Open Journal of Geology, 2018, 8, 383-398
http://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Whole-Rock Geochemistry of Host Rocks and K/Ar Age of Hydrothermal Mineral of the Co-O Epithermal Gold Deposit, Mindanao, Philippines

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How to cite this paper: Taguibao, K.J.L. and Takahashi, R. (2018) Whole-Rock Geochemistry of Host Rocks and K/Ar Age of Hydrothermal Mineral of the Co-O Epithermal Gold Deposit, Mindanao, Philippines. *Open Journal of Geology*, **8**, 383-398.
https://doi.org/10.4236/ojg.2018.84022

Received: February 8, 2018
Accepted: April 10, 2018
Published: April 13, 2018

Abstract

Whole-rock chemical composition of host rocks and recently acquired K/Ar age of hydrothermal mineral of the Co-O epithermal gold deposit in Mindanao Island of the Philippines are herein reported. Located along a Pliocene-Quaternary calc-alkaline magmatic zone at eastern Mindanao region, the Co-O gold deposit is of intermediate sulfidation epithermal Au (+Ag ± Cu ± Pb ± Zn) quartz vein type. Geological units in the area are probable Eocene to Oligocene basaltic-andesitic to andesitic volcanic flows and volcaniclastic rocks, Oligocene andesitic to dioritic stocks and dikes, a diatreme-maar complex, and an overlying sedimentary sequence. The mineralized quartz ± calcite veins are mainly hosted in the intrusive rocks and surrounding volcanic rocks that are hydrothermally altered generally to K-feldspar, chlorite and other clay minerals. Discrimination diagram using immobile elements such as Zr/TiO_2 vs. Nb/Y indicates that these rocks belong to sub-alkaline andesite and basaltic-andesite to basalt and alkali basalt in composition. The volcanic rocks plot in the island arc tholeiite and calc-alkaline fields of generally basaltic andesite and andesite composition, with a few in basalt and dacite. In the "alteration box plot", the samples mostly plot within the least altered intermediate volcanic host rocks in the hydrothermal alteration field. Plots of each rock unit show a general chlorite-carbonate (-pyrite) alteration trend, with plots of volcanic rocks more dispersed and a few fallen outside the least altered box. K/Ar dating of hydrothermal minerals from the andesite porphyry and polymictic diatreme breccia samples yielded ages of 28.6 ± 0.9 Ma (Late Oligocene) and 31.7 ± 1.9 Ma (Early Oligocene), respectively. Age dating of these hydrothermally formed minerals gives the age of the hydrothermal activity associated with the mineralization. This suggests that the hydrothermal activity associated with the Co-O epithermal vein system transpired immediately after or during the Oligocene magmatism in a tectonic setting that produced island arc tholeiitic to calc-alkaline magmas, prior to drifting to its present location and accretion with the central and western parts of the Mindanao Island; in contrast to more prominent Miocene and Pliocene to Pleistocene mineralization ages along the Philippine archipelago.

Keywords

Epithermal Gold Deposit, Co-O Deposit, Hydrothermal Alteration, K-Ar Age Dating

1. Introduction

In the southernmost main island of the Philippines (**Figure 1**), the Co-O mine sits in the Central Pacific Cordillera of the Eastern Mindanao Province (**Figure 2**). This region is saddled between the North Pacific Cordillera to the north and the South Pacific Cordillera to the south. Structural features separating these regions of the north-south trending cordillera are the Lianga Fault and Cateel Bay Fault. These regional structures including the Mati Fault to the south constitute the southern horsetail structure of the left-lateral strike-slip Philippine Fault that runs along the entire stretch of the Philippine archipelago [1] (**Figure 1** and **Figure 2**).

The Co-O gold underground mine is currently being operated by the Philsaga Mining Corp., which is a Philippine subsidiary of the Medusa Mining Ltd. As described in earlier consultancy works and company surveys, the Co-O deposit is characterized as an intermediate sulfidation epithermal gold (+Ag ± Cu ± Pb ± Zn) quartz vein type (*e.g.*, [2] [3]). The Co-O mine was first developed in the late 1980s and has since then been currently developed to about 350 meters below the adit level (Level 1) that is at 150 meters above mean sea level. East-west length of underground workings reaches to about 1000 meters per level. The reported reserve of the Co-O mine for mid-2017 is 1.64 M tonnes at 6.54 g/t for 345,000 ounces of gold [4].

With a purpose to reconstruct the tectonic history of the Co-O epithermal gold deposit and vicinity, this paper presents the results of recently conducted whole-rock geochemical analyses on the basis of X-ray fluorescence (XRF) spectroscopy and inductively coupled plasma-mass spectrometry (ICP-MS) and K/Ar dating of selected representative samples of host rocks of the Co-O epithermal gold vein deposit.

2. Regional Setting

As in earlier works (*e.g.*, [1] [5] [7]), the Philippine archipelago has been generally described as an amalgamation of magmatic rocks, ophiolitic suites,

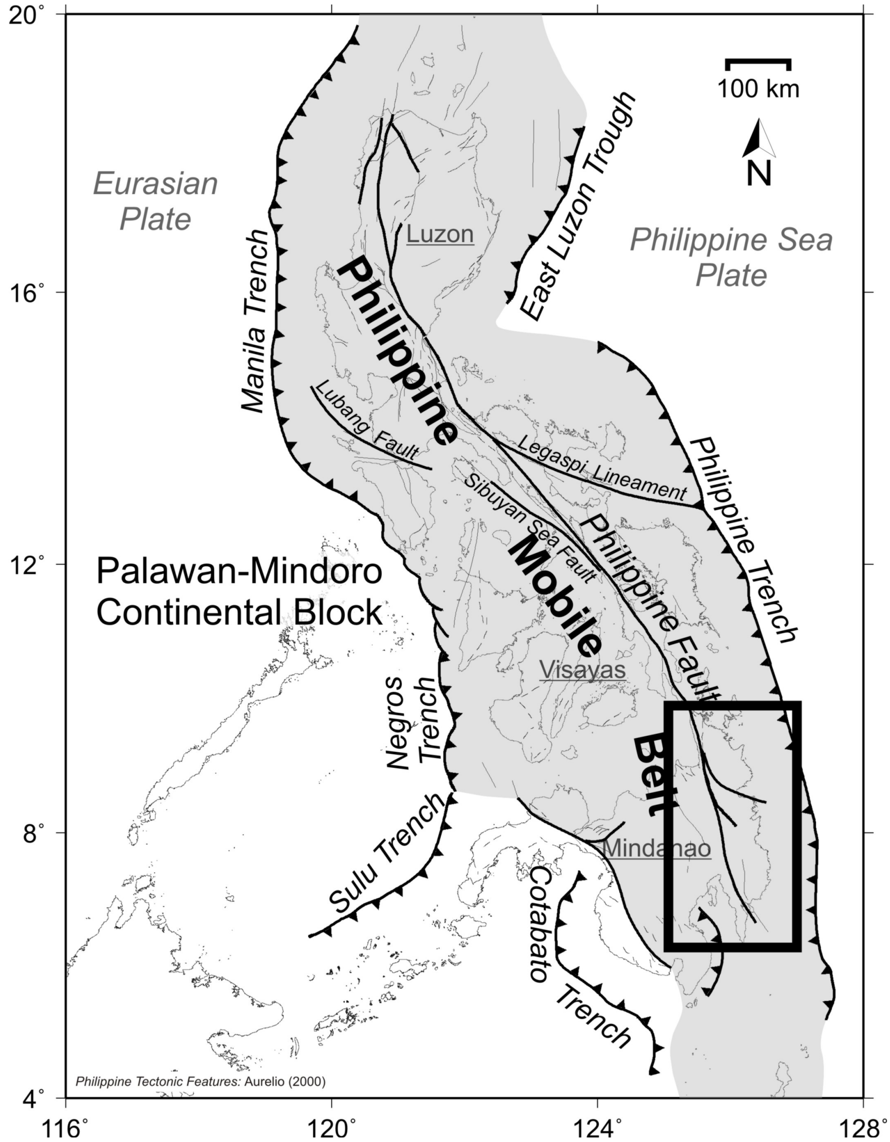

Figure 1. Regional map of the Philippines showing major tectonic features affecting the archipelago. Location of study area is indicated by black-outlined rectangle in the southern portion of the tectonically active Philippine Mobile Belt (PMB). Figure generated based from [5] with the Generic Mapping Tool (GMT) using Digital Elevation Model (DEM) of the Generic Bathymetric Chart of the Oceans (GEBCO) [6] as base image. Trace of PMB and other structural features are adopted from previous studies such as by [1] [5] [7].

sedimentary basins and metamorphic units that are grouped into two distinct tectono-stratigraphic terranes, namely: Philippine Mobile Belt (PMB) and Palawan-Mindoro Continental Block (**Figure 1**). The ophiolitic and metamorphic rocks constitute the pre-Tertiary basement of the Philippine archipelago [1].

The Philippine Mobile Belt is an active deformation zone between the Philippine Sea Plate to the east and the eastern margin of the Eurasian Plate to the west. It comprises majority of the whole length of the Philippine archipelago, from the whole Luzon island to most parts of the Visayas and Mindanao islands.

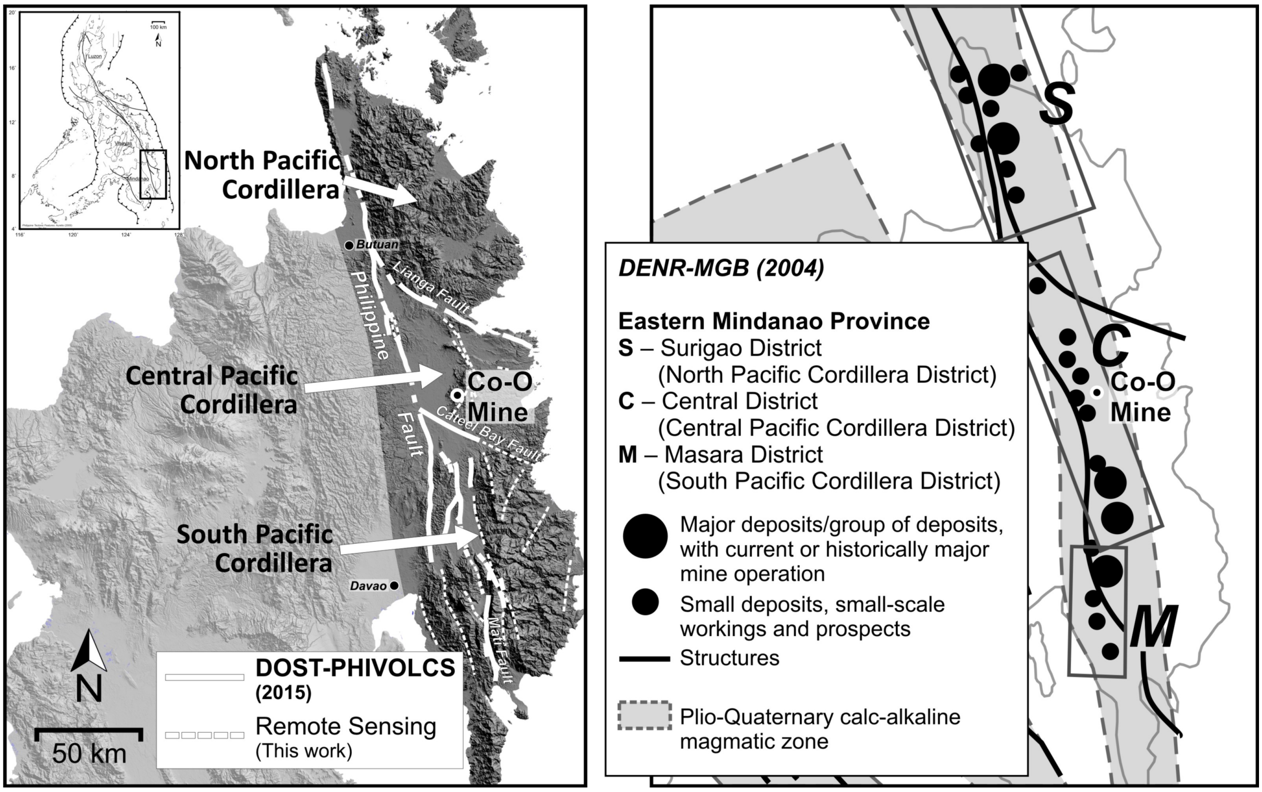

Figure 2. Maps showing regional geological structures traversing the eastern Mindanao region with location of mineral deposits along a Plio-Quaternary calc-alkaline magmatic zone. Location of the Co-O mine is indicated by white-outlined black dot. Left figure was generated using base image Satellite Radar Topography Mission (SRTM) data [8] with structural features from Philippine Institute of Volcanology and Seismology [9], earlier studies such as by [1] and [7], including remote sensing of satellite data from this work. Right figure was redrawn from the Department of Environment and Natural Resources-Mines and Geosciences Bureau (DENR-MGB) map of mineral districts in the Philippines [10] showing the Co-O epithermal gold deposit as part of the Central Pacific Cordillera or Central District. Inset map shows the location of the region discussed (as in **Figure 1**).

It is bounded on both sides by subduction zones of opposing polarities and traversed by the ~1200-km left-lateral strike slip Philippine Fault System (**Figure 1**). Tectonically separated from the PMB is the Palawan-Mindoro Continental Block at the western side of the archipelago. This block is believed to have been rifted from mainland Asia and drifted to its present position as it collided with the PMB (*e.g.*, [1] [5]).

Previous works on the eastern Mindanao Island are mainly focused on the Surigao and/or Masara District including other areas of the island and southern offshore regions with implications on the island's tectonic history (*e.g.*, [11] [12]). According to these studies, the pre-Miocene geological units of Eastern Mindanao were formed in southern latitudes and have moved towards the northwest until it collided with the pre-Miocene units of the Western Mindanao that were derived from the eastern Eurasian margin generally of continental affinity. Studies on the reconstruction of paleo-latitudes using onshore and offshore paleomagnetic declinations (*e.g.*, [13] [14]) reveal that the Eastern Mindanao during Oligocene (30 Ma) was located at 10˚S latitude, where a northeast-dipping subduction system was forming most of the Eastern Mindanao arc units.

3. Deposit Geology

Main lithologies associated with the Co-O gold deposit are volcanic and volcaniclastic rocks intruded by diorite, dacite and andesite porphyries, all in turn cut and overlain by a diatreme-maar complex typified by polymictic volcanic breccias (Figure 3).

These units are composed of typical mineral assemblages of volcanic and intrusive rocks of basalt-andesitic to andesitic composition. The porphyritic andesitic to basaltic-andesitic volcanic rocks consist of phenocrysts mainly of plagioclase partly altered to K-feldspar, calcite and/or clay (smectite, interstratified illite-smectite, chlorite ± kaolinite; confirmed through X-ray diffractometry), with subordinate hornblende and/or clinopyroxene altered into chlorite, and quartz, set in a microcrystalline groundmass. Intrusive andesite porphyries include similar assemblage and alteration minerals, with some containing xenoliths of porphyritic andesite. These rocks exhibit similar alteration assemblage to

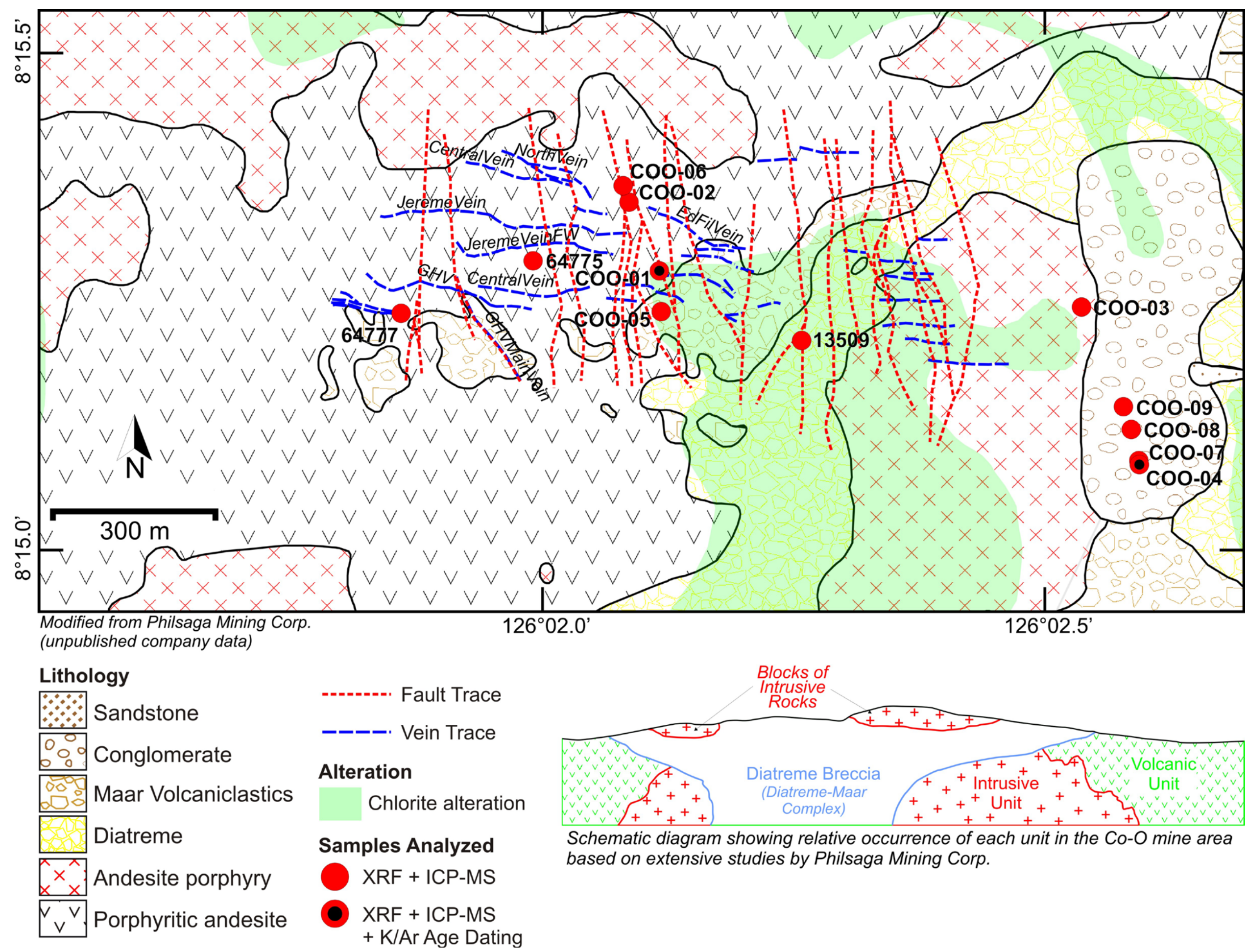

Figure 3. Composite map of the Co-O gold mine area and vicinity showing distribution of main lithologic units, alteration, surface-projected fault traces, major veins, and location of samples. Traces of major veins are projected in blue dashed lines, and faults by red dashed lines. Red dots indicate surface projection of location of samples. Distribution of lithologies, traces of veins and delineated faults are adopted from unpublished data of the Philsaga Mining Corporation. Outline of chlorite alteration region modified from unpublished data of the Philsaga Mining Corporation.

those of the volcanic rocks but of higher degree of alteration. Pyrite, ilmenite, and chalcopyrite are found in the volcanic rocks, while hematite, magnetite, pyrite, chalcopyrite and ilmenite are in the intrusive rocks. In both units, quartz ± calcite veins/veinlets are present. Polymictic diatreme volcanic breccias, as defined by the Philsaga Mining Corporation (unpublished internal report), generally contain clasts of the abovementioned units with detrital grains of quartz and feldspars set in a fine-grained (flour) or patches of quartzofeldspathic, calcitic, and chloritic minerals as matrix.

4. Whole-Rock Geochemistry of Volcanic Rocks

4.1. Field Sampling and Analytical Methods

Samples that were used for the analyses were mainly obtained from the Co-O underground mine and drill cores generally at depths 150 to 200 meters below sea level. Since all of the lithologic units are hydrothermally altered within the deposit area, the least altered samples were selected for the geochemical analyses.

Whole-rock major element compositions of representative samples of host rocks obtained from the underground mine workings and drill cores were measured using an in-house Rigaku ZSX Primus II X-ray fluorescence (XRF) spectrometer in the Faculty of International Resource Sciences at Akita University. One set of powdered samples contained in ceramic crucibles was dried to 110˚C and heated to 900˚C in a Yamato DX 400 drying oven to obtain the loss on ignition (LOI) value of each sample. Another set of the powdered samples was prepared into pressed pellets in polyvinyl chloride (PVC) rings using a press machine and flat type dies. This set of samples was analyzed using the XRF spectrometer with fundamental parameter (FP) method combined with empirical method. The results were normalized to 100 wt% total after adding the LOI values determined separately. Whole-rock trace element concentration of the host rocks were measured using inductively coupled plasma-mass spectrometer (ICP-MS) outsourced to ALS laboratory in Brisbane, Australia.

4.2. Major and Trace Element Composition of Host Rocks

Results of whole-rock geochemical investigation on the basis of measurements by XRF and ICP-MS (**Table 1**) of host rocks of the Co-O epithermal gold deposit indicate that these rocks belong to an island arc tholeiitic to calc-alkaline magma series of mainly sub-alkaline andesite and basaltic-andesite to basalt and alkali basalt in composition (**Figure 4** and **Figure 5**).

Since all of the units associated with the Co-O deposit are hydrothermally altered, as manifested by loss on ignition (LOI) values higher than 3 wt% (**Table 1**), plots that employ trace elements considered to be immobile during hydrothermal alteration are used in the discussion. Plots of whole-rock Nb/Y and Zr/TiO_2 of representative samples of the diatreme breccia, volcanic and intrusive rocks associated with the Co-O deposit in the diagram by [15] show that these units are plotted within the sub-alkaline andesite and basaltic-andesite to basalt

Table 1. Major (in wt%) and trace element (in ppm) compositions of the volcanic, intrusive, and polymictic diatreme breccia units of the Co-O epithermal gold deposit.

	13509-A	13509-B	64775	64777	COO-01
	Volcanic rock	Volcanic rock	Volcanic rock	Volcanic rock	Intrusive rock
SiO_2 (wt%)	54.06	55.04	56.83	52.88	49.30
TiO_2	0.74	0.66	0.26	0.74	0.91
Al_2O_3	16.35	16.29	6.40	18.55	20.94
Fe_2O_3	9.14	8.98	8.23	12.06	8.63
MnO	0.38	0.37	0.22	0.18	0.29
MgO	4.74	4.82	1.05	3.20	3.00
CaO	6.21	4.26	15.03	3.38	5.50
Na_2O	0.83	0.50	0.01	1.04	0.00
K_2O	2.06	2.51	1.26	2.49	3.67
P_2O_5	0.15	0.14	0.05	0.17	0.18
LOI	5.34	6.43	10.67	5.29	7.57
Sum	100.00	100.00	100.00	100.00	100.00
Ba (ppm)	84.9	84.0	54.3	191.7	230.0
Co	n.m.	n.m.	n.m.	n.m.	17.50
Cr	55.1	47.0	54.7	64.0	11.0
Nb	14.7	10.7	10.7	2.1	3.0
Ni	24.1	24.3	35.3	37.4	8.4
Rb	44.3	49.9	25.7	49.4	59.5
Sr	198.3	102.2	36.7	159.1	49.5
Th	n.m.	n.m.	n.m.	n.m.	0.64
V	223.3	218.4	75.1	310.5	189.0
Y	20.2	17.1	12.5	25.4	20.5
Zr	100.5	90.3	36.8	62.9	20.7
Nb/Y	0.73	0.63	0.86	0.08	0.15
Zr/Y	4.98	5.28	2.94	2.48	1.01

Continued

	COO-02	COO-03	COO-04	COO-05	COO-06
	Volcanic rock	Volcanic rock	Polymictic diatreme breccia	Intrusive rock	Volcanic rock
SiO_2 (wt%)	53.58	46.14	52.75	50.15	50.36
TiO_2	0.83	0.84	0.85	1.11	0.81
Al_2O_3	17.24	21.39	17.87	16.69	20.33
Fe_2O_3	12.88	5.72	8.48	8.92	6.75
MnO	0.12	0.17	0.19	0.32	0.21
MgO	3.22	4.18	3.95	3.84	2.44
CaO	5.40	7.91	5.35	7.49	6.51
Na_2O	0.88	0.73	2.39	2.36	0.00
K_2O	2.26	4.11	1.33	2.38	3.51
P_2O_5	0.28	0.13	0.15	0.24	0.15
LOI	3.30	8.69	6.69	6.49	8.92
Sum	100.00	100.00	100.00	100.00	100.00
Ba (ppm)	270.0	110.0	120.0	110.0	70.0
Co	10.20	29.80	19.90	29.90	37.90
Cr	22.0	16.0	31.0	15.0	25.0
Nb	1.3	1.9	2.4	3.5	1.8
Ni	16.3	13.6	15.2	12.4	20.4
Rb	50.2	57.6	22.7	48.4	16.3
Sr	227.0	282.0	136.5	167.5	277.0
Th	0.56	0.51	0.90	0.78	0.58
V	243.0	223.0	192.0	192.0	218.0
Y	23.5	13.6	20.0	25.4	21.5
Zr	11.8	2.3	60.9	20.4	16.2
Nb/Y	0.06	0.14	0.12	0.14	0.08
Zr/Y	0.50	0.17	3.05	0.80	0.75

Continued

	COO-07	COO-08	COO-09
	Polymictic diatreme breccia	Polymictic diatreme breccia	Volcanic rock
SiO_2 (wt%)	52.57	50.38	48.65
TiO_2	0.82	0.63	0.73
Al_2O_3	17.46	18.65	18.26
Fe_2O_3	8.43	5.40	10.08
MnO	0.19	0.16	0.26
MgO	3.87	3.32	4.72
CaO	6.04	9.10	6.69
Na_2O	2.33	2.30	0.56
K_2O	1.32	0.74	1.23
P_2O_5	0.16	0.14	0.18
LOI	6.81	9.18	8.63
Sum	*100.00*	*100.00*	*100.00*
Ba (ppm)	120.0	80.0	80.0
Co	20.80	13.80	26.40
Cr	23.0	22.0	54.0
Nb	2.3	2.1	1.8
Ni	12.2	11.0	22.8
Rb	19.2	7.5	21.3
Sr	147.5	269.0	212.0
Th	0.82	0.76	0.89
V	189.0	127.0	212.0
Y	21.3	18.7	23.3
Zr	56.1	37.4	20.3
Nb/Y	0.11	0.11	0.08
Zr/Y	2.63	2.00	0.87

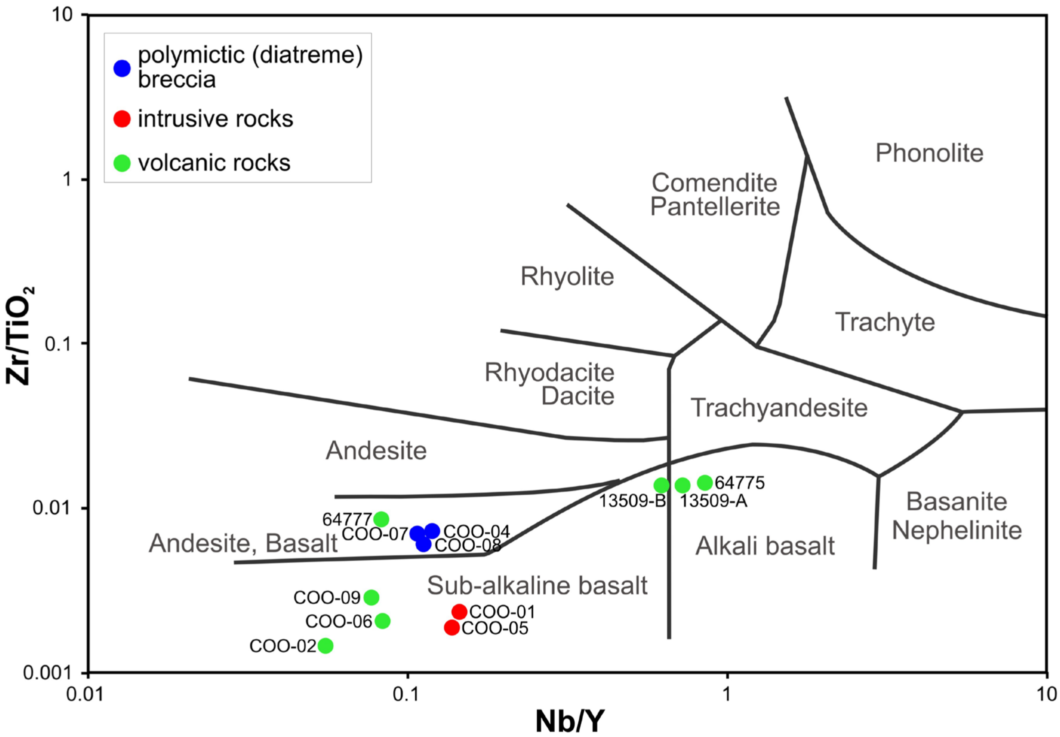

Figure 4. Whole-rock Zr/TiO_2 vs. Nb/Y plots of the polymictic (diatreme) breccia, intrusive and volcanic rocks associated with the Co-O deposit on the rock discrimination diagram by [15].

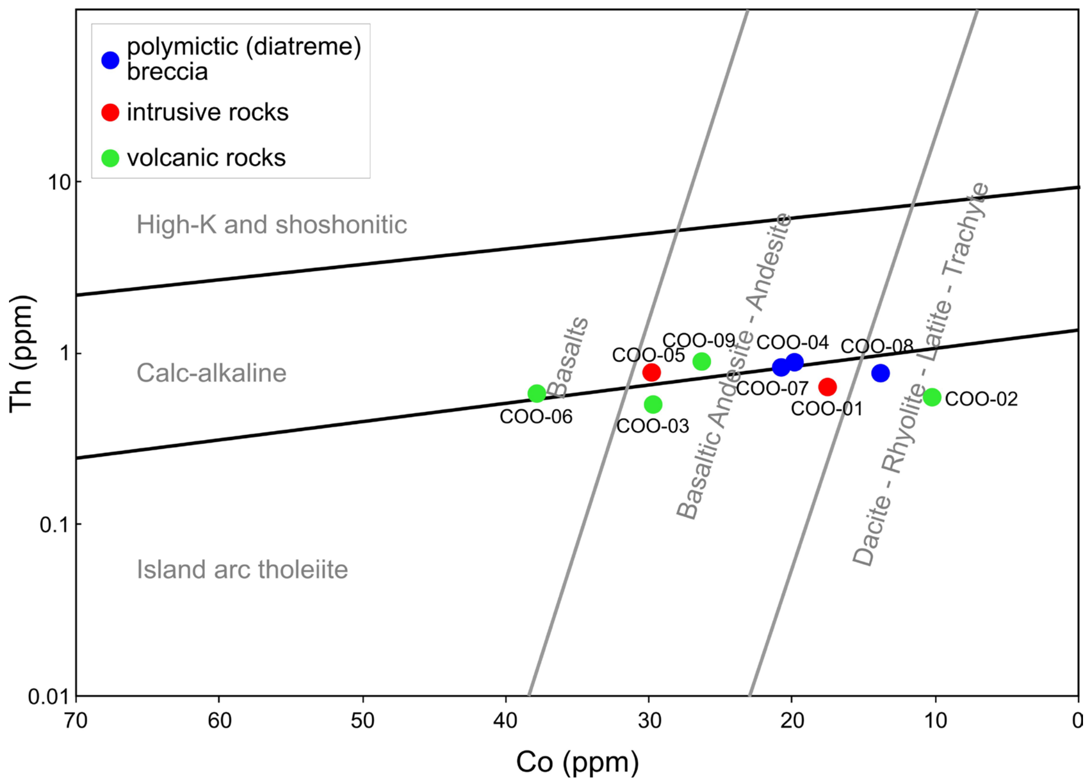

Figure 5. Whole-rock Th vs. Co of the polymictic (diatreme) breccia, intrusive and volcanic rocks associated with the Co-O deposit plot within the calc-alkalic to island arc tholeiitic magma series of basalt, basaltic andesite and andesite to dacite composition on the magma series discrimination diagram by [16].

and alkali basalt regions (**Figure 4**). Samples of the polymictic diatreme breccia mainly plot in the andesite-basalt field, intrusive rocks in the sub-alkaline basalt, and volcanic rocks in the sub-alkaline andesite-basalt to basalt and alkali basalt regions.

Polymictic (diatreme) breccia, intrusive and volcanic rocks mainly plot within the calc-alkaline and island arc tholeiite fields, with basalt, basaltic andesite and andesite to dacite composition in the whole-rock Th-Co discrimination diagram by [16] (**Figure 5**).

Previous works on whole-rock major and trace element compositions of the Oligocene igneous host rocks of the Co-O epithermal gold deposit (*i.e.*, [2] [3]) likewise plot representative samples of basalt, andesite, and dacite dominantly in the calc-alkaline magma series, with a few in the tholeiitic magma series. A more extensive geochemical study on Mindanao igneous rocks [17] suggested that the island was formed over time from different successive arc systems, two of which are the Eocene to Oligocene (45 - 25 Ma) island arc tholeiitic magmatism and Early Miocene (20 - 16 Ma) large ion lithophile element (LILE: Cs, Rb, Ba, U, K)-rich calc-alkaline to potassic calc-alkaline magmatism.

4.3. Alteration

In general, all of the polymictic diatreme breccia, intrusive and volcanic rocks associated with the Co-O deposit exhibit low to intermediate degree of alterations. These include chlorite alteration of hornblende and/or clinopyroxene, as well as K-feldspar, calcite and/or clay alteration of plagioclase.

Using the "alteration box plot" by [18], which incorporates Ishikawa alteration index (AI) [19] with chlorite-carbonate-pyrite index (CCPI), the alteration trends of the rocks directly show the alteration mineralogy and degree of alteration of each of the rock unit according to their lithogeochemistry (**Figure 6**). In the diagram, the AI reflects the ratio of the principal rock-forming elements that were gained (K_2O + MgO) during chlorite and sericite alteration with the total elements that were gained and lost (K_2O + MgO + Na_2O + CaO) [17] [18]. The CCPI, on the other hand, is used to measure MgO and FeO increase associated with the Mg-Fe chlorite development, wherein albite, K-feldspar, or sericite in volcanic rocks are typically replaced and lead to loss in Na_2O and K_2O content [18]. Mineral end-members such as epidote, calcite, dolomite, ankerite, chlorite, pyrite, sericite, K-feldspar, and albite plot on the box boundaries (**Figure 6**). The alteration box plot is composed of the diagenetic alteration field (lower left) and hydrothermal alteration field (upper right). At the center of the diagram is the box for least altered volcanic rocks, while beyond this box are the hydrothermally altered volcanics plotted at different locations depending on the main hydrothermal minerals contained. Common trend lines associated with hydrothermal alteration are, namely: weak sericite alteration, intense sericite-chlorite ± pyrite alteration, chlorite ± pyrite (±sericite) alteration, chlorite-carbonate alteration, sericite-carbonate alteration, and K-feldspar-sericite alteration.

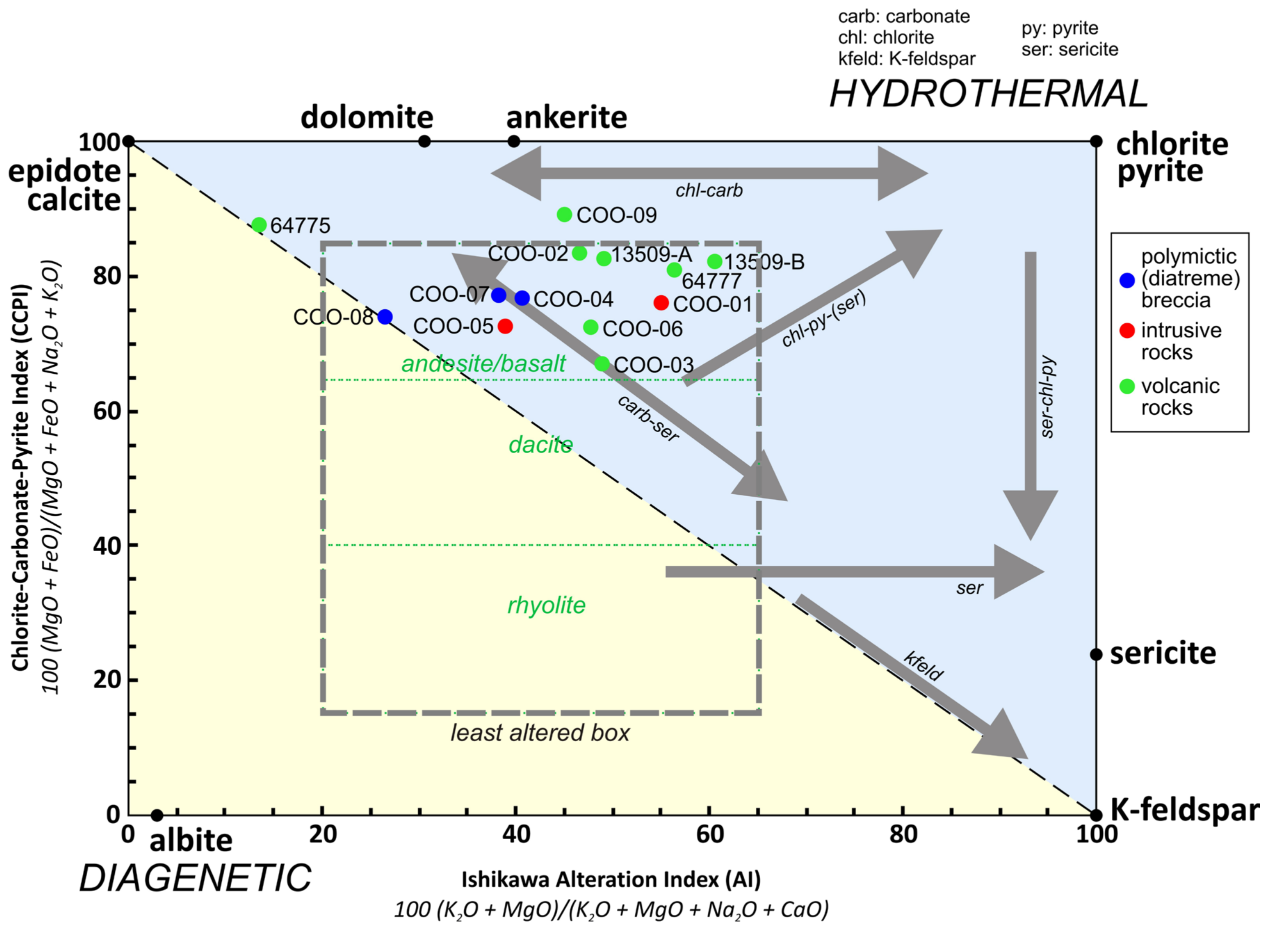

Figure 6. Plots of Chlorite-Carbonate-Pyrite Index [18] versus Alteration Index [19] of polymictic (diatreme) breccia, intrusive and volcanic rocks associated with the Co-O epithermal gold deposit on the "alteration box plot" of [18] showing relative degree of alteration and general alteration mineralogy.

Majority of the polymictic diatreme breccia, intrusive and volcanic rocks plot within the box of least altered intermediate volcanic host rocks (andesite-basalt region) mainly within the hydrothermal alteration field (Figure 6). These rocks generally exhibit trends which coincide with the chlorite-carbonate and chlorite ± pyrite (± sericite) alteration in the hydrothermal alteration field, consistent with the general alteration to chlorite, calcite and other clay minerals observed in these rocks. The chlorite ± pyrite (± sericite) alteration trend line is known to be typical of chlorite-dominated footwall alteration in felsic or mafic volcanic rocks mainly of volcanic-hosted massive sulfides [18]. Chlorite-carbonate alteration trend line whilst is normally developed proximal to massive sulfide lenses in a footwall in felsic or mafic host rocks [18].

The polymictic diatreme breccia mainly plot in the mid-portion of the least altered andesite-basalt box, with one polymictic breccia plotting in the border between the hydrothermal and diagenetic alteration fields (Figure 6). One andesite porphyry plots in the near mid-portion of the least altered andesite-basalt box, and the other towards the upper right corner of the least altered box, following a chlorite-pyrite (-sericite) alteration trend. The volcanic rocks are more dispersed in the alteration box plot, depending on their spatial distribution with respect to the deposit veins. Porphyritic andesite and andesitic volcaniclastic rocks obtained distal to the epithermal veins generally plot in the mid-portion of the least altered andesite-basalt box, whereas andesitic volcanic rocks obtained from the underground mine workings plot towards the upper right border of the least altered box, following a chlorite-pyrite (-sericite) alteration trend, with one sample just outside the upper left corner of the least altered box, following a chlorite-carbonate and/or carbonate-sericite alteration trend (**Figure 3** and **Figure 6**).

5. K/Ar Dating

Geochronological analysis using K/Ar dating of the andesite porphyry and polymictic diatreme breccia was outsourced to Activation Laboratories (Actlabs) in Ancaster, Ontario, Canada. Prior to K/Ar dating, bulk samples of these rocks were sent to Actlabs for quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) and mineral separation. Based on the modal mineralogical study, the mineral selected for age dating is feldspar, which may have partly replaced primary plagioclase (*e.g.*, [20]).

Selected representative sample of the andesite porphyry plots on the sub-alkaline basalt composition in the Zr/TiO_2 vs. Nb/Y discrimination diagram and on the island arc tholeiitic basaltic andesite-andesite in the Th vs. Co diagram.

For the polymictic diatreme breccia, geochemical analysis of the selected representative sample of this unit plots on the basaltic andesite composition in the Zr/TiO_2 vs. Nb/Y discrimination diagram and on the calc-alkaline basaltic andesite-andesite in the Th vs. Co diagram.

Results of the K/Ar dating of the feldspar concentrates yielded ages of 28.6 ± 0.9 Ma (Late Oligocene) for the andesite porphyry and 31.7 ± 1.9 Ma (Early Oligocene) for the polymictic diatreme breccia (**Table 2**).

In principle, for ideal settings (closed system), age dating of alteration products indicates the age of hydrothermal activity or alteration event, which is typically associated with the mineralization event forming the deposit system (*e.g.*, [21]). Age dating of the hydrothermal minerals therefore gives the age of the hydrothermal activity associated with the mineralization.

As in previous works (*e.g.*, [17]), the volcanic host rocks of the Co-O deposit is dated to be of Oligocene (~32 Ma) age, possibly attributing to the Eocene to

Table 2. Major (in wt%) and trace element (in ppm) compositions of the volcanic, intrusive, and polymictic diatreme breccia units of the Co-O epithermal gold deposit.

Sample ID (rock unit)	Dated Mineral/s	K, % ± σ	^{40}Ar rad, (ng/g)	% ^{40}Ar air	Age (Ma)	Error 2σ
COO-01 (andesite porphyry)	Feldspar concentrate	3.59 ± 0.4	7.17 ± 0.07	39.5	**28.6**	0.9
COO-04 (polymictic diatreme breccia)	Feldspar concentrate	0.682 ± 0.015	1.51 ± 0.03	68.6	**31.7**	1.9

Standards Bern 4M Muscovite and 1/65 "Asia" rhyolite matrix were measured for ^{38}Ar spike calibration.

Oligocene (45 - 25 Ma) island arc tholeiitic magmatism. This implies that the hydrothermal activity related to the Co-O epithermal vein system occurred immediately after or during the Oligocene magmatism.

6. Summary and Concluding Remarks

Main points of this study are summarized in the following:

1) Whole-rock geochemical analyses of the polymictic diatreme breccia, intrusive and volcanic rocks indicate general island arc tholeiitic and calc-alkaline magma series signatures, associated with an island arc subduction setting.

2) General composition of the polymictic diatreme breccia, intrusive and volcanic rocks ranges from sub-alkaline andesite, basaltic-andesite to basalt and alkaline basalt.

3) Typical alteration of the polymictic diatreme breccia, intrusive and volcanic rocks associated with the Co-O epithermal gold deposit follows the chlorite-carbonate and chlorite-pyrite (-sericite) alteration trend lines defined in the "alteration box plot" by [17], comparable with the dominant chlorite alteration observed through petrographic analysis of these rocks.

4) K/Ar dating of hydrothermal minerals from the andesite porphyry and polymictic diatreme breccia samples yielded ages of 28.6 ± 0.9 Ma (Late Oligocene) and 31.7 ± 1.9 Ma (Early Oligocene), respectively. These ages correspond to the age of the hydrothermal activity in the area, which is in turn related to the timing of the mineralization.

Integrated with earlier works on age dating and geochemistry of similar rock units along eastern Mindanao, whole-rock geochemical analysis of the volcanic host rocks and an Oligocene age date of the hydrothermal activity from this study corroborate an island arc setting of formation of the rock units corresponding to paleo-latitude reconstruction studies [13] [14], which situate the eastern Mindanao magmatic province to be forming with the Indian and Australian plate subduction along the Sunda-Java Trench system at about 10°S latitude during the Oligocene times, followed by or contemporaneous with the formation of the Co-O epithermal gold vein system prior to the accretion of the different terranes constituting the Philippine archipelago around Miocene.

This study further confirms the claim that the Co-O deposit is (one, if not) the oldest epithermal gold deposit in the Philippines [2] [3]. Since most of the deposits in the Philippines are dated to be of Miocene and Pliocene to Pleistocene ages, with some associated with the Philippine Fault that was formed in response to the present geodynamic setting of the archipelago since Miocene times (*e.g.*, [22] [23] [24]), the study of older deposits such as the case of the Co-O epithermal gold deposit could provide supplementary lines of evidence in understanding the occurrence and preservation of such deposits in an actively deforming region. In line with this, additional studies, particularly on the characterization of the Co-O epithermal vein system with tectono-kinematic analysis of structural controls and other related structural features, still need to be conducted on the deposit. Additionally, further study on the occurrence of the hydrothermal products must be conducted to ensure the results of the age dating, since this bears a significant impact on the interpretation for the research.

Acknowledgements

The authors would like to express their gratitude to the assistance of the Medusa Mining Ltd. and Philsaga Mining Corp. for permitting the research study to be conducted within their mining tenements, and providing technical and logistical support throughout the research. Technical support from the members of the Economic Geology Laboratory in Akita University, with funding and assistance from the New Frontier Leading Program, its staff, and faculty members, and the Japanese government (Monbukagakusho) scholarship program are greatly appreciated. The authors would likewise wish to express their appreciation to Dr. Akira Imai for imparting his knowledge on the subject matter.

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