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Prediction of Potential Acid Mine Drainage Formation in High Sulfidation Epithermal Deposit Using Geochemical and Mineralogy Approaches

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ABSTRACT

Identification of acid mine drainage (AMD) can be predicted using a geochemical and mineralogy characterization approach to identify rocks forming and neutralizing acids. Geochemical characterization was conducted using static and kinetic tests. The static test is the first step to determining the potential for acid formation in rocks by comparing the potential for forming and neutralizing acids, which are characterized by uncertain behavior that causes predictions to be inaccurate. Kinetic tests were carried out to predict the long-term acid-producing potential better. Furthermore, mineralogical characterization is needed to assess the importance of sample mineral content in predicting AMD. Tests were conducted on rock samples from high sulfidation epithermal (HSE) deposits in North Sulawesi, Indonesia. The samples represent the different geological domain conditions found in HSE deposits. The main acid-producing components are pyrite and secondary minerals (alunite) capable of buffering acidity. The results showed a lower change in leachate pH (from day 30 to 180) and were accompanied by the release of species (high dissolved metals).

Keywords: AMD, geochemical, mineralogy, HSE, pyrite, alunite, leachate pH.

INTRODUCTION

Indonesia is located in a metallogenic mandala system related to hydrothermal deposits and associated with subduction zones where gold deposits are abundant [1]. One of them is the epithermal deposit. Epithermal deposit is one type of deposit that is located in a shallow hydrothermal system and is in various tectonic settings. The hydrothermal fluid in this system fills faults and joints resulting from volcanic processes and mineral deposits [2]. One type of epithermal deposit discussed is high sulfidation epithermal (HSE). HSE is formed in a hydrothermal fluid system from the remains of a reasonably acidic magmatic intrusion [3].

Mining operations often carried out to extract gold ore contained in HSE deposits generally use the open pit mining method and processing using the heap leach method. A series of mining activities can never be separated from the environmental problems caused. One of the impacts of mining activities is the opening of materials containing sulfide minerals and causing contact with water and air so that it has the potential to produce acid mine drainage [4].

Acid mine drainage (AMD) is a highly time-dependent phenomenon, and its generation is controlled by several factors such as pH, mineralogy composition, climatic conditions, and particle size distribution [5]. The oxidation of sulfide minerals is mainly concentrated in sulfate, iron, and dissolved metals [6],[7]. It is necessary to characterize it using a geochemical and mineralogical approach to understand the potential for AMD formation.

Geochemical characterization was carried out using static and kinetic tests. Static tests were carried out to determine the balance between rock samples acid-forming and consuming components. Kinetic tests were carried out to determine and predict the evolution of AMD geochemical reactions under laboratory conditions using the free-draining column leach test (FDCLT) method. Mineralogical characterization was carried out to identify minerals that have the potential to form and neutralize AMD, which is caused by weathering and is affected by the rate of oxidation during the kinetic test so that it can be predicted that the material has the potential acid-forming (PAF) or non-acid-forming (NAF). This study links geochemical analysis (static and kinetic) with mineralogy. The formation of AMD in the long term is not only influenced by the geochemical reaction but also by the mineral composition of the rock.

MATERIAL

The material used in this study is a rock sample from a gold mine with an HSE deposit type in North Sulawesi, Indonesia. The models were differentiated based on geological domains (alteration, lithology, and oxidation level) and are summarized in Table 1. The study area was dominated by massive silica alteration, which belongs to the silicic group, which is dominated by quartz [8]. The silica-advanced argillic type is dominated by quartz, which contains alkaline leaching products such as feldspar, kaolinite, and alunite [8]. The argillic type is characterized by the presence of kaolin member minerals (kaolinite and illite) and the presence of chlorite minerals [9].

Table 1. Sample description based on geological domain.

Geological Domain	AAT-01	AAT-02	AAT-03
Alteration	Silicic Massive	Silica-Advanced Argilic	Argilic
Oxidation State	Completely oxidized	Moderately oxidized	Un-oxidized
Lithology	Diatreme Breccia	Andesitic Tuff	Dacitic Tuff

The level of oxidation that develops, based on the variation and intensity of oxidation, includes completely oxidized, which is the completely oxidized zone and is the top leaching. Moderately oxide is a transition state between leachate zones, and unoxidized is a condition with no indication of consumption by sulfide minerals [10]. Lithology dominated by breccia diatreme is the result of intrusion by sub-vertical geometry. Andesitic tuff is tuff with a geochemical composition derived from andesitic rocks. Dacitic tuff has a geochemical composition derived from dacitic rock [11].

METHODOLOGY

Geochemical Approach

Commonly used geochemical approaches in static tests include pH paste tests, net acid generation (NAG), and acid-base accounting (ABA) [12]. Static tests are carried out relatively quickly (single measurement in time). A kinetic test with a laboratory scale (Figure 1) was carried out for 180 days. The kinetic test carried out is the free draining column leach test (FDCLT), designed based on wet and dry cycles in simulating natural weathering, which is set based on daily, three days, and weekly cycles. The dry cycle was affected by heating an incandescent lamp (60 watts) for 12 hours every day at a temperature of 30–33ºC adjusted to the field's irradiation length. The wet cycle was simulated by sprinkling distilled water into the rock sample, as much as 600 ml, which was adjusted to the annual average rainfall at the study site with the sample surface area.

Figure 1. Kinetic test installation at ITB Mining Environment Laboratory.

Mineralogy Approach

Mineralogy helps evaluate the extent to which acid-forming and neutralizing minerals react. Mineralogical characterization used several tests, including the XRD test, to determine mineral composition using Smartlab and XRF to determine elemental composition using Supermini.

RESULTS AND DISCUSSION

Mineralogy

Based on mineralogy testing, the study area consists of four (4) mineral groups identified and summarized in Table 2, namely silicate, which is dominated by quartz minerals that are abundant in nature and resistant to weathering. Aluminosilicates are found in the form of primary and secondary minerals. Primary minerals are feldspar and muscovite; secondary minerals are alunite, dickite, illite, montmorillonite, and chlorite. The sulfide minerals found are pyrite, and the oxide is hematite. It is estimated that the pyrite mineral in the AAT-01 sample has been completely oxidized to Fe-oxide, leaving only hematite. Carbonate minerals as the primary neutralizing agent in AMD were not well detected in the samples.

Secondary minerals of aluminosilicate (dickite and alunite) are considered capable of being potential acid neutralizers, but their content and reaction rate are lower than carbonate minerals (calcite) [13]. Aluminosilicate minerals dissolve more slowly kinetically, which can also inhibit AMD formation.

Table 2. Summary of minerals in the study area.

Mineral Group	AAT-01	AAT-02	AAT-03
Silicate	Quartz	Quartz	Quartz
Aluminosilicates	Alunite	Feldspar, muskovite, dickite, illite, montmorillonite	Feldspar, muskovite, montmorillonite, chlorite
Sulfide		Pyrite	Pyrite
Oxide	Hematite	Hematite	

Table 3. Elemental content in the research area.

Oxide Components (%)	HSE-01	HSE-02	HSE-03
Al_2O_3	20.00	22.80	25.50
SiO_2	48.10	63.80	61.40
SO_3	22.70	5.04	6.44
K_2O	5.38	4.35	1.43
Fe_2O_3	2.98	2.44	3.52
TiO_2	0.02	0.40	0.45
Cl	0.50	0.50	0.24
MgO	0.30	0.30	0.75
P_2O_5	0.62	0.05	0.08
CaO	0.15	0.08	0.07
SrO	0.02	0.02	0.01
ZrO_2	0.02	0.02	0.01
MnO	<0.01	0.02	0.02
Na_2O	<0.01	0.07	0.07
CuO	<0.01	0.08	0.01

The dominant elements found in HSE deposits using the XRF test are summarized in Table 3, showing that the principal oxides in the sample are SiO_2, followed by Al_2O_3, SO_3, and Fe_2O_3. There are also elements K_2O, CaO, and Na_2O, which are the main products of feldspar hydrolysis recorded in small numbers. The abundance of SiO_2 in all samples is due to the elements SiO_2 being widely available in nature and its resistance to weathering. The dominant alunite content caused the content of SO_3 in the AAT-01 sample. The concentration of CaO can control the acid potential. When it is low, there is acid potential occurring in the material. Al_2O_3 and Fe_2O_3 play a role in the acid metal release and metalloid mobilization [14],[15].

Geochemical Static Test

The results of static tests are summarized in Table 4. Paste pH provides a rapid evaluation of the acid-base balance in the sample. Paste pH ranges from 6.70 to 6.99. All samples produced positive NAPP values ranging from 60.94 to 148.84 kg H_2SO_4/t. A positive NAPP value indicates that the sample has a low ANC, resulting in insufficient neutralization capacity, causing the sample to be classified as PAF.

Table 4. Preliminary geochemical characterization.

Samples	Paste pH	NAG pH	Total Sulfur (%)	MPA (kg H_2SO_4/t)	ANC (kg H_2SO_4/t)	NAPP (kg H_2SO_4/t)
AAT-01	6.99	4.78	4.86	148.84	<0.50	148.84
AAT-02	6.70	2.89	1.99	60.94	<0.50	60.94
AAT-03	6.84	2.23	4.12	126.18	<0.50	126.18

The acid-generating potential can be well drawn using more comparisons from the static test results to produce a high level of confidence based on the results obtained. This study used several classifications of static test results, summarized from previous studies. TS and NAPP (Figure 2a) show the amount of sulfur content in the form of acid that has the potential to form AMD [16]. Most samples entered class 2 (ARD persisting for a long time). This condition is due to the high sulfur content, which is considered capable of forming acid for a long time.

Compare paste pH values and NAG pH (Figure 2b) to show the long-term behavior of the samples [17]. The models were grouped into 2 AMD conditions: non-acid forming (NAF) and potential acid forming (PAF).

All samples were classified as PAF when comparing MPA and ANC (Fig. 2c), comparing values between maximum neutralizing and acid-forming capacities [18]. And the comparison of NAPP and NAG pH (Figure 2d) [12] was grouped into 2 AMD conditions, one as acid-forming (NAF) and two as potential acid-forming (PAF). The weakness in static classification is uncertain, making it challenging to classify samples. Therefore, it is necessary to carry out AMD-forming evolution using a laboratory-scale kinetic test, as shown in Figure 3.

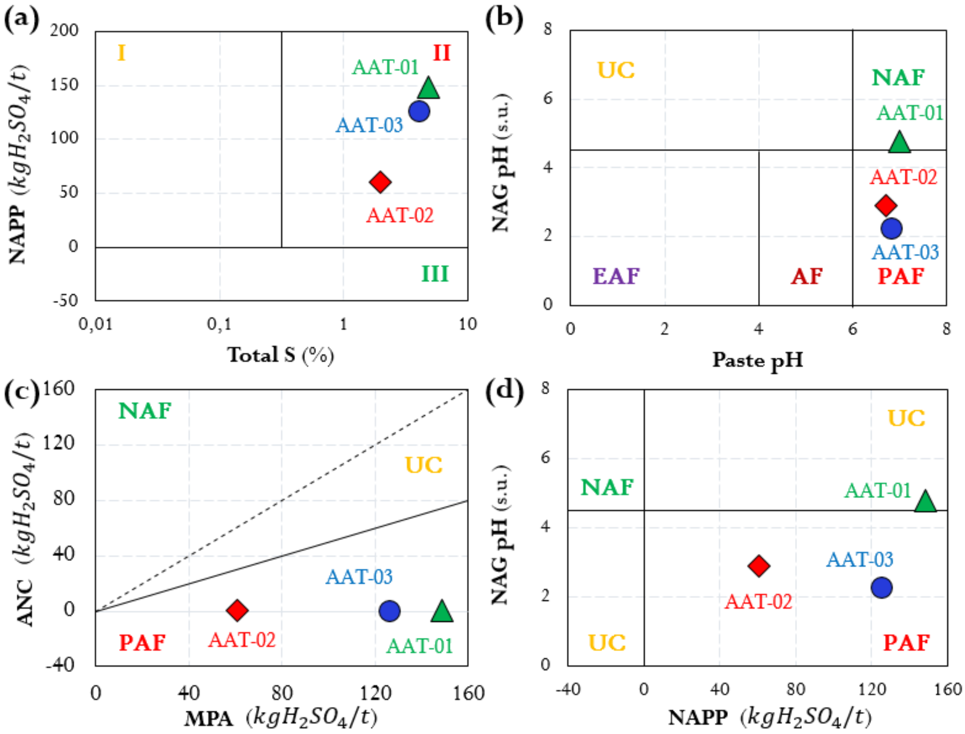

Figure 2. Preliminary geochemical characterization based on a) TS vs. NAPP, b) paste pH vs. NAG pH, c) MPA vs. ANC, d) NAPP vs. NAG pH.

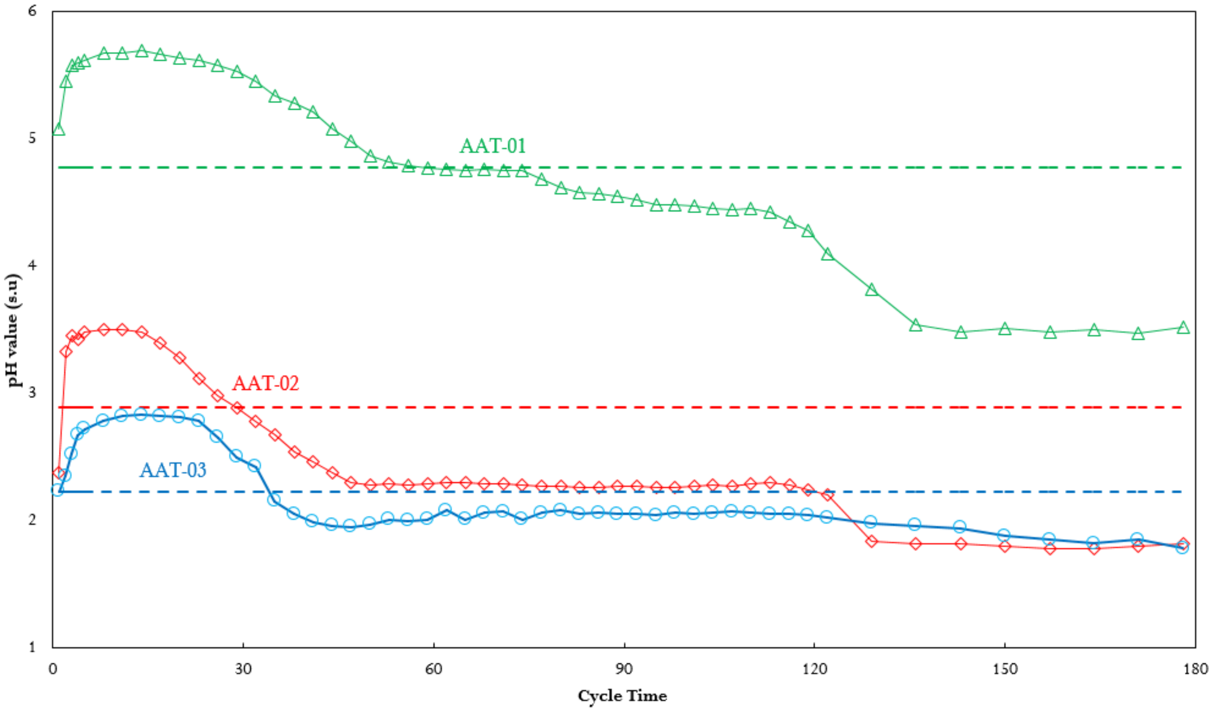

Figure 3. Kinetic testing for 180 days.

Geochemical Kinetic Test

At the beginning of the cycle, all samples move from the NAG pH value (static). The NAG pH value is the initial picture of the kinetic pH value. Then, the leachate pH value fluctuated towards a pH of 4.5 (until day 10). This shows that up to day 10, the minerals in the rock samples are still being washed, re-leaching the oxide minerals that have existed before from the field conditions to the laboratory. In this condition, it is possible that the exposed sulfide minerals have not yet entered the complete oxidation phase. The decrease in pH value continued to be stable until day 60 (AAT-01), day 30 (AAT-02), and day 35 (AAT-03). Stable pH values were observed for all samples during the 3-day cycle and relatively decreased when entering the weekly cycle on day 100, as shown in Figure 3.

Samples AAT-02 and AAT-03 showed pyrite as an acid-forming source. This condition can be seen in Figure 3. Both samples have a reasonably low leachate pH in the range <3. In the AAT-01 sample, which has an uncertain classification in the static test, the leachate pH is relatively lower after the kinetic test, so it has the potential to form acid in the long term. Based on the mineralogy test, it is known that the aluminosilicate contained in the AAT-01 sample is alunite. Alunite from samples that have been completely oxidized includes a significant amount of the mineral alunite sulfate. The high sulfur sulfate content in the sample indicates that alunite is the dominant sulfur species of total sulfur (static test). In the static test, very low ANC values were detected in the sample. Alunite will control the pH of the leachate in the range of 4 to 5, as seen in the kinetic test (Fig. 3). Thus, the alunite dissolves kinetically slowly. Thus, the amount of acid released from the dissolution process is low. This low pH condition is of environmental concern because it can increase the solubility of some species (high dissolved metals).

CONCLUSION

The results of the relationship between geochemical and mineralogical approaches predict the potential for AMD formation in HSE deposits. Pyrite is the primary source of AMD formation. Besides that, secondary minerals also have an essential role in metal dissolution. Geochemical and mineralogical approaches confirm each other's evolution of AMD formation.

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