epithermal deposit: insight from new discovered Kumbokarno Prospect, Trenggalek District, East Java

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Abstract. We conduct microscopic and microprobe quantitative analyses to confine characteristics of the newly found Cu-Au high sulfidation deposit which interestingly seems to highly associate with the presence of iron oxide-hydroxide complex. The resulting paragenesis shows four generation phases, which are magmatic, deep hypogene, shallow hypogene, and supergene. The alteration pattern suggests presence of a concealed intrusion which ascends the hypogene mineralization forming-fluid. Quantitative microprobe analysis shows enrichment of copper and gold in various types of iron oxide-hydroxide texture. A unique repetitive pattern of high and low copper concentration is found overlaps with goethite-hematite band of colloform texture. An interesting pattern between gold and titanium is also found as gold is almost exclusively located inside or near Fe-rich leucoxene. We propose a model of leached Cu-Au porphyry shoulder high-sulfidation epithermal deposit system to explain the prevalent condition of Kumbokarno Prospect where intensive late oxidation acts as the main process of metal concentration.

1. Introduction
Looking from the scope of mineral resources, there are two potentially economic arc in southern Java. Those are Mio-Pliocene volcanic arc and Plio-Pleistocene volcanic arc.[1] Plio-Pleistocene volcanic arc is proven to be economically productive in which some of the world-class Cu-Au deposits, such as Tumpangpitu and Batuhijau, are found spreading from eastern Java to Nusa Tenggara Archipelago. On the contrary, the Mio-Pliocene volcanic arc is less explored but nevertheless contains potentially economic Cu-Au deposits which are yet to be discovered.

Kumbokarno Prospect is a part of Mio-Pliocene volcanic arc which is located in Trenggalek District, East Java. Antam East Java Regional Mapping Program (unpublished data) reports 5.26 ppm Au, 1240 ppm Cu, and 294 ppm Mo in a totally oxidized vuggy quartz sample and determines the location as a high-sulfidation epithermal deposit. Copper and gold content of this deposit are one of the highest among other high-sulfidation deposits along the arc which respectively are second only to Gunung Tukung (1970 ppm Cu) and Gunung Gembes (33.16 ppm Au). It should also be noted that Gunung Tukung has much lower Au content (1.91 ppm) and there is no significant Cu concentration in Gunung Gembes. Therefore, the significant content of both copper and gold in Kumbokarno underlines its high potential resource.
There are still minimum data regarding this deposit, whereby simple alteration mapping and microscopic analysis, for examples, even have not been done. Data resourcefulness from diverse and integrated perspectives are needed to uncover the full potential of this deposit. This research offers data diversity and model integrity where microscopic analysis accurately identifies the paragenetic sequence of hydrothermal component and microprobe analysis detects the concentration of copper and gold in a detailed textural constraint. Unveiling this deposit genesis means adding further explanation to the general characteristic of potentially-explored Mio-Pliocene volcanic arc deposit system of southern Java.

2. Regional Geology
Kumbokarno Prospect is physiographically included in Southern Mountain Zone[2] which is an uplifted block of the southern part of Java. Generally, this zone is composed of two main lithology, which are carbonate rock and volcanic rock. The carbonate rock makes a karstic morphology and volcanic rock creates a rugged volcanic terrain. The prospect itself is a part of the rugged volcanic terrain.

More locally, the prospect is located inside Tulungagung Geological Map.[3] The location is composed of two rock formation (figure 1). The oldest is Mandalika Formation which consists of volcanic breccia, lava and tuff, and intercalations of sandstone and siltstone. This formation is intruded by intrusive rock complex of diorite, dacite, and andesite. This volcanic rock complex then are overlain by sandy sediment which grain apparently comes from the surrounding rugged hills as its composition is similar with the prospect.

Figure 1. Left: part of Tulungagung Map. Red box is the research location. Right: stratigraphic section of the prospect. Red box is the position of the prospect. In this box, yellow, orange, and pink column respectively represents Arjosari Formation, Mandalika Formation, and intrusive rocks.
The prospect is associated with three trends of structures, which are NE-SW trending sinistral strike-slip, NW-SE trending dextral strike-slip, and E-W trending normal dip-slip faults. There has not been a detailed structural mapping inside the location. Thus, the structural information of this prospect is minimum.

3. Research Methodology

This research includes two main methods, which are geological mapping and laboratory analysis. The geological mapping is done in a scale of 1:25,000. Two activities are done in this method, which are the mapping itself and rock sampling. The mapping results in three maps, those are geomorphological map, geological map, and alteration map. For discussion accuracy, the maps shown in this paper are only geological and alteration map. Rocks are dominantly sampled as float as the location is highly oxidized and, therefore, soil formation is in advance and outcrop is rarely encountered. Total of 110 samples are obtained in which 41 of them are prepared furthermore for laboratory analysis.

There are three type of samples for laboratory analysis, those are thin section, polished section, and powder sample. 27 samples are prepared as thin section to be analysed petrographically. Four of this samples are furthermore coated by carbon to be analysed in SEM (JSM-7610F Plus Schottky Field SEM) and EPMA (FE-EPMA JEOL JXA series 8530-F). There are 111 analysed points, where 53 points are located in colloform texture, 23 in globular, 16 in bladed, 13 in pseudograined, and 6 in radial. 13 samples are prepared as powder to be analysed in XRD.

4. Results

4.1. Deposit Geology

4.1.1. Geology and hydrothermal alteration. There are two compositionally different intrusions within the prospect (figure 2). Andesitic intrusion is located in the western part of the prospect and mainly composed of plagioclase, quartz, and minor pyroxene as pseudomorphed phenocryst. Meanwhile, dacitic intrusion located in the centre of the prospect. Embayed quartz fragment is the only primary composition relict identified within this intrusion. Figure 3a-b shows the images for these intrusions (figure 4a-b).

Alteration is relatively low in andesitic intrusion in which phenocrysts and groundmass are still often preserved. There are two alteration zones with distinct mineral assemblage in this intrusion, which are chlorite+epidote+calcite zone and quartz+sericite+pyrite zone (figure 3). The former resembles a propylitic alteration zone of the classical model by Lowell & Guilbert[4] and the latter resembles a phyllic alteration with distinctive QSP (quartz-sericite-pyrite) assemblage. Individual mineral zonation is also identified in chlorite+epidote+calcite zone where epidote is concentrated nearest to dacitic intrusion and calcite farthest to it. Chlorite can almost be found scattered pervasively all over the zone. Most of these minerals alter the primary phenocryst and groundmass in a pseudomorphic manner (figure 4d). This zone contain little oxide and without ore.

Quartz+sericite+pyrite zone is distributed restrictively in the southernmost part of andesitic intrusion that is directly bordered by Damas Gulf. This zone shows a different characteristic compared to its propylitic counterpart where primary texture and composition cannot be presently identified. Quartz, sericite, and pyrite are three most abundant minerals in this zone (figure 4c). Ilmenite and svanbergite are sometimes found associated with pyrite but never as a dominant composition. This zone also does not contain any ore, especially for both targeted copper and gold.

More variety of alteration zones can be found in dacitic intrusion. This intrusion consists of four alteration zones which form a concentric pattern. Vuggy quartz alteration centres the pattern and gradually changes into alunite+quartz zone, pyrophyllite+alunite+diaspore zone, and sericite+kaolinite zone respectively to the outermost part of the intrusion.

The vuggy quartz zone is almost exclusively composed of quartz with vug that resembles leached phenocryst. Alunite gradually presents and becomes ample in alunite+quartz zone
whereby vug abundance becomes minor. The transition moves peripherally into pyrophyllite+alunite+diaspore zone where pyrophyllite forms slightly more significant than alunite. Pyrophyllite and alunite uniquely never in contact with each other. Diaspore is found associated with every mineral in this zone but still less common than both pyrophyllite and alunite. The outermost part of dacitic intrusion is rimmed by sericite+kaolinite zone with muscovite as the main sericitic mineral. Muscovite usually has larger size compared to other microcrystalline sericitic minerals. Kaolinite is only detected from XRD data and identified as spot-filling clay mineral among larger sericite groundmass in petrography. Figure 4e-h show images for these zones.

Figure 2. Geological map of the prospect. There are two identified intrusions which underlies sandy sediment. The intrusions are cut by an estimated sinistral strike-slip fault.
Figure 3. Hydrothermal alteration zone map of the prospect. Note that each intrusion has a characteristic alteration patterns with argillic-advance argillic within dacitic intrusion and propylitic-phyllitic within andesitic intrusion.
Figure 4. Images from field and microscopy observation for (a-b) andesitic and dacitic intrusion, (c-d) propylitic-phylllic alteration zones, and (e-h) argillic-advance argillic alteration zones.
4.1.2. Supergene alteration. Intensive supergene activity is the main characteristic of Kumbokarno Prospect. Every alteration zone which covers the dacitic intrusion is an object to further oxidative alteration that forms another distinctive mineral assemblage. Hematite and goethite are two most abundant phases produced by this activity. The two minerals can be detected by both reflected microscopy and backscattered image as referred by Taylor[5]. Immiscibility texture of hematite and goethite can be found by reflected microscope. Phases of titanium oxide also forms some distinctive texture and can only be identified by backscattered image. This oxide-hydroxide mineral complex can be divided texturally into five groups. These five groups are radial, globular, colloform, bladed, and pseudogranular. Figure 5 shows images from microscopy observation for these textures.

Globular and colloform are the most widespread textures encountered in the prospect. Globular is commonly found as vug-filling hematite, but occasionally is identified bordering the colloform band. The colloform texture itself is a repetitive band of hematite and goethite. This texture forms as a pseudomorph after some unidentified mineral and creates a drusy habit within alunite+quartz zone. The colloform texture shifts from pseudomorph to vein toward the more peripheral alteration zones as stockwork becomes abundant.

Radial, pseudogranular, and bladed textures are exclusively encountered in alunite+quartz zone. Radial texture is always composed of goethite and sometimes found as growth continuity of pseudogranular or globular textures. Pseudogranular texture consists of two phases, which are iron-rich oxide and titanium rich-oxide phase. Hematite and leucoxene respectively are the main phases composing iron-rich oxide types and titanium rich-phase. Bladed texture can only be found associated with shredded alunite texture in the alunite+quartz zone. This texture creates a flow or reticulate aggregate and peculiarly behaves as pseudomorph after other oxide textures.

Figure 5. Images from microscopy observation of (a) radial and globular textures, (b) colloform and globular textures, (c) globular and bladed textures, and (d) pseudogranular textures. Rad = radial, Glb = globular, Col = colloform, Bld = bladed, Psd = pseudogranular.
4.2. Microprobe Quantitative Analysis
Quantitative analysis is done in four samples from two alteration zones. Three are sampled from alunite+quartz zone and one is from sercite+kaolinite zone. Eight standards are measured, each for every targeted element. The targeted elements are Cu, Au, Ag, As, S, Pb, Zn, Fe, and Ti with Cu and Au as the main target. The focus point of this analysis is the various textures of oxide-hydroxide complex. Therefore, the results will be shown within the constraint of these textures. There are 111 analysed points, where 53 points are located in colloform texture, 23 in globular, 16 in bladed, 13 in pseudogranular, and 6 in radial. Below are results acquired from quantitative analysis with copper and gold as their main interests.

4.2.1. Copper quantitative analysis. Quantitative microprobe result shows that copper is concentrated in colloform texture, specifically in goethite band. Copper concentration in globular, pseudogranular, and bladed texture are above copper detection limit (0.0072%). However, the copper concentration within these textures is sporadic with no pattern detected. Radial texture does not have any copper inside.

Four bivariate graphs are made to show the correlation between copper concentration and other elements. These correlated elements are arsenic, iron, sulphur, and titanium. These graphs only show points from colloform, pseudogranular, globular and bladed texture as they have copper concentration above detection limit. Figure 6 show the plot for As vs Cu, Fe vs Cu, S vs Cu, and Ti (log) vs Cu respectively. There is a clear positive trend in S vs Cu, faint negative trend in Fe vs Cu, and no significant trend in As vs Cu and Ti (log) vs Cu.

Colloform texture becomes a special interest by means of its high copper concentration. Copper concentration interestingly correlates in a positive trend with the presence of goethite. However, the concentration of copper in hematite band is very low or even nil. The repetitive pattern of goethite and hematite makes a unique feature of high and low copper concentration.

![Figure 6. Bivariate graphs between Cu and (a) As, (b) Fe, (c) S, and (d) Ti. Glb = globular, Psd = pseudogranular, Col = colloform, Bld = bladed.](image-url)
4.2.2. Gold quantitative analysis. Gold quantitative analysis is more difficult than copper as it has a very low concentration. Therefore, the detected concentration points are usually lie below detection limit (0.0105%). Some points still stand well above detection limit but the number of these points is not sufficient for any quantitative data presentation. Thus, most of the graph presented below will merge every point detected from every texture to accommodate data sufficiency and, consequently, the objectivity and validity of further interpretation.

Quantitative analysis result shows that pseudogranular texture has the highest concentration of gold and is the only texture to reach a level beyond detection limit. Bladed, colloform, and globular textures also have acknowledgeable gold concentration albeit the fact that it lies below detection limit. Radial texture does not contain any gold. Gold concentration in pseudogranular texture also shows a pattern in which high gold concentration is located in association with the high content of titanium oxide and vice versa for its low gold concentration counterpart.

This pattern is shown in a more general sense by figure 7 where combination of every texture datum is plotted in each graph. There are two graphs shown, those are Ti vs Au and Fe vs Au. The Fe vs Au shows a fairly negative trend. However, Ti vs Au graph does not show any clear trend. But still, the population of high gold concentration points correlates with high titanium concentration. This somewhat gapping populations also indicates that the minimum amount of titanium contained in oxide-hydroxide complex is about 40% which moreover supports the occurring of rutile, ilmenite, and leucoxene.

Figure 7. Bivariate diagram between Au and (a) Ti, and (b) Fe. Note the concentration gap until 40% for Ti vs Au.

5. Discussions

5.1. Deposit paragenesis
Paragenesis is constructed by analysing textural cross-cutting relationship for each deposit component. Table 1 shows the paragenetic sequence for every identified phase. This includes minerals, oxide textures, and vein types. The generation of the deposit can be divided into four phases. These phases are magmatic, deep hypogene, shallow hypogene, and supergene phase. Table 1 summarizes this paragenetic sequence.

Magmatic phase includes every component which is added during the generation of the intrusion. Thus, feldspar and quartz are put within this phase. Other minerals which are included in this phase is ilmenite. This mineral is a common accessory component in igneous rock and the primary source of titanium of the deposit. The presence of svanbergite as APS mineral in subsequent hypogene phase indicates that apatite is also presence as significant accessory component[6].
The second phase is the generation of deep hypogene alteration and mineralization. This phase is identical with porphyry alteration zones of Sillitoe.[7] Every component of chlorite+epidote+calcite and quartz+sericite+pyrite zone is included in this phase. This means that the whole alteration process within andesitic intrusion happens during this phase. The evidence of this can be clearly seen in the pseudomorphic texture usually found between alteration products and the primary minerals. Massive A, massive B, and stockwork vein are also interpreted to be generated in this phase.

A problem rises regarding the presence of argillic-advance argillic alteration within the dacitic intrusion which coexists with stockwork vein. Models such by Hedenquist and Taran[8], Richards[9], and Sillitoe[10] do not accommodate this positioning. Clay zone is not commonly found positioned in the same level with stockwork vein. The presence of muscovite within sericite+kaolinite zone also supports this spatial inconsistency as muscovite represents a high-temperature environment. Therefore, it is suggested that there is an overprinting process which creates the argillic-advance argillic forming-fluid. Based on this interpretation, we suggest the presence of second shallower hypogene phase which happens after the preceding deep hypogene phase. This includes the formation of every component associated with vuggy quartz, alunite+quartz, pyrophyllite+alunite+diaspore, and sericite+kaolinite zone. The most dominant minerals in this phase are quartz and alunite which can be found in every alteration zone. Vug is also commonly found covering the intrusion. Other minerals in this phase are only abundant in their coinciding alteration zones. The presence of multiple intrusions system confirmed its typical presence as suggested by Berger et.al.[10], Gustafson [11], and Silitoe[7].

Copper sulphide-sulfosalts is interpreted to be formed mainly in the shallow hypogene phase. This is implied by the presence of copper-bearing oxide-hydroxide complex within the alunite+quartz zone. This complex creates a pseudomorph texture from what is inferred as copper sulphide-sulfosalts minerals. This furthermore is supported by the high percentage of arsenic which is one of sulfosalt main forming-element. The presence of copper actually can be traced back to deep hypogene phase. In this phase, copper-rich oxide-hydroxide complex is located in stockwork veins. But its presence is less significant than its shallow hypogene counterpart.

Gold, in the other hand, is only detected in shallow hypogene phase. The presence of gold is associated with pseudogranular and bladed titanium oxide which are located in a limited area within alunite+quartz zone. These textures are also accompanied by the presence of shredded alunite that suggests a disequilibrium event between this zone and the subsequent influencing fluid within. We interpret this as an insight of a concealed intrusion below the dacitic intrusion. The high titanium anomaly within this gold rich zone implies that the intrusion below has a titanium-rich state. This intrusion, therefore, is the syn-gold mineralization intrusion and might also be a syn-copper mineralization.

Supergene is the last phase which is still active up to recent days. This phase is controlled by chemical weathering from exogenic process[12]. The main component created in this phase is the oxide-hydroxide complex with various texture and composition. Globular, colloform, and radial texture is generated in the early time of this phase. Then, the gold-enriched bladed and pseudogranular texture form in later time which pseudomorphs other oxide textures. From this, it can be seen that there is a time gap between the formation of the argillic-advance argillic alteration zones and the gold enrichment of dacitic intrusion. The time gap is filled with the early supergene process which alters the former copper sulphide-sulfosalts. The implication of this repeating magmatic-supergene phases toward the overall ore enrichment in the location is discussed furthermore in deposit genetic model subsection.
Table 1. Paragenetic sequence of the deposit which is divided into four phases, which are magmatic, deep hypogene, shallow hypogene, and supergene. Straight line, stripped line, and bold line respectively mean certain presence, estimated presence, and abundant presence. Mineral abbreviation follows Whitney & Evans.[13]

| Component | Magmatic | Deep hypogene | Shallow hypogene | Supergene |
|-----------|----------|---------------|------------------|-----------|
| Fase      |          |               |                  |           |
| Qz        |          |               |                  |           |
| Pl        |          |               |                  |           |
| Alu       |          |               |                  |           |
| Pyr       |          |               |                  |           |
| Dsp       |          |               |                  |           |
| Ill       |          |               |                  |           |
| Kaol      |          |               |                  |           |
| Ser       |          |               |                  |           |
| Chl       |          |               |                  |           |
| Ep        |          |               |                  |           |
| Kalsit    |          |               |                  |           |
| Py        |          |               |                  |           |
| Hem       |          |               |                  |           |
| Gth       |          |               |                  |           |
| Mle       |          |               |                  |           |
| APS       |          |               |                  |           |
| Ilm       |          |               |                  |           |
| *Leucosene* |          |               |                  |           |
| Cu-ore    |          |               |                  |           |
| Gold      |          |               |                  |           |
| Vein      |          |               |                  |           |
| Massive A |          |               |                  |           |
| Massive B |          |               |                  |           |
| Stockwork |          |               |                  |           |
| Oxide Textures |    |               |                  |           |
| Globular |          |               |                  |           |
| Radial   |          |               |                  |           |
| Colloform|          |               |                  |           |
| Pseudogranular |    |               |                  |           |
| Bladded  |          |               |                  |           |
5.2. **Deposit genetic model**

The genetic model of this prospect is based on the component paragenesis and microprobe quantitative analysis. The paragenesis analysis gives insight into the temporal and spatial distribution for every component found in the prospect.

Figure 8 shows the deposit genetic model of current condition. It shows three intrusion, which, in older to younger order, are andesitic intrusion, dacitic intrusion, and an introduced concealed intrusion below the dacitic intrusion that might also be a potential porphyry deposit. Both andesitic and dacitic intrusion are pre-mineralization intrusions. The concealed intrusion is interpreted to be a syn-mineralization of both porphyry and high-sulfidation epithermal deposit.

The pattern of alteration zones is controlled by difference of water/rock ratio within the location as explained generally by Reed.[14] The dacitic intrusion has higher water/rock ratio which is caused by the presence of sinistral strike-slip that overlaps with the centre of alteration zones of dacitic intrusion. This structure might facilitate the migration of hydrothermal fluid from concealed intrusion below to the dacitic intrusion above. On contrary, the andesitic intrusion has a relatively low water/rock ratio which is manifested by propylitic zone as discussed by Reed.[14]

The supergene activity is bordered by the minimum boundary of highly oxidized zone which is interpreted to spread around sea level. The supergene product itself can be divided into three zones, which are hematite-rich barren zone, copper-rich oxide zone, and gold-rich pocket. Hematite-rich barren zone overlies the underneath vuggy quartz zone, while copper-rich zone overlapses with alunite+quartz, pyrophyllite+alusite+diaspore, and sericite+kaolinite zone. This zone is dominantly covered by pseudomorphing copper-rich iron oxide-hydroxide complex near the central zone and gradually changes into vein-altering copper-rich iron oxide-hydroxide complex outward. Most of the copper is contained inside colloform texture, especially within the goethite band. The enigmatic emplacement of gold pocket is interpreted to be caused by second titanium-rich fluid pulse from the concealed intrusion. An insufficient amount of sample restricts a comprehensive interpretation between this gold-rich pocket with the overall deposit characteristic.

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**Figure 8.** Deposit genetic model that is constructed from paragenetic sequence and microprobe analysis.
The integration of all data suggests that the deposit can be categorized as porphyry shoulder high-sulfidation epithermal deposit as summarized by Corbett & Leach.[15] The upper portion of this deposit is leached as described by Anderson.[12] His model also suggested the presence of supergene enrichment zone below the leached zone with copper oxide as its defining phase. This could also be the case in this prospect, thus the presence of inferred supergene enrichment zone in the model. Therefore, the deposit can be defined as leached Cu-Au porphyry shoulder high-sulfidation epithermal deposit.

Nevertheless, there are still several weaknesses within this model. The first is that it cannot characterize, or even clearly ensure, the presence of the hypothesized concealed intrusion. The second is that it cannot explain some details such as the transition of argillic-propylitic zones and the formation of gold-rich pocket. These can be solved if there is further supporting subsurface data.

6. Conclusion
Kumbokarno Prospect has a dynamic deposit history, within which at least three magmatic phases, two hydrothermal phases, and two supergene phases creates such prospect observed today. The combination of these events creates an intriguing and unique deposit characteristic in which economic metal are enriched within various texture of oxide-hydroxide complex. The involvement of hypothesized concealed intrusion and its subsequent supergene activity also complicates the system furthermore.

From this prospect, one can understand at least two challenges of exploring Mio-Pliocene volcanic arc of southern Java. The first is the presence of multiple intrusion system which not always revealed to the surface. The concealed intrusion precisely will refine the complexity of hypogene alteration and mineralization. The second is the enhanced supergene activity within the system. Its older age compared to the Plio-Pleistocene arc indeed making the Mio-Pliocene volcanic arc has a bolder supergene characteristic. Therefore, a mindset framework toward leached system is a necessity. Notwithstanding these obstacles, Mio-Pliocene volcanic arc has an interesting potential of economic ore mineralization.

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