Integrated geophysical study of the Subika Gold Deposit in the Sefwi Belt, Ghana

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Abstract: Geophysical datasets, namely, electrical resistivity, induced polarization, magnetic susceptibility were measured and aeromagnetic interpreted on the Subika concession of Newmont Ghana Gold Limited in order to delineate and model the zone of gold mineralization. The electrical resistivity and induced polarization results delineated the gold mineralized zone as a narrow discrete resistor (>4900 Ωm) and high chargeability (>7.2 ms) zone with a strike length of about 2 km. A strip log plots of 12 diamond drilled core samples showed the zone of mineralization with high alteration and low magnetic susceptibility. Analysis of laboratory magnetic susceptibility measured on selected samples from the pit and selected core samples from the mineralized zones showed a negative correlation between the magnetic susceptibility and gold grades with a correlation coefficient of −0.2 and −0.74, respectively. Similarly, magnetic depth slice produced from the 3D model of the aeromagnetic data depicts the zone of gold mineralization with a low magnetic signature. The zone mineralization was also observed to be striking in the north-east direction. Mineralogical analyses of rock samples revealed alteration processes such as carbonization, sericitization, silicification, chloritization and sulphidation resulting from hydrothermal alteration which accounted for the low magnetic and the magnetic susceptibility signatures of the mineralization zones. The strong resistivity and chargeability response of the mineralized zones are therefore attributed to...

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PUBLIC INTEREST STATEMENT

Gold mineralization is of importance to the development of any nation that has discovery this precious mineral in it land. The discovery of gold provides job opportunities for citizens and also serves a major foreign exchange earner for most of these countries. In Ghana, gold mineralization occurred mainly in six north-east south-western trending Birimian mobile belts and control by geological structures. The discovery of these gold hosting structures requires the application of a number of exploration tools that are sensitive to the mineral, its hosting environment, and associated pathfinder minerals. This research, therefore, adopted a number of geophysical techniques and mineralogical analysis of rock sample as a means of delineating gold mineralization zones in the Subika Concession of Newmont Ghana Gold Limited. The results show the effectiveness of integrated geophysical, petrophysical as well as the mineralogical study of rock samples in revealing gold mineralization potential of the study area.
the silicification and sulphidation alteration, respectively. The results show the effectiveness of applying integrated geophysical, petrophysical as well as mineralogical study in revealing gold mineralization potential of the Subika deposit and the Sefwi belt as a whole.

**Subjects:** Earth Systems Science; Geology - Earth Sciences; Geophysics

**Keywords:** Magnetic susceptibility; resistivity; induced polarization; gold; mineralization

1. **Introduction**

In mining, exploration has proven to be one of the stages where no returns are made on investment and therefore considered as a high-risk stage. In this vein, there is always the need to look for less expensive but efficient exploration techniques for fast and efficient discovery of mineral deposits. The integration of petrophysical analyses of rock samples with geophysical data has been very effective in ore delineation in many parts of the world. In Canada, petrophysical properties were used in the characterization of mineralized and nonmineralized rocks in Yellowknife and Giant and Con mine areas (Connell, Scromeda, Katsube, & Mwenifumbo, 2000; Scromeda, Connell, & Katsube, 2000; Connell, Hunt, & Li, 2004). The petrophysical datasets used in most of these cases, serve as the basis for geophysical exploration methods that are applied at a field scale. Generally, geophysical prospecting aids in the search for mineral deposits by in-situ measurements. It thus helps in target definition and delineation of ore zones (Anand, Wildman, Varga, & Phang, 2001). This makes geophysical applications in the mining industry very important. Despite the success of geophysical techniques in the mineral industry, the methods used have not been extensively applied to gold exploration in Ghana. Most companies both foreign and local have used traditional methods, namely, stream sediments analyses, soil sampling, conventional geological mapping, drilling and other techniques based mainly on the geological structure of the formations in the exploration of gold from the reconnaissance to the exploitation stages (Lawrence, Treloar, Rankin, Harbidge, & Holliday, 2013; Tsiboh & Grant, 2009).

Newmont exploration over the years has employed a number of geophysical methods in the exploration of a gold deposit in various parts of the world. In Ghana, the company has employed methods such as magnetic, gravity, induced polarization, resistivity and electromagnetics in gold mineralization target definition. These methods adopt distinct signatures that are associated with the host rock, the gold mineralization and pathfinder minerals, degree of alteration as well as structural features in the mineralization target definition. The magnetic method adopts the variation in the magnetic susceptibility of the crustal rocks in mapping the crustal geology, geological structure as well as degree of alteration of magnetic minerals in the rock (Boadi, Wemegah, & Preko, 2013; Jessell et al., 2013; Wemegah et al., 2015). Similarly, resistivity, induced polarization and electromagnetic exploration methods use the resistivity and chargeability signatures associated with graphitic shear zones, fractures as well as sulphidation and silicification which are the main alterations associated with the Birimian gold mineralization (Griffis & Agezo, 2000; Kesse, 1985) to delineate the mineralization zones. Furthermore, the adoption of the gravity method which depends on the variation in density of the background rocks plays a very important role in the mapping of the geology and the zone the mapping of zones of gold mineralization. These geophysical methods have helped in the discovery of the company mineral reserves.

Although these methods provide important insights into the loci of mineral deposits, the proper delineation of the shape and size of an ore body require the integration of geophysical and geological information, especially from both surface and borehole data. Each dataset provides a means which outlines the relevant changes in the petrophysical properties of interest in relation to gold mineralization. Wilford, Bierwirth, and Craig (1997) revealed that the effective way of using geophysical techniques for the discovery of potential mineral target is the adoption of integrated geophysical data which help to resolve ambiguity associated with the output of the individual data especially in deeply weathered terrains due to the complex regolith-parent rock relationships. This paper, therefore, aims at
integrating the geophysical datasets available with the company (i.e. magnetic susceptibility, aeromagnetic and induced polarization datasets) to help map and model the zone of mineralization of the Subika Deposit of Newmont Ghana Gold Limited. This work contributes to the understanding of the physical properties of the Subika Deposit.

2. Methodology

2.1. Location and physiography of the study area
The Subika Deposit is located in Kenyase in the Brong Ahafo Region of Ghana, about 300 km northwest of Accra the capital of Ghana. The site lies between the longitude 2°27’00” W and 2°23’00”W and latitude 7°03’0”N and 6°57’10”N (Figure 1). The project area comprises low rounded hills with elevations from 182 m to 228 m above mean sea level. Seasonal streams and tributaries of the Tano river basin drain the broad flat valleys. The area falls within the wet semi-equatorial climatic zone of Ghana with biennial raining seasons. The major season starts from March to June and the minor season from September to the end of November. The average annual rainfall of the metropolis is between 150 and 170 mm.

2.2. Geology and mineralization
The study site lies within the Eburnean Tectonic Province (1,800–2,166 Ma) in the West African Craton with the Birimian formation consisting of the metasediment and the metavolcanic units. The Ahafo Project site for which the Subika Deposit forms part is located in the Sefwi Belt, one of the five NE-SW trending Birimian volcanic belts exposed in south-western Ghana. This belt is bounded to the northwest by the Sunyani basin and to the southwest by the Kumasi Basin. Contacts between the volcanic belts and the sedimentary basins are all major shear zones characterized by ductile fabrics superimposed by brittle shear zones (Griffis & Agezo, 2000) which host major gold deposits. The regional shear zone controlling mineralization in the area is the Kenyase Thrust. This thrust forms the western contact of the Sefwi metavolcanic belt and the Sunyani metasedimentary basin. Intruded into this formation is the belt type granitoid which hosts the Subika reserve, the only granitoid hosted gold deposit identified in the area (Figure 2).

Figure 1. Map of the study area showing the location of the Subika Concession.
The Birimian gold mineralization is associated with graphitic shear zones, fractures and sulphide minerals with their associated alterations (Kesse, 1985). The mineralization zones undergo different degrees of alteration and metamorphism from low-grade greenschist facies metamorphism to amphibolite metamorphism (Allibone et al., 2002). The Subika gold mineralization like all the Birimian gold mineralization, originated as a hydrothermal mobilization of gold from the basement volcanic rocks and as hydrothermal leaching of the Birimian volcanic pile (White, Waters, & Robb, 2015). The gold deposits are mainly brittle, fracture-controlled ore bodies within intrusives. They consist of “rock hosted” deposit (Groves, Goldfarb, Gebre-Mariam, Hagemann, & Robert, 1998; Lawrence et al., 2013) in association with needles of gold-bearing pyrite and chalcopyrite (Mumin, Fleet, & Chryssoulis, 1994). These usually show a direct correlation with gold grade and sulphide concentration (Newmont Mining Corporation, 2003). The mineralization is focused in highly fractured and intensely altered splay of the Kenyase Fault. These produce variations in mineral composition, hence, they have different magnetic susceptibility responses. This makes it possible for magnetic susceptibility to be used as a tool for mapping the mineralized zones.

2.3. Sampling and analysis

Rock samples, on which the magnetic susceptibility and the mineralogical analysis were carried out, were sampled from the Subika pit and also from diamond drilled half cores. The samples were selected based on their degree of alteration (which ranged from 0 to 3, based on a classification code by Newmont Ghana Gold Limited), mineralization, position, and depth. Diamond drilled half core sample from 12 boreholes from the site were used to acquire magnetic susceptibility readings. The other half drilled core were fire assayed for the determination of the gold assay value of the rock. The results were used to plot the strip log, to provide visual relation between the magnetic susceptibility, rock type, rock alteration, and gold assay. In addition, 12 drilled half core samples with known gold assay values were sampled at different depths from three drilled core samples for laboratory analyses of their chargeability, magnetic susceptibility, and induced polarization. These analyses were done at the Mesoscale Laboratory Data Systems Exploration (NSW) Pty Limited, Australia. These analyses were done to determine the correlation between gold grade and magnetic susceptibility as well as between gold grade and chargeability.
Also, Rock samples from the pit (Figure 3) were picked from the mineralized and non-mineralized zones of the hanging and the footwall of the fault hosting the mineralization in the area. A total of thirty five (35) samples were taken and their magnetic susceptibility values determined. Four of these samples representing the various rock alterations (Table 1, Figure 4(a,b)) were selected for their mineralogical analysis. The samples were prepared into thin sections and studied under the Leitz Laborlux petrological microscope at the Geology Department of the University of Mines and Technology, Tarkwa, Ghana.

2.4. Magnetic susceptibility measurements
Magnetic susceptibility measurements were performed on the rock samples with the SM-30 magnetic susceptibility meter with a sensitivity of $1 \times 10^{-3}$ SI, using the average mode of data collection. The measurements were carried out in three stages. The first and the third measurements (referred to as the compensation stages) were carried out by holding the magnetic susceptibility meter in the air without a sample, while the second stage measurement (the pickup stage) was performed with the meter placed in contact with the sample. In taking this measurement, the meter was first held in the air and the magnetic susceptibility reading taken. The meter was then brought into direct contact with the surface of the rock and the magnetic susceptibility reading taken. The reading was repeated over at least 10 positions of a meter long sample (of the same lithology) during the pickup stage. The meter was then removed from the rock and the reading taken again in the air. The average of the free air measurements taken during the compensation stages was then subtracted from the average pickup reading to obtain the average magnetic susceptibility value for the rock sample. The same procedure was used for the measurement of the magnetic susceptibility of the whole drilled core and values plotted as strip logs.

2.5. Geophysical surveys
The aeromagnetic data used for the interpretation was surveyed by Fugro Airborne Survey Limited over the whole of the Sefwi Belt for Newmont Ghana Gold Limited. This data was collected with line spacing of 200 m and terrain clearance of 100 m using a fixed-wing stinger-mounted single sensor magnetic system. Newmont in-house magnetometer-VLF system in a discrete mode with a cycling rate of 5 s was used to collect the base station data and used for the diurnal correction of the magnetic data. The field exercise lasted for a period of six weeks from November—December 2005. Similarly, the resistivity/induced polarization survey was done using the IRIS Elrec Pro receiver and VIP 4000 transmitter. Gradient array with station separation of 25 m and line separation of 50 m was used for the survey.

| Sample No. | Location     | Field Name | Description                |
|------------|--------------|------------|----------------------------|
| ALT 0 (H/W)| Hanging-Wall | Granodiorite| Granitic rock              |
| ALT 1      | Mineralized Zone | Alteration 1 | Aplite-Felsite contact |
| ALT 2      | Mineralized Zone | Alteration 2 | Granite-Aplite contact |
| ALT 3      | Mineralized Zone | Alteration 3 | Banded granite contact |
2.6. Results and discussion
The results from integrated geophysical datasets and petrological studies of rocks from the Subika Concession of the Newmont Ghana Gold Limited were used to delineate and characterize the zone of gold mineralization within the study area. The geophysical datasets acquired for this work include magnetic susceptibility, magnetic, resistivity, and induced polarization as well as mineralogical studies of the rocks. The magnetic data were used to delineate and model the loci of gold deposition in the area. The resistivity/IP data helped in mapping the mineralized zone using the strong anomaly associated with these zones. The magnetic susceptibility measurements provided information about the relationship between the magnetic susceptibility, gold mineralization, and rock alterations. Furthermore, the mineralogical analysis provides information on the mineral composition of the host rock and the zone of mineralization. This has provided insight into the source of the geophysical signatures that are associated with the zone of gold mineralization.

2.7. Magnetic susceptibility of rock samples
The mean magnetic susceptibility values of the various rocks sampled from the pit are given in Table 2. The rocks from the non-mineralised zones with a low degree of alteration recorded high magnetic susceptibility values. The nonmineralized rocks from the hangingwall recorded 10 magnitudes of magnetic susceptibility value less than those from the footwall. The mineralized rocks generally produced values in magnitude of 10 to 100 less than the nonmineralized rocks. The degree of alterations was observed to control to a large extent, the magnetic susceptibility values within the area.

Figure 4 represents strip log plots of rock alteration, magnetic susceptibility, and gold assay values of drilled holes AEP01, AEP04, AEP08, and AEP12. These aided in the direct correlation of the rock alteration, magnetic susceptibility, and gold assay values within the holes under consideration.

It is observed from Table 2 and Figure 4 that the magnetic susceptibility values of the rocks decrease with increasing degree of rock alteration. Thus, rocks with high degrees of alteration (alteration three) generally have low magnetic susceptibility values, while those with low degrees of alteration (alteration zero) generally have high magnetic susceptibility values. There is also a general negative correlation between the assay values and the magnetic susceptibility values. The magnetic susceptibility values decrease drastically for rocks with...
high gold assay values while those with very low gold assay values generally have high magnetic susceptibility values.

The low magnetic susceptibility readings with the corresponding high gold assay values and high alterations were recorded at various sample core depths within the drilled holes. In drilled hole AEP01 (Figure 4(a)), the low magnetic susceptibility with a corresponding high gold assay value was recorded at a depth interval of 225 to 270 m. For hole AEP04 (Figure 4(b)) this was mainly recorded at depth intervals of 300 to 350 m and 380 to 424 m. This zone was observed in the depth interval of 270 to 315 m for AEP08 (Figure 4(c)) and 290 to 335 m and 410 to 445 m for AEP012 (Figure 4(d)). It was also noted that the non-mineralized granitoid generally had a high magnetic susceptibility value. These values decrease with increasing degree of alteration of these rocks. Magnetic susceptibility also correlates well with rock mineralization. The magnetic susceptibility values are very low in rocks with high gold assay values and high in those with low gold assay values.

The generally low magnetic susceptibility values recorded within the zone of mineralization are as a result of decreasing mafic or magnetic mineral content (magnetite, monoclinic pyrrhotite) within this zone. This may be attributed to the destruction of the main magnetic minerals (magnetite, monoclinic pyrrhotite) by the hydrothermal processes that deposited the gold. The main alteration types identified in the zone of gold mineralization include, carbonatization, silification and sulphidisation alteration (Newmont Mining Corporation, 2004). These alterations were also observed in the mineralogical analysis of the rocks from the area (Figures 8–11). These processes led to the destruction of magnetite in the altered zones and the surrounding rocks (Airo, 2002; Clark, 1997). The sulphidisation alteration caused the break down of magnetic minerals mainly magnetite and released iron which was assimilated into the sulfide mineral structure leading to the production of iron-sulphide minerals such as pyrite within the zone of mineralization. This process resulted in a decrease in ferric iron content of these rocks. The general decrease in the magnetic susceptibility values with the corresponding increase in iron-sulphide minerals within the zone of mineralization confirms this fact.

Generally, rocks with high mafic (basic) mineral content recorded high magnetic susceptibility values while those with high felsic (acidic) mineral content had low magnetic susceptibility values. The silification alteration produced more silica within the alteration zone. The process increased the acidity of the mineralized rocks by producing more rocks rich in felsic composition in the mineralized zone. This alteration led to a general decrease in the magnetic susceptibility of the mineralized rocks. Similarly, the greenschist metamorphism associated with the Subika gold mineralization generally led to a demagnetization of basic rocks in which it occurs (Airo, 2005). This, therefore, accounts for the decrease in the magnetic susceptibility values of the zone of mineralization.

### 2.8. Magnetic susceptibility and chargeability of core samples

The results obtained from the laboratory magnetic susceptibility and chargeability measurements are plotted against gold grades as shown in Figure 5. Figure 5(a) showed a strong

| Sample Location     | Description | Magnetic Susceptibility (SI) |
|---------------------|-------------|-----------------------------|
| Main hosting rocks  | Alteration 3| $1.0 \times 10^{-5}$         |
|                     | Alteration 2| $2.7 \times 10^{-5}$         |
|                     | Alteration 1| $1.7 \times 10^{-5}$         |
| Nonmineralised rock | Hangingwall | $5.1 \times 10^{-3}$         |
|                     | Footwall    | $6.1 \times 10^{-4}$         |
positive correlation between chargeability and gold grade with a correlation coefficient of 0.83. It shows an increase in gold assay values with increasing chargeability in the area. This implies that the Subika deposit has a chargeability signature at depth with high gold mineralization which could be attributed to the sulphide alteration (mainly pyrite, Figure 6) association with the zone of gold mineralization as observed in most the Birimian gold mineralization (Griffis et al., 2002). The magnetic susceptibility, on the other hand, has a correlation coefficient of −0.73, showing a general decrease in magnetic susceptibility with an increase in gold grade in the area. There is, therefore, a strong correlation between gold grade and magnetic susceptibility on one hand and chargeability values on the other. The general decrease in the gold assays with increasing magnetic susceptibility (Figure 5(a)) could be attributed to the destruction of magnetic minerals (mainly, magnetite) in the zone of mineralization by the hydrothermal processes associated with the zone of mineralization. The strong positive correlation between gold grade and chargeability value, on the other hand, could be attributed to the presence of disseminated sulphides within the zone of gold mineralization. Sulphidation is the main hydrothermal alteration associated with the Birimian mineralization (Griffis et al., 2002; Kesse, 1985). The sulphide minerals generally produce strong induced polarization effect, leading to strong chargeability values, while the breakdown of the magnetite leads to the decrease in the magnetic susceptibility.

2.9. Resistivity and induced polarization

Figure 6 shows the resistivity and induced polarisation data were collected over the study area using a gradient array configuration. This helped in determining the lateral variation in resistivity over the area. From the results, the main fault that hosts the Subika Deposit (B-B) coincides with the point of high electrical resistivity. This is due to the high silica alteration that is associated with the mineral alteration assemblage of the area. From the gradient array data, the survey area has a minimum resistivity of 1520 Ωm and maximum of 6120 Ωm with an average resistivity value of 3500 Ωm the high resistivities recorded in the survey area was due to the fact that the deposit is wholly hosted in a granitoid package. The MFZ (magic fracture zone) which hosts the Subika mineralization has an average resistivity of 4350 Ωm. The induced polarization data has a minimum value of 5.0 ms and a maximum of 8.2 ms and an average of 6.1 ms, with a weak correlation between mineralization and chargeability was seen in the surface data.

The alteration assemblage that dominated the mineralization includes quartz—carbonate—feldspar—chlorite—muscovite—pyrite (Jessell et al., 2013; Tsiboah & Grant, 2009). Two other parallel resistivity zones (C and D) were also identified. The linear nature and positions with respect to the main fracture zone (MFZ), show that they form part of the splay of faults that are associated with
the Kenyase Fault. Test holes, drilled on these high resistivity anomaly zones recorded no potential gold mineralization. The gold-barren signature of these faults testifies to the assertion that although faults form a good hosting feature for gold mineralization in the Birimian formation, not all faults are mineralized (Griffis et al., 2002; Kesse, 1985; White et al., 2015). The induced polarisation data shows general high chargeability value at the northeastern (A) and southwestern (B) ends of the image with moderate values in between. The association of the Birimian gold mineralization with sulphidation alteration makes these high chargeability areas potential gold mineralization zones. The drilled holes whose core samples were used for the measurement of the magnetic susceptibility were all from these zones. The strong chargeability response of the mineralized zone is due to the disseminated pyrite content of this zone (Groves et al., 1998; Griffis et al., 2002; Jessell et al., 2013). It can be observed from the two images that the high resistive zones that do not record any mineralization (C, D) from their dilled core samples recorded low chargeability which could be attributed to the absence of pyrite one of the main pathfinder minerals of gold in the area which gives rise to the chargeability responses in the mineralized zones.

2.10. Aeromagnetic modeling
An unconstrained 3D modeling of the aeromagnetic data was carried out, employing the use of the residual grid of the Subika total magnetic intensity (TMI) and a high-resolution DEM covering the Subika deposit. made it possible to map out the zone that hosts the Subika Deposit. The inversion was carried out using UBC MG3DINV software using a core cell size of 25 × 25 × 25 m and a depth extent of 300 m, inclination of −12° and a declination of −5° with a field strength of 32,000 gammas. Data error was set to 5% and a noise floor of 0.1. Elevation depth slices (Figure 7) were generated from the 3D block model to help with the data interpretation. The Subika deposit sits within a magnetically depleted zone caused by the impact of the hydrothermal fluids. The results from the modeling picked up the MFZ as a magnetically depleted zone as seen in the magnetic susceptibility data collected on the drilled core. Low magnetic susceptibility anomalous areas were considered to account for the alteration which is also controlled by faults, fractures and shear zones. Birimian gold mineralization is of the low-grade greenschist alteration which generally leads to the destruction of magnetic mineral hence low magnetic and magnetic susceptibility signatures as observed in the magnetic depth slices as well as the magnetic susceptibility of the samples. Also, well noted in this image is the NE-SW trending nature of the low magnetics zone.
2.11. Mineralogical analyses

Photomicrographs of Subika rocks sampled from the pit revealed different, alterations, degrees of mineralization of the primary minerals in the rock samples selected from the area. Polished hand samples and thin sections of the samples hence, helped to determine the mineralogical compositions of the rock samples.

2.11.1. Alteration 0

In the hand specimen (Figure 8(a)), the sample appears flecked and predominantly whitish-grey with dark speckles. It has black inclusions that appear to be xenoliths. It is a plutonic, holocrystalline, igneous rock with granitic texture with the mineral grains stretched and drawn out indicating its metamorphic history. The sample may be described as a foliated granitoid made up primarily of: Amphibole (amph) (predominantly hornblende (hnbd), 40–50%; altered Alkali or K-feldspar (field), 30–40%; Plagioclase feldspar (plag), 10–15%, Quartz (qtz) 2–5%; and Sericite (ser) alteration minerals < 1%.

The mineralogical composition with the texture suggests foliated hornblende granite. The amphiboles are predominantly hornblende and consist of large laths which show green to brown pleochroism in plane polarised light and moderate second-order birefringence of brown to pale green under crossed polars (Figure 8(b)). Two main types of feldspars were identified. These are:—Type 1 feldspar, labeled “feld” (Figure 8(b,C), is an unaltered plagioclase which is often twinned. Type 2 feldspar, which is referred to as “sauussurite”, is made up fine aggregates and clusters of sericite and appears to have resulted from the alteration of original primary K-feldspar. The quartz is anhedral and interstitial indicating that it is a late primary mineral (Figure 8(d)). Sericite is the main alteration mineral in the sample and is mostly secondary resulting from the breakdown of K feldspar (Figure 8(b)).

The polished section showed that gold mineralization in this sample is restricted to tiny rounded pyrite (py) grains that are sparsely distributed through the rock (Figure 8(d)) with occasional sub-rounded and subhedral pyrite grains.

Figure 8. Photomicrograph of Subika rocks sampled from the pit revealed different, alterations, degrees of mineralization of the primary minerals in the rock samples selected from the area. Polished hand samples and thin sections of the samples helped to determine the mineralogical compositions of the rock samples.
2.11.2. Alteration 1
In the hand specimen, (Figure 9(a)) is a dark grey rock sampled at the contact between a coarser-grained granitic rock (bottom) and a finer-grained metamorphosed rock (top) which could possibly be slate or schist. The thin section (Figure 9(b)) reveals that the rock consists of two parts (Figure 9(b)). The coarser grained part consists of altered granite and opaque minerals. Although the rock is heavily altered, relict feldspar laths and corroded quartz grains suggesting a granitic composition are observable. In the second portion, however, the rocks are completely obliterated and only carbonate and opaque minerals are observed. The rock may be described as “propylite”.

The polished section of the alteration 1 sample showed that ore mineralization in the sample is different from that of the alteration 0. The sample contains sphalerite (sph) in addition to the two generations of pyrite namely, pyrite 1 and 2 (py1 and py2) which were observed in the previous samples. Pyrite1 (py1) occurs as tiny heavily corroded grains while porphyroblastic pyrite (py2) is euhedral. Py1 is intimately associated with relict sphalerite while euhedral pyrite (py2) carries numerous inclusions of undigested rock material to underscore its rapid growth in a solid state (Figure 9(b)). Though both py1 and py2 are observed in the coarser-grained part of the sample only (py2) is present in the fine-grained part. The sphalerite is mostly skeletal and closely associated with (py1). It is more prolific in the finer grained slaty part of the sample. The occurrence of finely disseminated anhedral to euhedral pyrite with was also recorded in the Ashanti Belt by Mumin et al. (1994).

2.11.3. Alteration 2
The hand specimen, Figure 10(a), represents the contact of two different granitic rocks both of which are greyish in color. One part is coarse-grained while the other part is fine-grained. The thin section (Figure 10(b)) shows that the coarser-grained part of the sample is made up of sericitic feldspar, plagioclase, quartz, and secondary quartz and opaque minerals (Figure 10(b)). The finer-grained part is completely altered and presently consists of secondary sericite, carbonate, and quartz (Figure 10(c)).
In the polished section, Figure 10(d), pyrite continues to be the main ore mineral in the sample and is associated with skeletal sphalerite. Both corroded py₁ and euhedral py₂ are present in the rocks but generally, py₂ is more dominant in the finer grained part of the sample while the reverse is observed in the coarser-grained section. Sphalerite which generally occurs as skeletal aggregates commonly replaces the silicates at the core and grain boundaries.

2.11.4. Alteration 3

The rock is folded and foliated with the dark grey and white bands contorted into pytgmatic folds (Figure 11(a)) with a photomicrograph of the representative specimen showing signatures of shearing and the presence of disseminated pyrites. In thin section, the rock shows foliation between slaty cleavage and schistosity. The main minerals are quartz, sericite, chlorite, and carbonate (Figure 11(b)). Quartz and sericite which are minor constituents of the rock occur as tiny grains and flakes, respectively. Quartz grains vary in width from 0.03 to 0.1 μm to 1 to 1.5 μm in length while the sericite flakes have a width less than 0.3 μm and about 0.05 μm in length. Chlorite and carbonate minerals in the rock occur in bands. The stratification of the rock into chlorite (chl) rich and alternate carbonate-rich bands give it the observed color banding (Figure 11(b)). The photomicrograph of the sample in the polished section shows pyrite grains aligned in the plane of foliation of the banded phyllite (Figure 11(c)).

3. Conclusions

The magnetic susceptibility data from the 12 drilled holes reviewed, and the selected rock samples showed a negative correlation between susceptibility and gold grade. Chargeability data for the drilled cores gave a very good positive correlation with the gold grade. These results revealed that Subika deposit has a chargeable signature which can be traced at depth but not at the surface as shown in the induced polarization data. The results from the strip log plot revealed that the mineralized zone has low magnetic susceptibility and high level of alteration. The gradient array resistivity/induced polarization datasets delineated the zone that hosts the deposit as a narrow discrete resistor trending in NE-SW direction with a strike length of 2 km. The 3D-modelling was
Figure 10. a) Hand specimen of granitoid of alteration 2. b) Photomicrograph showing shearing with the rock. c) Photomicrograph of granitoid showing euhedral and triangular pyrite d) Photomicrograph showing disseminated pyrites.

Figure 11. a) Hand specimen of granitoid of alteration 3. b) Photomicrograph showing a highly sheared rock with chlorite (chl) band, carbonate band identified and disseminated pyrite. c) Photomicrograph of granitoid showing euhedral and pyrite.
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References
Airo, M. L. (2003). Aerogeophysics in Finland 1972–2004: Methods, system characteristics and applications. Geological Survey of Finland Special Paper, 39, 1–197.
Allibone, A. H., McCuaig, T. C., Harris, D., Etheridge, M., Munroe, S., Byrne, D., Gyapong, W. (2002). Structural controls on gold mineralization at the Ashanti gold deposit (Vol. 9, pp. 65–93). Obuasi, Ghana: Society of Economic Geologists, Special Publication.
Anand, R. R., Wildman, J. E., Varga, Z. S., & Phang, C. (2001). Regolith evolution and geochemical dispersion in transported and residual regolith—bronzewing gold deposit. Geochemistry: Exploration, Environment, Analysis, 1(12), 256–276. doi:10.1144/geochem1.3.265
Boodi, B., Wemegah, D. D., & Preko, K. (2013). Geological and structural interpretation of the Konongo area of the Ashanti gold belt of Ghana from aeromagnetic and radiometric data. International Research Journal of Geology and Mining, 3(3), 124–135.ISNN 2276-6618.
Clark, D. A. (1957). Magnetic petrophysics and magnetic petrology: Aids to geological interpretation of magnetic surveys. AGSO Journal of Australian Geology and Geophysics, 17(2), 83–103.
Connell, S., Hunt, P., & Li, J. (2004). Electrical conductivity mechanism of graphitic shale from the Astarte River Formation, Pilgrim Group, Baffin Island, Nunavut. Geophysics, 69(5–6), C87–C95. doi:10.1190/1.1811366.
Connell, S., Scromeda, N., Katsube, T. J., & Mwenifumbo, J. (2000). The electrical characteristics of mineralised and non-mineralised rocks from Giant and Con mine areas. Northwest Territories: Geological Survey of Canada, Current Research 2000E.
Cook, K. (2007) Aeromagnetic data interpretation of Ahafo District. doi:10.1007/PD00193506
Griffis, R. J., & Agefo, F. L. (2000). Mineral occurrence and exploration potential of northern Ghana. Mineral Commission Report.132–1133, Accra.
Griffis, J., Barning, K., Agefo, F. L., & Akosa, F. (2002). Gold deposits of Ghana prepared on behalf of Ghana mineral commission. Ghana: Accra, 432.
Groves, D. I., Goldfarb, R. J., Gebre-Mariam, M., Hagemann, S. G., & Robert, F. (1998). Orogenic gold deposits: A proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geology Reviews, 13, 7–27. doi:10.1016/S0169-1368(97)00012-7.
Jessell, M. W., Ampomah, P. O., Baroutou, L., Asiedu, D. K., Loh, G. K., & Ganne, J. (2013). Crustal-scale transient shear in the Paleoproterozoic Sefwi-Sunyani-Comoe region, West Africa. Precambrian Research, 212–213, 155–168.
Kesse, G. O. (1983). The rock and mineral resources of Ghana. Rotterdam: A. A. Balkema.
Lawrence, D. M., Treloar, P. J., Rankin, A. H., Harbidge, P., & Holliday, J. (2013). The Geology and Mineralogy of the Loulo Mining District, Mali, West Africa: Evidence for two distinct styles of orogenic gold mineralization. Economic Geology, 108, 199–227. doi:10.2113/econgeo.108.2.199.
Mumin, A. H., Fleet, M. E., & Chrysoulias, S. L. (1994). Gold mineralization in As-rich mesothermal gold ores of the Bogosu-Prestec mining district of the Ashanti Gold Belt, Ghana: Remobilization of “invisible” gold. Mineral Deposita, 29, 445–460. doi:10.1007/BF00193506.
Newmont Mining Corporation, Annual report 2003 Newmont Mining Corporation, Annual report 2004
Scromeda, N., Connell, S., & Katsube, T. J. (2000). Petrophysical properties of mineralized and nonmineralized rocks from Giant and Con mine areas, Northwest Territories; in: Current Research 2000 (pp. 7). Geological Survey of Canada, Calgary, Canada.
Tsiboah, T., & Grant, T. (2009). Application of geophysics to gold exploration in Ghana: Examples from Newmont. ASEG Extended Abstracts 2009: 20th Geophysical Conference, pp.1–5, ASEG 20th Geophysical Conference and Exhibition, February, Adelaide. doi:10.1071/ASEG2009ab089.
Wemegoh, D. D., Preko, K., Noye, R. M., Boadi, B.,
Menyeh, A., Danuor, S. K., & Amenyoh, T. (2015).
Geophysical Interpretation of possible gold minerali-
zation zones in Kyerano, South-Western Ghana using
aeromagnetic and radiometric datasets. Journal of
Geoscience and Environment Protection, 2015(3),
67–82. doi:10.4236/gep.2015.340
White, A. J. R., Waters, D. J., & Robb, L. J. (2015).
Exhumation-driven devolatilization as a fluid source
for orogenic gold mineralization at the damang
deposit, Ghana. Economic Geology. Economic
Geology, 110, 1009–1025. doi:10.2113/
econgeo.110.4.1009
Wilford, J. R., Bierwirth, P. N., & Craig, M. A. (1997).
Application of airborne gamma-ray spectrometry in
soil regolith mapping and applied geomorphology.
AGSO Journal of Australian Geology and Geophysics,
17(2), 201–216.