INDONESIAN MINING JOURNAL Vol. 24, No. 1, April 2021 : 31 - 45

LITHOGEOCHEMICAL EXPLORATION FOR DELINEATING PRIMARY GOLD OCCURRENCES IN WEST KAO AREA, NORTH HALMAHERA DISTRICT, NORTH MALUKU PROVINCE

EKSPLORASI LITOGEOKIMIA UNTUK MENDELINEASI KEBERADAAN EMAS PRIMER DI DAERAH KAO BARAT, KABUPATEN HALMAHERA UTARA, PROVINSI MALUKU UTARA

ARIFUDIN IDRUS[1*] and FADLIN[2]
[1] Department of Geological Engineering, Universitas Gadjah Mada, Yogyakarta
[2] Study Program of Geological Engineering, Universitas Jenderal Soedirman, Purwokerto
*Corresponding author: arifidrus@ugm.ac.id

ABSTRACT

Halmahera Island retains several gold deposits. One of the gold deposits is called as low sulphidation epithermal (LSE) quartz veins which is currently being mined and is situated in the Gosowong goldfield. The veins mostly originated in N-S and NNE-SSW direction. This study is aimed to determine the prospect area in the northern portion of Gosowong goldfield covering the West Kao sub district based on surface mapping and rock/float- and BLEG stream sediment survey. A total of 16 rock/vein float and 120 BLEG samples were analyzed by FA/AAS and CNO_2 cyanide leach methods, respectively. The study area is occupied by tuffaceous sandstone, andesite, porphyritic andesite and lava andesite units. In the eastern part, tuffaceous sandstone is suffered from argillic and propylitic alteration, which may be controlled by the NW-SE-trending structures. The gold grade of rock/float samples is up to 0.044 ppm. BLEG data indicates a calculated threshold of 10 ppb for Au and 72 ppb for Ag. The highest Au and Ag contents (anomalies) are identified in the eastern part of the study area. This is spatially (and maybe genetically) related to the argillic-altered tuffaceous sandstone, structures and occurrences of quartz vein floats. To follow up this finding, a detailed exploration is recommended to be conducted within the prospect area.

Keywords: BLEG, exploration, geochemical anomaly, Halmahera.

ABSTRAK

Pulau Halmahera memiliki beberapa endapan emas, salah satunya yang disebut sebagai urat kuarsa epitermal sulfidasi rendah (LSE) yang sekarang sedang ditambang berada dalam lading emas Gosowong. Urat kuarsa tersebut umumnya berorientasi N-S dan NNE-SSW. Studi ini bertujuan menentukan daerah prospek pada sisi utara lading emas Gosowong yang meliputi daerah Kao Barat, berdasarkan pemetaan dan survei litogeokimia batuan dan sedimen sungai BLEG. Sebanyak 16 percontoh batuan/serpihan dan 120 percontoh BLEG dianalisis dengan metode FA/AAS dan pelindian sianida CNO_2. Daerah penelitian ditempati oleh satuan batupasir tufaan, andesit, andesit porfiritik dan andesit lava. Pada bagian timur, batupasir tufaan mengalami alterasi argilik dan propilitik, yang mungkin dikontrol oleh struktur berarah NW-SE. Kadar emas pada batuan/serpihan menyampai 0,044 ppm. Data BLEG menunjukan nilai ambang batas 10 ppb Au dan 72 ppb Ag. Kadar Au dan Ag tertinggi sebagai anomali teridentifikasi di bagian timur daerah penelitian. Hal ini secara spasial dan mungkin genetik berkaitan dengan alterasi argillik batupasir tufaan, struktur dan keberadaan serpihan urat. Eksplorasi rinci direkomendasikan untuk dilakukan khususnya pada daerah prospek tersebut.

Kata kunci: BLEG, eksplorasi, anomali geokimia, Halmahera.

Received: 12 February 2021, first revision: 14 March 2021, second revision: 20 April 2021, accepted: 11 October 2021.
DOI: 10.30556/imj.Vol24.No1.2021.1173

INTRODUCTION

Gold deposit is a natural resource that plays a very important role in providing raw material for humankind and industrial development. The occurrences of gold deposits in any region may serve the increasing of national and local region economic growth. The need for gold has been lately increased rapidly, on the other hand, the availability of this commodity is very limited (Yousef and Shehadeh, 2020). In accordance with the dramatic increase in the gold price in world market recently (Shafiee and Topal, 2010; Weng *et al.*, 2020), leads to exploration activities are extensively carried out. The current gold price today (May 8th, 2021) is approaching USD 1,830/Oz (Kitco.com, 2021). One of the important gold deposit types contributing significant gold resources and production in Indonesia is a low sulphidation epithermal (LSE) gold deposit, referred to the terminology from Buchanan (1981), Robb (2005), and Ridley (2013), etc. In Java Island, for instance, 15.4% of 1,004 tonnes of the gold endowment is derived from the LSE deposit type (IAGI-MGEI, 2015). In Halmahera Island, gold is currently being produced from the Gosowong LSE goldfield such as Gosowong, Toguraci and Kencana vein zones (Carlile *et al.*, 1998; Gemmell, 2007). Several sub-economic porphyry deposit types are also discovered in Halmahera Island such as Bora, Matat, Tobobo and Ngoali porphyry prospects (Gemmell, 2007). Geographically, the Gosowong goldfield is situated in the northern arm of Halmahera Island. Gosowong and Toguraci vein zones generally show N-S to NNE-SSW direction (Gemmell, 2007). The curious question arises including: does the gold-bearing quartz veins that occurred in the Gosowong goldfield extend to the northern and NE portion of the goldfield of the PT. Nusa Halmahera Minerals concession area?

Due to the scarcity of the exploration data to the north of the goldfield, this study is, therefore, carried out as a follow-up of the conceptual basis to prove the continuity of the gold-bearing veins to the north and northeast within the tenement area of PT. Hibualamo Jaya (Figure 1). Administratively, most of the study area is located in the West Kao sub district including Ngoali, Momoda and Toliwang villages, with an approximate total area of 16,000 ha. This study is aimed to determine the most prospective area which is delineated from surface geological and alteration mapping, and BLEG (Bulk-Leach Extractable Gold) stream sediment lithogeochemical survey. In a more specific objective, this study enables to determine the dispersion pattern of secondary gold called *floating gold* in stream sediment, which is assumed as a geochemical anomaly to delineate the occurrences of primary gold deposits in the area.

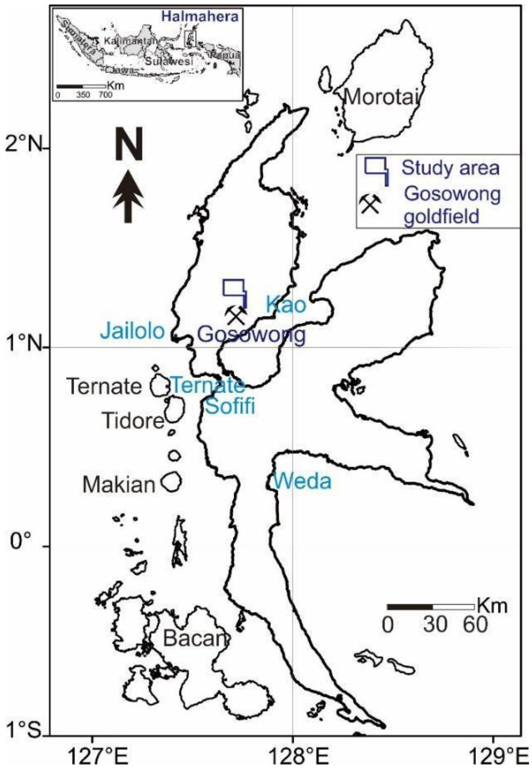

Figure 1. Location map of the study area in West Kao sub district, North Halmahera.

REGIONAL GEOLOGY

Physiographically, the K-shaped of Halmahera Island is similar to Sulawesi in the west (Katili, 1978; Hamilton, 1979; Hutchison, 1989; Hall, 2002). Halmahera Island is the region which is mostly covered by a highland area with Mt. Togohi (1,233 m) above sea level located in the west of Tobelo. Mt. Togohi is the highest mountain on the island. The mountain ranges in the east were formed by Tertiary volcanic activity, while in the west, the mountains were formed by Quaternary active volcanos. Some active volcanoes are noted within this area such as Gamkonora, Sahu, and Ibu mounts.

Regionally, the study area lies within the Neogene magmatic arch that extending around 350 km from Bacan Island in the south up to Morotai in the north (Carlile *et al.*, 1998). Halmahera Island can be divided into two geological domains, namely western Halmahera and eastern Halmahera (Gemmell, 2007). The western Halmahera is dominated by volcanic sequence and associated with mineralized magmatic arc (Carlile and Mitchell, 1994; Garwin, Hall and Watanabe, 2005). It was formed by eastward subduction to the Maluku sea plate. The western part of Halmahera is mainly formed by the basement of the Late Mesozoic or Early Tertiary in age. This complex is covered by Neogene intrusion and volcanic rock in which is locally underlain by Quaternary volcanic rock. The volcanic arc within the region mainly comprises four volcano-sedimentary rock sequences that mutually overlapping (Gemmell, 2007).

According to the regional geological map of Moratai sheet by Supriatna (1980), the volcanic rock complex in the study area and its vicinity is composed of:

a. Bacan Formation (Tomb), Paleogene in age that consists of basaltic and andesitic lava and breccia. This formation is interfingering with Tutuli Formation.
b. The Upper Miocene of Gosowong Formation. This Formation is dominated by volcanic clastic sequences with intermediate in composition.
c. Pliocene Kayasa Formation (Qpk), consists of lava and breccia with andesitic composition.
d. Quaternary volcanic rocks.

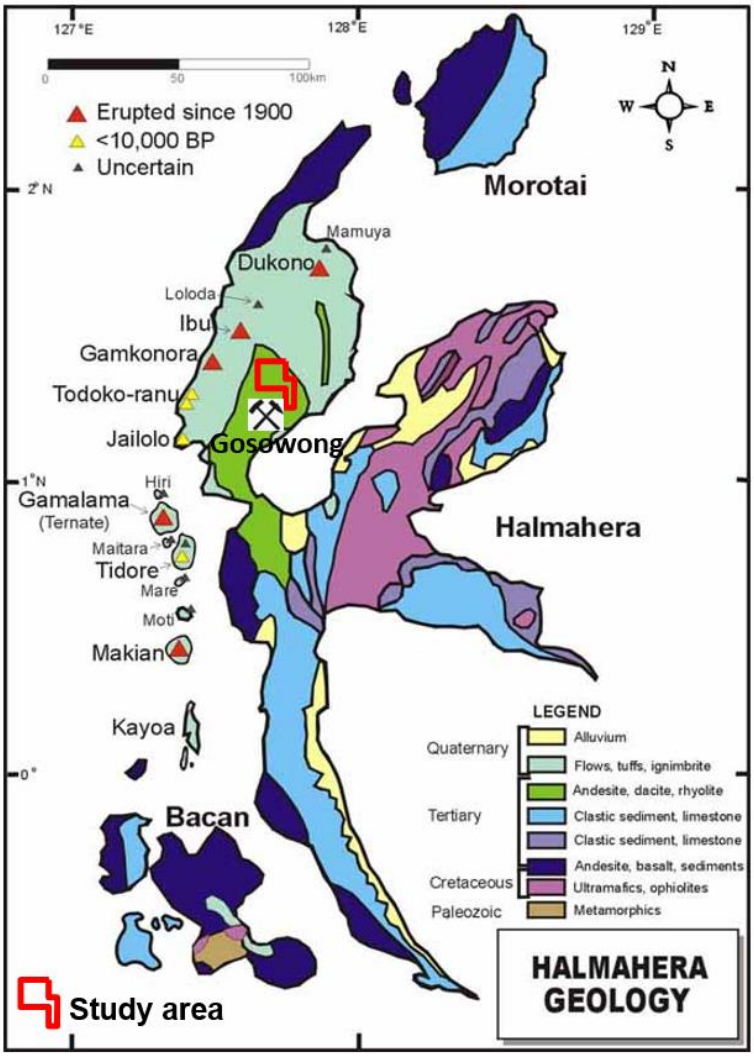

Figure 2. Regional geological map of Halmahera Island (modified from Gemmell, 2007).

METHODS

In general, the research method consists of surface geological mapping and the alteration-mineralization zone mapping of the prospect area with a scale of 1: 25,000, sampling of altered and mineralized rocks and stream sediment sampling using the Bulk Leach Extractable Gold (BLEG) method. The limitation of this study is that the determination of rock name and alteration type is only based on megascopic analysis. No microscopic analysis was made. The selected samples are analyzed in a geochemical laboratory. A total of 16 rock and vein float samples was analyzed by FA/AAS method, whereas 120 BLEG samples were analyzed by the CNO_2 cyanide leach method. The following is a detailed description of BLEG sampling techniques.

Bulk Leach Extractable Gold (BLEG) is considered the most reliable geochemical sampling/survey tool used during exploration for gold (Rose, Hawks and Webb, 1979; Joyce, 1984; Böhmer and Kucera, 1986; Yilmaz *et al.*, 2020). Reproducibility of the geochemical method is good, for instance, as shown by Arne and MacFarlane (2014). It was developed in the early 1980s to address concerns relating to accurately measuring fine-grained gold, and dealing with problems associated with sample heterogeneity (Levinson, 1974). BLEG has been tried and tested over 20 years, applied successfully in different climatic settings, provides robust, excellent repeatability of results and has an important role in the discovery of major Au deposits such as Batu Hijau and Dodo Elang in Sumbawa Island (Meldrum *et al.*, 1994; Maula and Levet, 1996; Maryono *et al.*, 2018). A successful story of stream sediment survey is also shown by Cohen, Dunlop and Rose (2005). Traditionally, BLEG sampling involves a large number of samples (between 2 and 5 kg) are digested or leached with cold sodium cyanide (NaCN) solution (generally 0.1 % NaCN), for one to several days (Yilmaz, Cohen and Sonmez, 2017). The gold is dissolved through its formation of a cyanide complex, which is concentrated through the solvent exchange process into an organic solvent and subsequently analyzed. The use of large sample weights and solvent extraction enables low detection limits, as low as 0.1 ppb. The digest is analyzed for Au (0.01 ppb), Cu (0.01 ppm), Ag (0.5 ppb), and other elements (Rose, Hawks and Webb, 1979).

Recently, it is common practice to collect only fine-sized material – silt to clay - where the fine flakes of gold will reside (Xuejing and Xueqiu, 1991; Yilmaz, Cohen and Sonmez, 2017). Given their shape, these fine flakes of gold don’t act hydro-dynamically like heavy minerals, and will not settle in the same locations in a stream bed. Where possible, attempts should be made to sample flash flood sites (where finer material concentrates) over bank deposits. BLEG method is usually used by a geologist in regional sampling before doing a gold exploration and the BLEG sampling method has a catchment area of approximately 20-30 km to represent a large area, but the BLEG geochemical survey method activities in this research site have a special specification that is more sealed spaces sampling approximately 1 km distance between samples (Carranza, 2004). The benefit gained from BLEG sampling is more efficient because it can represent a large area, cheap, fast, higher accuracy rate, and many others (Theobald *et al.*, 1991; Kirkwood *et al.*, 2016). In this BLEG sampling method that must be considered is quality control in the sampling area should be done away from the population or remote area, sampling approximately 2-5 kg and when doing sampling must not wear metallic materials.

The important thing to consider before doing the research with the BLEG sampling method is how to understand the procedure in preparing *magnafloc solution* that will be used as a substance to accelerate the clotting of the mud samples. Some steps in preparing a *magnafloc solution* include:

a) Heat the water to taste and pour that hot water into a basin or bucket of plain water at least 2 liters in order to get the ideal temperature (lukewarm).
b) Then pour 2 tablespoons of the granules magnafloc into the water then stirred gently for about 2 hours or until all the granules magnafloc blended with water to form a viscous solution which we called *magnafloc solution*.
c) Then pour the *magnafloc solution* into the container that more effective and efficient way to carry it around everywhere.

Some steps in BLEG sampling techniques describes below and illustrated in Figure 3.

a. Collecting fine-sized stream sediment fraction at several points within an active stream with a total sample weight of 2-5 kg. Sampling can be carried on the side of the river, under a rock that has been transported, in the middle of the river. In this case, the sample may not be taken near the outcrops and former debris from the hills. The expected target of this method is to trap the floating gold (gold floating fraction) which transported from upstream. A total of 120 BLEG samples were collected.
b. Sieving the samples to collect the fine fraction using sieves with a mesh size of 200.
c. The material from the previous step is still a mix of water and sediment fine fraction/clay (mud). Remove the water from mud or fine-grained sediment by mixing it with *magnafloc solution* with a concentration of approximately 10% and then stir the mixture to agglutinate the mud.
d. Remove the water to get the agglutinated mud. The mud is then sieved using the cloth to fully separate the water from the solid.
e. The solid part is the final BLEG samples which will be sent to the laboratory for analysis.

BLEG samples were analyzed in the Intertek geochemical laboratory in Jakarta, particularly for the gold (Au) and silver (Ag) element using the CNO_2 analysis method that is able to detect the presence of floating gold in the very fine fraction to levels of up to 0.01 ppb. The interpretation of geochemical dispersion map of Au and Ag elements in BLEG samples is expected to reveal the anomalies areas which have a high prospect of primary gold occurrences (e.g. epithermal quartz veins) (Grunsky, 2010; Chen *et al.*, 2016; Sun *et al.*, 2016).

Figure 3. BLEG sampling techniques: (A) Collecting sample mud – fine sand grained along the river, weighing about 2 kg, (B) Sieving the sample to collect the fine fraction, (C) Stirring up the mud with the *magnafloc solution,* and (D) Packing and draining the BLEG samples

RESULTS

Local Geology

On the basis of the field observation for the rock exposures within the exploration area, generally, the lithology may be classified into 5 (five) units, sequentially from the oldest to the youngest as follows: tuffaceous sandstone, andesite, porphyritic andesite, lava andesite and Quaternary deposits. Those lithological units may correspond with Paleogene Bacan Formation (Tomb), consisting of basaltic and andesitic lava and breccia, which are interfingering with Tutuli Formation (cf. Supriatna, 1980). The geological map of the study area is displayed in Figure 4. Tuffaceous sandstone lies in the eastern part of the area that extends from the north to the south. This unit covers around 20 % of the total area of study. Field examination for this unit at Momoda River showed medium to light grey, clastic, and medium to coarse grains, the thickness of layers between 5 and 30 cm, massif, in places was found fragments with the shape of angular to sub-angular.

Andesite unit is exposed at the south-eastern margin of the block. Field observation of the rock exhibits medium to dark grey in the color, fine-grained, massif, composed mainly of plagioclase, biotite and lesser pyroxene. Fracture spacing was noted between 15 and 30 cm with the main trend of the north-northeast and south-southwest. Porphyritic andesite covers approximately 5% of the total study area. The rock outcrops were found at Momoda and Ngoali rivers. Based on the topographic expression and the relationship with surrounding rocks, so that this unit can be categorized as a shallow intrusion and it form stocks. The outcrop of porphyritic andesite around the Momoda River shows medium to dark grey when fresh, but it exhibits a medium to light brown with light spots when it gets weathering. The texture is commonly porphyritic, massive and composed of plagioclase as phenocryst with sub rounded to angular in shape. This mineral is enclosed in microlite of plagioclase, hornblende, and biotite. Fractures spacing ranges of 2 – 20 cm with a trend N65ºE/30º. Field description for porphyritic andesite found at Ngoali river show medium to dark grained, porphyritic texture, massif, composed mainly of plagioclase, with lesser biotite, hornblende, and pyroxene.

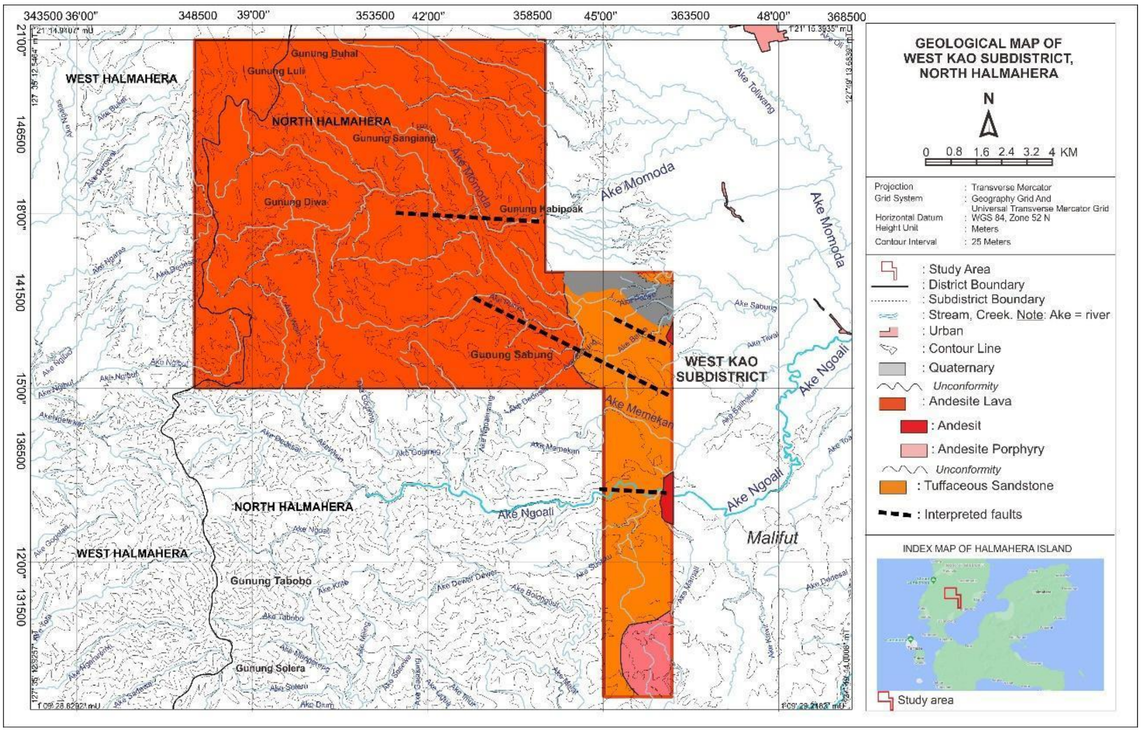

Figure 4. Geological map of West Kao area, North Halmahera.

The andesitic lava unit occupies around 70% of the total study area. These units mostly extend to the northwest portion of the block. Field observation of the outcrop displays medium to dark grey in color, porphyry-aphanitic texture, and massif. The mineralogy comprises mainly medium to fine-grained plagioclase as phenocryst with a lesser amount of hornblende and trace pyroxene. At the outcrop scale, this rock shows the existence of vertically columnar joints. In place, the structures of lave flow were also noted. The quaternary deposit was found at the north-central margin of the study area. It lies around Momoda river and occupies approximately 5 % of the total study area (see attached geologic map). The principal components of this unit are loose materials consisting of sand to gravel with grain shapes range from sub-rounded to angular. The larger components (gravel to a boulder) are mainly derived from andesitic rocks that have undergone any movement from the upstream.

The structures developed within the study area are mainly joints or fractures. Some indications of faults may also exist. The pattern of contour lines in the topographic map and the results of field observation were taken as the basis to interpret the possibilities of fault occurrence in the study area. Strike-slip and normal faults are expected to be developed where the strike faults generally have west-northwest and east-southeast trending (Figure 4). Normal faults are indicated by the presence of scarps. Some waterfalls are also found within the study area which may indicate the presence of geological structures i.e. fault zone in the area.

Hydrothermal Alteration and Quartz Vein Floats

The indication of the presence of argillic and propylitic alteration was observed at a tributary of the Ngoali river. The windows of the propylitic and argillic altered rocks were recognized on the side of the river. The argillic altered rock shows light grey to greenish cream in color, composed of clay, chlorite and iron oxides. Silicic alteration is overprinted with the argillic zone, however, silicification tends to be dominant so that the argillic zone is included in the silicic zone. Propylitic alteration zone extends outward from the argillic zone. The propylitic alteration is characterized by the presence of chlorite and epidote replacing the primary mafic minerals such as pyroxene, biotite, and hornblende. The Distribution of alteration zones in the study area is exhibited in Figure 5.

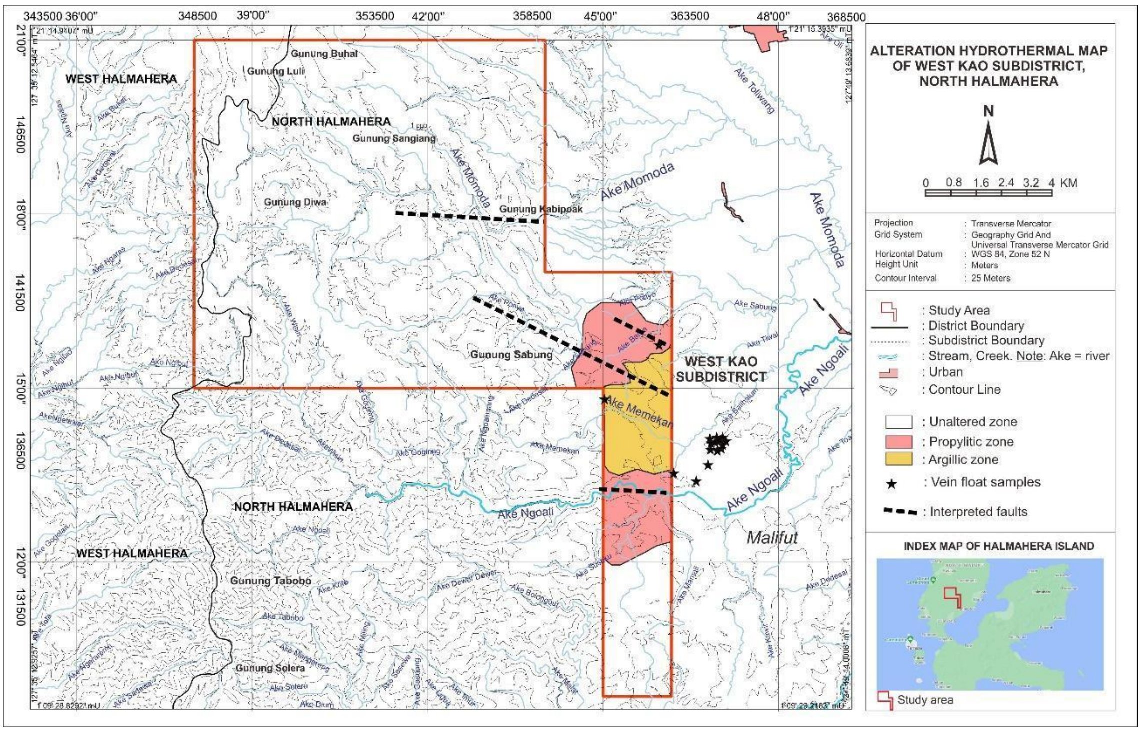

Figure 5. Hydrothermal alteration and vein float map of West Kao area, North Halmahera.

Hydrothermal alteration within the study area is in association with the presence of some floats found at the slope and creeks. A large of quartz vein float associated with clay minerals were found in the creeks or tributaries of the Ngoali River on the north side (Figure 5). The distribution pattern of these floats is expected to have a trend relatively north-northeast to south-southwest. However, the indication of alteration and mineralization was not found on the south side of the Ngoali River, due to the absence of floats at the creeks and tributaries. Rock floats of silicic or argillic alteration show white cream, the float size around ~30 cm with sub-rounded in shape (Figure 6A).

Some other floats are found on the hill slope at the center of the block showed the indication of alteration and sulfide mineralization. Rock floats about 25 cm in diameter display light grey when fresh but it looks reddish-brown when weathered. The relict texture is visible like the remnant of plagioclase phenocryst. Most the primary minerals have undergone alteration to some degree. Quartz and clay minerals were noted to be the main alteration product. Very fine-grained disseminated pyrite is present. Lesser galena, sphalerite and chalcopyrite may also occur. Some veinlets (~0.1 cm) were observed within the float showing the oxidized brownish color (Figure 6B). It is formerly expected as sulfide minerals. In addition, some altered rock floats show fine-grain texture, massif, and are composed mainly of quartz, clay minerals, trace chlorite (Figure 6C) which is occasionally cut by sulfide stringers (Figure 6D). Based on the characteristics of quartz vein floats, vein texture, wall rock alteration types and ore minerals identified, the hydrothermal deposit occurred in the study area is possible of low sulphidation epithermal gold type (cf. White and Hedenquist, 1995; Simmons, White and John, 2005; Hedenquist and Arribas, 2017; Prihatmoko and Idrus, 2020).

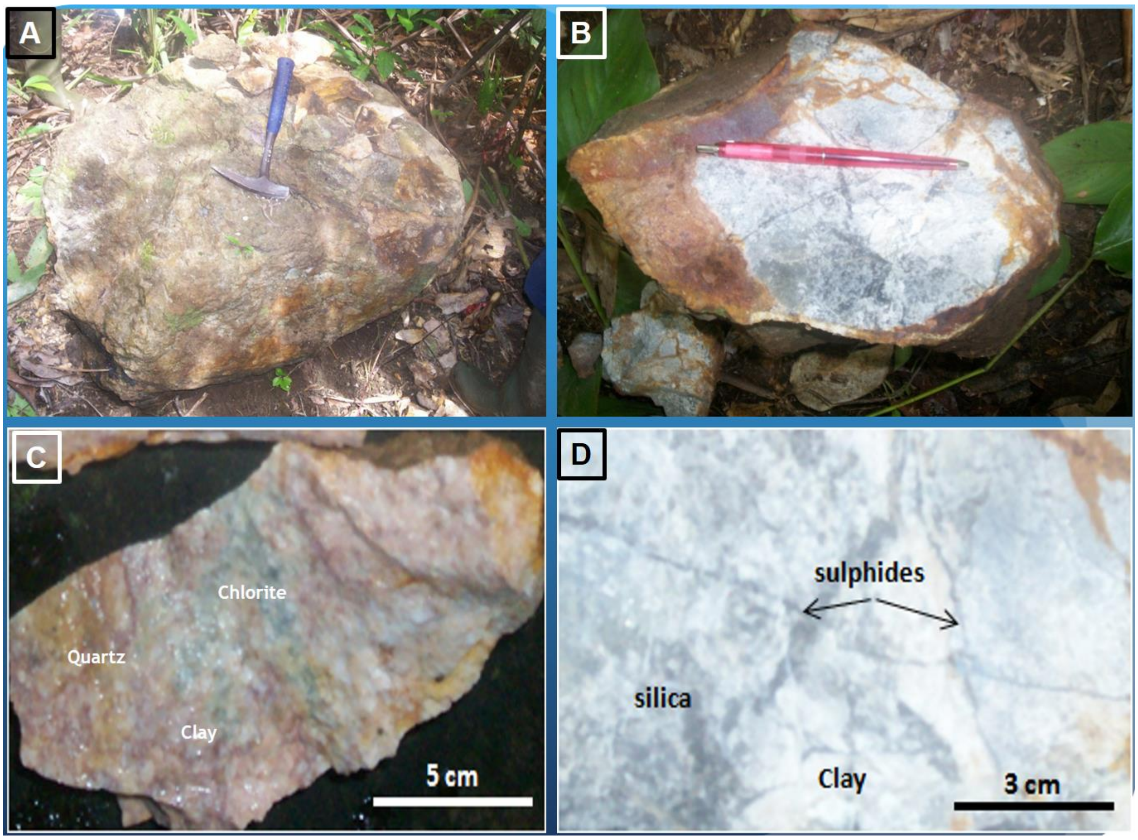

Figure 6. (A) A boulder of quartz vein of about 1 m in diameter found in the north of Ngoali river, (B) Float associated with disseminated sulphide (i.e. pyrite) and veinlets, (C) Close-up of altered rock floats mainly composed of quartz, clay minerals and trace chlorite, and (D) sulphide stringers cut the argillic altered rocks.

In order to clarify the content of gold, silver and other base metals, a total of 16 vein samples have been selected for chemical analysis. The results of the chemical analysis show that 4 samples have Au content over the detection limit (0.005 ppm). Sample B-06.2 shows the highest Au grade (0.044 ppm) followed by sample B-06 (0.012 ppm). Sample B-06.2 also contains the highest Cu (75 ppm) accompanied by sample D-1 (70 ppm). Two other samples have Au content slightly over the detection limit, namely sample D-1 (0.009 ppm) and D-2 (0.007 ppm). The other 12 samples have Au values below the detection limit. Meanwhile, all analyzed samples contain very low Ag or below the detection limit (<1 ppm). However, significant values of As were also noted for three samples. Sample D-1 contains 67 ppm As followed by B-06 (59 ppm As), and B-06.2 (30 ppm As). Generally, the Pb content of all studied samples is low, ranging from 4 – 50 ppm with a detection limit of 4 ppm. It is expected that there is a good relation between Au, Cu, and As. In contrast, there is no correlation between Pb and Au, Cu and As.

BLEG Stream Sediment Geochemistry

This section discusses the results of the BLEG lithogeochemical survey, which is focused on gold (Au) and silver (Ag) geochemical anomalies.

Gold (Au) anomaly

A total of 120 BLEG samples was collected from the streams of the study area. The weight of each sample taken varies between 1.5 to 2 kg and all samples were dried and prepared to be analyzed by using the CNO_2 method. The chemical analysis indicates that Au grade varies from 0.1 to 49.2 ppb with a detection limit of 0.01 ppb. Statistically, the threshold formula is calculated by using: Mean + 2SD (Rose, Hawks and Webb, 1979; Ranasinghe *et al.*, 2009). The calculation indicates that the gold threshold value from the whole BLEG analytical data is 10 ppb. As a result, only one BLEG sample displays Au grade above threshold value i.e. 49.2 ppb of Sample HU-IV/23; this value is called a gold anomaly. Moreover, Sample HU-IV/23 consistently has a high silver content (~88 ppb). The sample with a high Au anomaly is situated in the most eastern part of the study area which is closed to the study area boundary (Figure 7). In addition, five BLEG samples have a value of 3.6-10 ppb Au distributed irregularly in the study area. This data range of gold may be categorized into mineralization backgrounds. Most of the BLEG data show a gold grade of less than 3.6 ppb, and this data range may be categorized into the regional background.

Silver (Ag) anomaly

Similarly, a total of 120 samples was also chemically analyzed using the CNO_2 method for silver (Ag) grade. The chemical analysis indicates that the Ag grade ranges between 6 and 140 ppb with a detection limit of 0.01 ppb. Statistically, using the threshold formula of mean + 2SD, the silver threshold value from the BLEG data is 72 ppb. As a result, four BLEG samples show the Ag grade is above threshold value and is classified as the silver anomaly including 140 ppb (Sample HU-I/26), 132 ppb (Sample HU-IV/32), 112 ppb (Sample HU-IV/34) and 88 ppb (Sample HU-IV/23). As discussed above, the last sample also consistently contains the high gold, which is categorized into gold anomaly located at the most eastern boundary of the area (Figure 8). Moreover, three other samples with the highest Ag content (Ag anomaly) are also situated in the eastern part of the study area. The samples with silver values between 41 to 71 ppb may be categorized into mineralization backgrounds which are partly distributed in the south-eastern part of the study area and some samples are distributed in the middle part of the study area. The Ag values below 41 ppb of the analyzed samples are grouped into the regional background of silver.

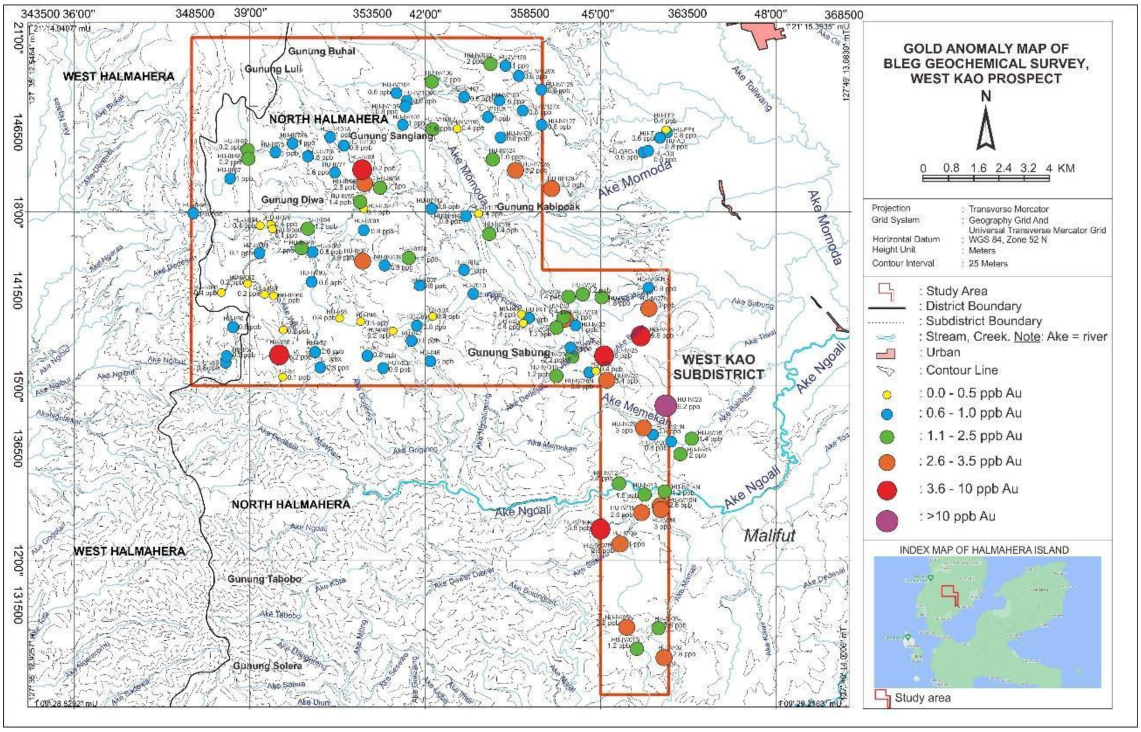

Figure 7. Gold anomaly map of BLEG stream sediment geochemical survey.

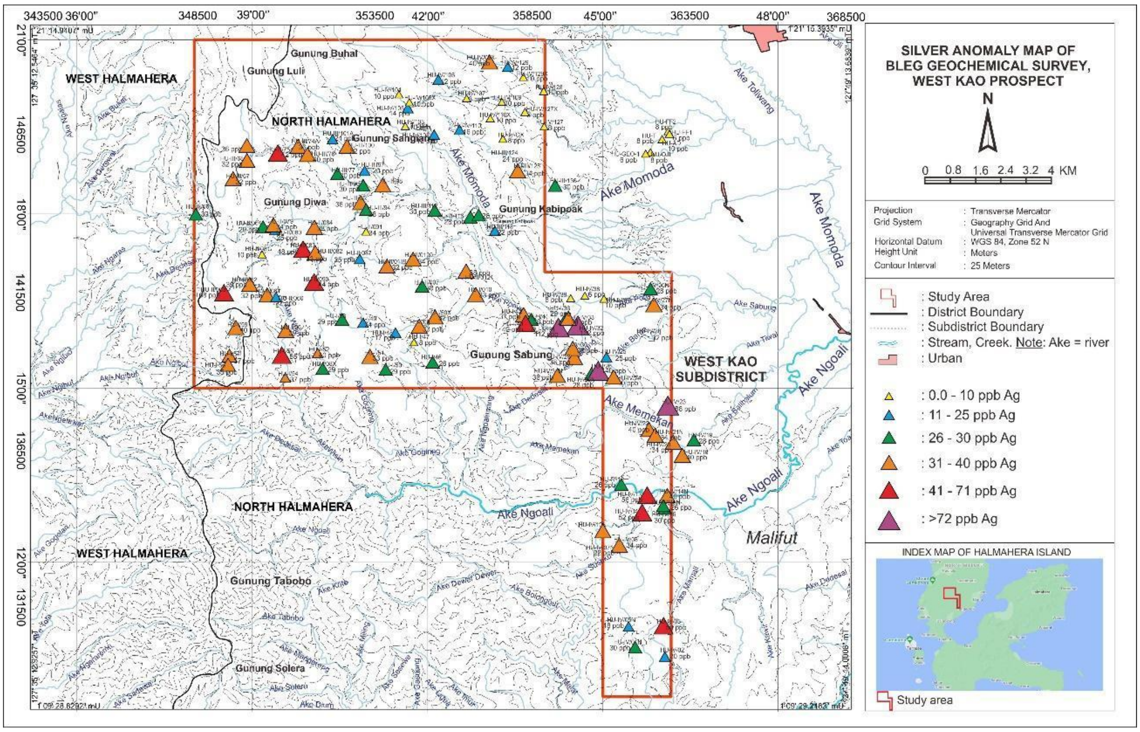

Figure 8. Silver anomaly map of BLEG stream sediment geochemical survey.

DISCUSSION

Relationship Between Geology, Alteration and Geochemical Anomalies

This section discusses the relationship between local geology, hydrothermal alteration/quartz vein float and gold and silver geochemical anomalies. Geological and hydrothermal alteration frameworks of the study area have been mapped out as shown by Figure 4 and Figure 5, respectively. Lithologically, the study area is predominantly occupied by fresh Quaternary andesitic lava particularly in the middle and western part of the study area. The eastern side of the area is mostly occupied by Tertiary tuffaceous sandstone which is subsequently intruded by andesite porphyry and andesite. The Tertiary tuffaceous sandstone is strongly argillic-altered and it may host the gold mineralization. Propylitic-altered rocks are also mapped out in the periphery of the argillic alteration zone. A close relationship between the argillic-altered tuffaceous sandstone and ore mineralization is supported by the spatial distribution of quartz vein floats which are widely found in the upstream creeks and on the slope of the hilly morphology of the area. The alteration and mineralization may also be controlled by the NW-SE-trending geological structure i.e. Tertiary pre-and/or syn-mineralization faults in the eastern part of the area. The presence of the pre-/syn-mineralization structures is obviously defined by the geological map. Moreover, the BLEG samples with the highest gold and silver contents (Au and Ag anomalies) identified in the eastern part of the study area are closely related to the strong argillic-altered rocks, geological structures and the occurrences of quartz vein floats spatially and genetically (Figure 9 and Figure 10). In addition, it is interpreted that the mineralization direction may be consistent with the gold-bearing quartz veins in the Gosowong district, which is directly located in the south of the study area. The gold-bearing epithermal quartz veins in the Gosowong goldfield are relatively directed to N-S – NNE-SSW for Gosowong and Toguraci vein zones as well as NW-SE direction for Kencana vein zones (cf. Gemmell, 2007).

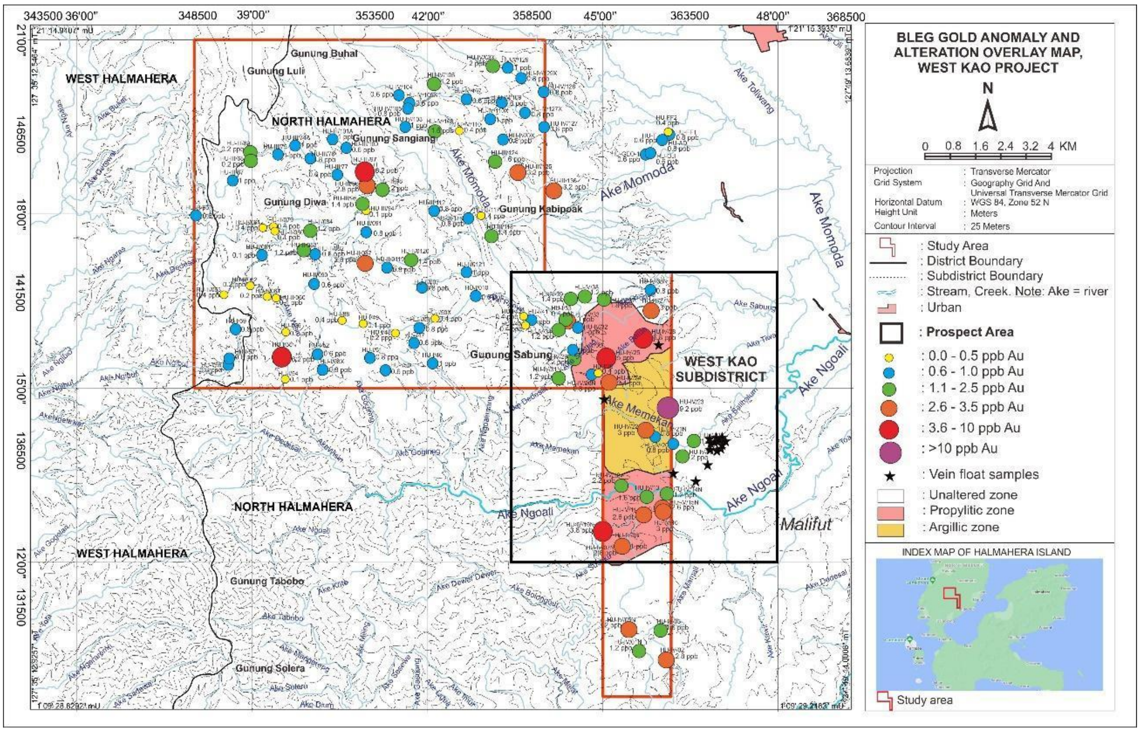

Figure 9. Overlay map of hydrothermal alteration zones and BLEG stream sediment geochemical gold anomalies.

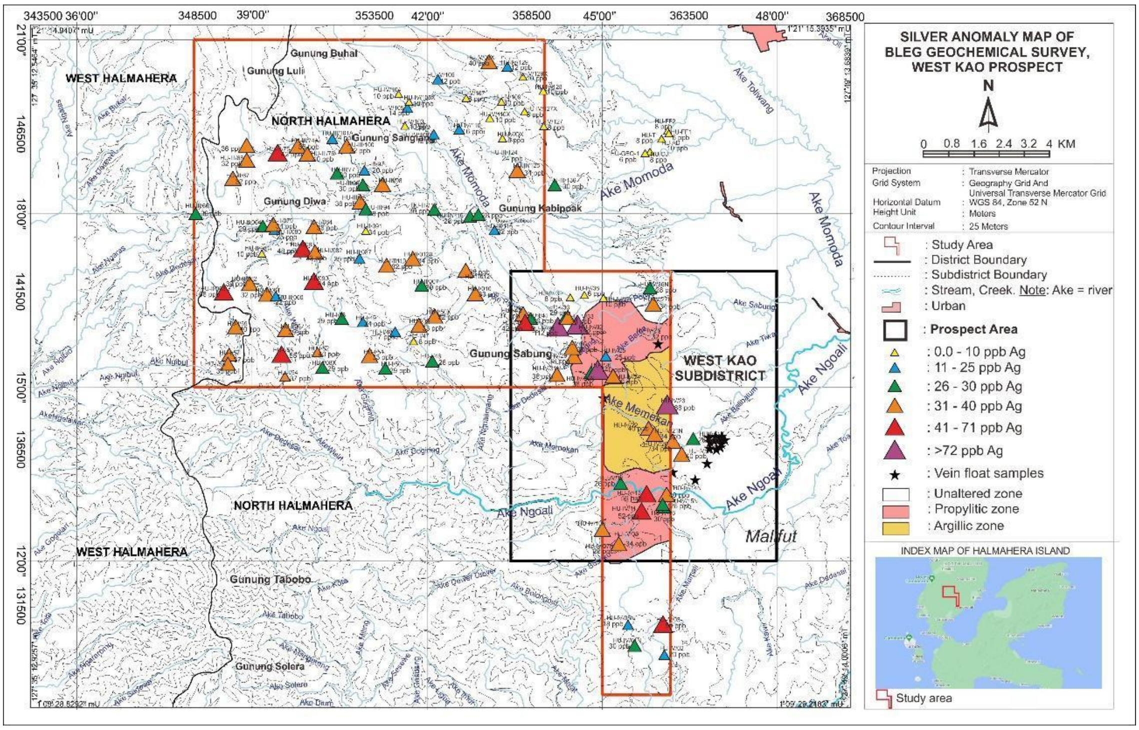

Figure 10. Overlay map of hydrothermal alteration zones, vein float and BLEG stream sediment geochemical silver anomalies.

Recommended Prospect Area and Follow-up Exploration

As outlined before, the most prospective area is located in the eastern part of the study area, which is obviously shown by the highest Au and Ag anomalies (Figure 9 and 10). To follow up on this finding, it is strongly recommended to do a next-step exploration program, particularly an aero-magnetic survey. This geophysical survey could be combined with a soil geochemical survey. An aero-magnetic survey is aimed not only to confirm the presence of Au and Ag anomalies from stream sediment geochemical survey in the restricted prospect area highlighted, but also to see the geophysical magnetic anomaly in the whole study area. Soil geochemical survey is done particularly focusing on the prospect area defined by stream sediment geochemical survey. Soil geochemical survey is aimed to define the occurrences of primary dispersion of gold mineralization within the study area. In addition, soil sampling could be combined with detailed geological and hydrothermal alteration mapping. These follow-up exploration programs will be beneficial to delineate the target area.

CONCLUSIONS

1. The study area is lithologically covered by volcanic sequences consisting of Tertiary tuffaceous sandstone, andesite, porphyritic andesite and Quaternary andesitic lava. In the eastern part of the area, the tuffaceous sandstone is strongly altered to argillic (the mineral assemblage of quartz, clay, and lesser pyrite) and propylitic (chlorite and epidote). Sulphide mineralization is predominantly indicated by the presence of pyrite and lesser galena, sphalerite and chalcopyrite contained by quartz veins found as floats in the upstream creek and on the hilly slope in the eastern part of the study area. It is also interpreted that the NW-SE-trending pre-/syn-mineralization faults in the eastern part of the study area also controlled the ore formation.
2. On the basis of BLEG stream sediment geochemical data, the most prospective area is located in the eastern part of the study area. This is supported by the BLEG samples with the highest gold and silver contents (Au and Ag anomalies of 49.2 ppb and 88 ppb, respectively) identified in the eastern part of the tenement area. This is concluded that there is a very close

relationship between the strong argillic-altered tuffaceous sandstone, geological structures and the occurrences of quartz vein floats in the recommended prospect area spatially and genetically.

ACKNOWLEDGEMENTS

This paper is a part of company service works led by the first author, which was served for the management of PT. Asindo Setiatama in Makassar, a funding partner of PT. Hibualamo Jaya in Tobelo, North Halmahera. Therefore, we wish to express our sincere thanks to the management of PT. Asindo Setiatama for their project funding, and their permission to utilize the data for this publication. Surface mapping and BLEG sampling in the remote area of West Kao was very challenging and difficult, mostly conducted by flying camp. Many thanks and appreciation are directed to all geologists and helpers for their excellent works, and the leader and people of the West Kao sub-district for their acceptance and support during the survey. Constructive revisions from reviewers are acknowledged.

REFERENCES

Arne, D. and MacFarlane, B. (2014) 'Reproducibility of gold analyses in stream sediment samples from the White Gold District and Dawson Range, Yukon Territory, Canada', *Explore*, (164), pp. 1–10.

Böhmer, M. and Kucera, M. (1986) *Prospecting and exploration of mineral deposits, Volume 21*. 2nd edn. Amsterdam: Elsivier.

Buchanan, L. J. (1981) 'recious metal deposits associated with volcanic environments in the Southwest', in Dickinson, W. R. and Payne, W. D. (eds) *Relations of tectonics to ore deposits in the southern Cordillera*. Arizona Geological Society Digest, pp. 237–262.

Carlile, J. C., Davey, G. R., Kadir, I., Langmead, R. P. and Rafferty, W. J. (1998) 'Discovery and exploration of the Gosowong epithermal gold deposit, Halmahera, Indonesia', *Journal of Geochemical Exploration*, 60(3), pp. 207–227. doi: 10.1016/S0375-6742(97)00048-4.

Carlile, J. C. and Mitchell, A. H. G. (1994) 'Magmatic arcs and associated gold and copper mineralization in Indonesia', *Journal of Geochemical Exploration*, 50(1–3), pp. 91–142. doi: 10.1016/0375-6742(94)90022-1.

Carranza, E. J. M. (2004) 'Usefulness of stream order to detect stream sediment geochemical anomalies', *Geochemistry: Exploration, Environment, Analysis*, 4(4), pp. 341–352. doi: 10.1144/1467-7873/03-040.

Chen, X., Zheng, Y., Xu, R., Wang, H., Jiang, X., Yan, H., Cai, P. and Guo, X. (2016) 'Application of classical statistics and multifractals to delineate Au mineralization-related geochemical anomalies from stream sediment data: a case study in Xinghai-Zeku, Qinghai, China', *Geochemistry: Exploration, Environment, Analysis*, 16(3–4), pp. 253–264. doi: 10.1144/geochem2016-424.

Cohen, D. R., Dunlop, A. C. and Rose, T. (2005) 'Contrasting dispersion patterns for gold in stream sediments at Timbarra, NSW, Australia', *Journal of Geochemical Exploration*, 85(1), pp. 1–16. doi: 10.1016/j.gexplo.2004.08.002.

Garwin, S., Hall, R. and Watanabe, Y. (2005) 'Tectonic setting, geology, and gold and copper mineralization in Cenozoic Magmatic Arcs of Southeast Asia and the West Pacific', in Hedenquist, J. W. et al. (eds) *One Hundredth Anniversary Volume*. Society of Economic Geologists, pp. 891–930. doi: 10.5382/AV100.27.

Gemmell, J. B. (2007) 'Hydrothermal alteration associated with the Gosowong epithermal Au-Ag deposit, Halmahera, Indonesia: Mineralogy, geochemistry, and exploration implications', *Economic Geology*, 102(5), pp. 893–922. doi: 10.2113/gsecongeo.102.5.893.

Grunsky, E. C. (2010) 'The interpretation of geochemical survey data', *Geochemistry: Exploration, Environment, Analysis*, 10(1), pp. 27–74. doi: 10.1144/1467-7873/09-210.

Hall, R. (2002) 'Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations', *Journal of Asian Earth Sciences*, 20(4), pp. 353–431. doi: 10.1016/S1367-9120(01)00069-4.

Hamilton, W. (1979) *Tectonics of the Indonesian region*. U.S. Geological Survey. doi: 10.3133/pp1078.

Hedenquist, J. W. and Arribas, A. (2017) der features relevant to exploration and asses'Epithermal ore deposits: first-or sment', in *Proceeding of 14th SGA Biennial Meeting: Mineral Resources to Discover - Volume 1*. Quebec, Canada: Society for Geology Applied to Mineral Deposits, pp. 47–50.

Hutchison, C. S. (1989) 'Geological evolution of South-east Asia', in. Clarendon Press, p. 368.

IAGI-MGEI (2015) 'Indonesia mineral endowment', in *IAGI (Indonesian Association of Geologists) on Road Map of Indonesian Mining*. IAGI & MGEI, p. 35.

Joyce, A. S. (1984) *Geochemical exploration*. Glenside: Australian Mineral Foundation.

Katili, J. A. (1978) 'Past and present geotectonic position of Sulawesi, Indonesia', *Tectonophysics*, 45(4), pp. 289–322. doi: 10.1016/0040-1951(78)90166-X.

Kirkwood, C., Everett, P., Ferreira, A. and Lister, B. (2016) 'Stream sediment geochemistry as a tool for enhancing geological understanding: An overview of new data from south west England', *Journal of Geochemical Exploration*, 163, pp. 28–40. doi: 10.1016/j.gexplo.2016.01.010.

Kitco.com (2021) *Gold price today*, *www.kitco.com*. Available at: https://www.kitco.com/scripts/hist_charts/daily_graphs.cgi?au=5&dailycharts=7&dailycharts=2021&submitau=View+Charts (Accessed: 8 May 2021).

Levinson, A. A. (1974) *Introduction to exploration geochemistry*. United States: Applied Publishing.

Maryono, A., Harrison, R. L., Cooke, D. R., Rompo, I. and Hoschke, T. G. (2018) 'Tectonics and geology of porphyry Cu-Au deposits along the Eastern Sunda Magmatic Arc, Indonesia', *Economic Geology*, 113(1), pp. 7–38. doi: 10.5382/econgeo.2018.4542.

Maula, S. and Levet, B. K. (1996) 'Porphyry copper-gold signatures and the discovery of the Batu Hijau deposit, Sumbawa, Indonesia', in *Conference on Porphyry Related Copper and Gold Deposits of the Asia Pacific Region*. Cairns, Australia: Australian Mineral Foundation, pp. 8.1-8.13.

Meldrum, S. J., Aquino, R. S., Gonzales, R. I., Burke, R. J., Suyadi, A., Irianto, B. and Clarke, D. S. (1994) 'The Batu Hijau porphyry copper-gold deposit, Sumbawa Island, Indonesia', *Journal of Geochemical Exploration*, 50(1–3), pp. 203–220. doi: 10.1016/0375-6742(94)90025-6.

Prihatmoko, S. and Idrus, A. (2020) 'Low-sulfidation epithermal gold deposits in Java, Indonesia: Characteristics and linkage to the volcano-tectonic setting', *Ore Geology Reviews*, 121, p. 103490. doi: 10.1016/j.oregeorev.2020.103490.

Ranasinghe, P. N., Fernando, G. W. A. R., Dissanayake, C. B., Rupasinghe, M. S. and Witter, D. L. (2009) 'Statistical evaluation of stream sediment geochemistry in interpreting the river catchment of high-grade metamorphic terrains', *Journal of Geochemical Exploration*, 103(2–3), pp. 97–114. doi: 10.1016/j.gexplo.2009.07.003.

Ridley, J. (2013) *Ore deposit geology*. Cambridge: Cambridge University Press.

Robb, L. (2005) *Introduction to ore-forming processes*. Oxford: Wiley-Blackwell.

Rose, A. W., Hawks, H. E. and Webb, J. H. (1979) *Geochemistry in mineral exploration*. New York: Academic Press.

Shafiee, S. and Topal, E. (2010) 'An overview of global gold market and gold price forecasting', *Resources Policy*, 35(3), pp. 178–189. doi: 10.1016/j.resourpol.2010.05.004.

Simmons, S. F., White, N. C. and John, D. A. (2005) 'Geological characteristics of epithermal precious and base metal deposits', in Hedenquist, J. W. et al. (eds) *One Hundredth Anniversary Volume*. Society of Economic Geologists, pp. 485–522. doi: 10.5382/AV100.16.

Sun, X., Zheng, Y., Wang, C., Zhao, Z. and Geng, X. (2016) 'Identifying geochemical anomalies associated with Sb–Au–Pb–Zn–Ag mineralization in North Himalaya, southern Tibet', *Ore Geology Reviews*, 73, pp. 1–12. doi: 10.1016/j.oregeorev.2015.10.020.

Supriatna, S. (1980) 'Peta geologi lembar Morotai Skala 1:250.000'. Bandung: Pusat Penelitian dan Pengembangan Geologi (P3G), p. 1.

Theobald, P. K., Eppinger, R. G., Turner, R. L. and Shiquan, S. (1991) 'The effect of scale on the interpretation of geochemical anomalies', *Journal of Geochemical Exploration*, 40(1–3), pp. 9–23.

Weng, F., Chen, Y., Wang, Z., Hou, M., Luo, J. and Tian, Z. (2020) 'Gold price forecasting research based on an improved online extreme learning machine algorithm', *Journal of Ambient Intelligence and Humanized Computing*, 11(10), pp. 4101–4111. doi: 10.1007/s12652-020-01682-z.

White, N. C. and Hedenquist, J. W. (1995) 'Epithermal gold deposits: Styles, characteristics, and exploration', *SEG Newsletter*, (23), pp. 1, 9–13.

Xuejing, X. and Xueqiu, W. (1991) 'Geochemical exploration for gold: a new approach to an old problem', *Journal of Geochemical Exploration*, 40(1–3), pp. 25–48. doi: 10.1016/0375-6742(91)90030-X.

Yilmaz, H., Ghezelbash, R., Cohen, D. R., Sari, R., Sönmez, F. N. and Maghsoudi, A. (2020) 'Comparison between the geochemical response of BLEG and fine fraction stream sediments to mineralization in the Eastern Black Sea region, Turkey', *Journal of Geochemical Exploration*, 217, p. 106609. doi: 10.1016/j.gexplo.2020.106609.

Yilmaz, H., Cohen, D. R. and Sonmez, F. N. (2017) 'Comparison between the effectiveness of regional BLEG and −80# stream sediment geochemistry in detection of precious and base metal mineral deposits in Western Turkey', *Journal of Geochemical Exploration*, 181, pp. 69–80. doi: 10.1016/j.gexplo.2017.07.003.

Yousef, I. and Shehadeh, E. (2020) 'The impact of COVID-19 on gold price volatility', *International Journal of Economics and Business Administration*, VIII(Issue 4), pp. 353–364. doi: 10.35808/ijeba/592.