Structurally Controlled Prospectivity Map of the Sefwi Volcanic Orogenic Belt of Ghana*

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Abstract

In this study, datasets obtained from ground magnetic and electrical resistivity geophysical surveys were integrated with existing solid geology and structural lineaments to map out structures in the Sefwi Belt of Southern Ghana. The prospecting and exploration stages of mining involve long periods of investment with a high risk of failure. In view of that, prospecting for gold needs to be optimised and that requires choosing the right techniques that will enhance the success of the exploration projects. It is for this reason that this paper exploits the integration of geological, geophysical (magnetic and electrical) and structural dataset to produce a prospective map of the study area. Elrec Iris 10 channel Induced receiver and Geometrics 859 magnetometer were used for Induced Polarisation (IP) and Resistivity and Magnetic data acquisition respectively. The magnetic data obtained were corrected and enhanced using Reduced-to-pole (RTP), first vertical derivative and analytical signal filters. These data were integrated and built into a GIS framework which is capable of displaying the inferred geometry, structure and nature of the mineralised body. The outcome of the electrical resistivity and IP inversions indicate that depths ranging from 50 to 200 m suggest conductive and chargeable bodies. The low-resistivity zones coincided with sheared and altered acidic meta-sedimentary rock. The geophysical signatures obtained from the enhanced magnetic data and the electrical data show that the study area is structurally complex with a few of the structures corresponding to D1 deformation and most structures corresponding to D2 deformation. The study resulted in better illuminating geological structures and lithological boundaries, and thus has demonstrated the worth of geophysical data as an enhancement tool in mapping possible geological structures that host gold mineralisation within the Sefwi volcanic orogenic gold belt of Ghana. Seven diamond drill holes were intuitively planned to test the results and to determine the depth of the resistive-chargeable anomalous units as well as litho-structural boundaries.

Keywords: Volcanoclstic, Birimian, Metavolcanic, Auriferous, Pole-Dipole, Reduce-To-Pole

1 Introduction

Among the six known volcanic orogenic gold belts in Ghana, the Sefwi belt-type is most likely to succeed the proliferous Ashanti gold belt which has produced over a hundred million ounces in the past millennia. However, the former is believed to have lots of resemblance to the latter and Boyle (1979) noted that these types of lode deposits have broad similarities in relation to structure, mineralogy, alteration, geochemistry and regional setting.

Exploration may involve mapping and integration of geology, soil geochemistry, geophysics and structural signatures in defining prospective areas. Common structural features such as thrust and strike-slip faults are basically associated with shear zones. They are commonly heated (between 7 and 12 km in depth) at or close to the transition from ductile to brittle regions in the crust (Heureux et. al., 2007). Gold deposits in Ghana can also be broadly categorised into tourmalinised turbidite - Hosted, disseminated gold Sulphides, Tarkwaian paleoplacers, mesothermal auriferous arsenopyrite and Quartz Vein Mineralisation and Mesothermal Gold-Quartz Vein Deposits (Griffis et. al., 2002). The vein systems cover a very broad category and include a close association with disseminated sulphides. Sefwi-Bibiani Belt is a fairly typical Birimian volcanic belt of considerable width (40-60 km) and lateral extent (Griffis et. al., 2002). It is predominantly of extensive belt-type diorite intrusive complexes, mafic volcanic and metasedimentary rocks. Some of these units host considerable auriferous deposits as in Newmont's Ahafo mine, along the north-western corridor of the belt. Structurally, the Sefwi Belt has been remobilised into complex fault systems having crosscutting features. These structural settings make magnetic geophysical technique the precise tool in its investigation characterisation and defining potential auriferous targets. Regionally, the study area is within Birimian volcanic/volcanoclastic and Birimian sedimentary units and overlain by belt-type granitoid.

Like other geophysical techniques, magnetic methods measure spatial variations in the Earth's magnetic fields. Changes in gravity are caused by variations in rock density and those in the magnetic field by variations in rock magnetism, which is mostly controlled by a physical property called magnetic susceptibility. Magnetic surveys are relatively inexpensive and are widely used for the

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direct detection of wide varieties of subsurface problems as well as different types of ore deposits. The area of study is situated in geologically complex and highly thrusted /faulted area and falls within the Birimian metavolcanic and basement metasedimentary rock units. These features make magnetic method an excellent method to aid in the understanding of the geological setting of the area.

Magnetic survey is often supplemented by other geophysical techniques including combined IP-chargeability and resistivity surveys. In the Sefwi orogenic volcanic belt investigated in this study, gold mineralisation is associated with metallic sulfides and oxides, which are excellent electrical conductors, making geo-electrical exploration methods excellent alternative technique to use (Kearey et. al., 2002; Reeves, 2005 and Dentith and Mudge 2014)

Over the years, Geographic Information System (GIS) techniques have been developed to grade and manage spatial data sets. The integration of GIS and geophysical dataset have proven to be powerful tools in the understanding of ore deposits (Kearey et. al., 2002 and Reeves, 2005). Upon considerations of such datasets, potentially economic areas can be located and regional bedrock geology or major structural trends defined and delineated (Hinze et. al., 2013 and Dentith and Mudge 2014).

In magmatic ore deposit, hydrothermal fluids cause alteration in wall rocks, resulting in vein-type mineralisation (Fon et. al., 2012). First, this paper aims at the integration of geophysical and structural datasets, using GIS-based tools, to produce prospectivity map of the study area. Secondly, it will also provide new insights into the deformational processes which shapes and controls mineralisation during post tectonic settings. Finally, the paper also attempts to build confidence and inspire investors to fully explore the Sefwi belt.

2 Resources and Methods Used

2.1 Study Area and Data Source

The study area in Fig. 1 is located 5 km North and 7 km South-West of Edukrom and Ankasi respectively, in the Juabeso district of Western corridor of Southern Ghana. The area is bounded by latitude 4.9072° N and longitude 2.2275° W. The study area can be traced 100 km NE of known Kenyase (Newmont mine) mineralisation configuration. The Sefwi Belt can be related to the main lode deposit of Ghana and notably one of the largest volcanic belts with prominent auriferous gold deposits on the south-east and north-west peripherals. Boyle (1979) noted that these types of lode deposits occur in rocks of all ages (Archean to Cenozoic) and have broad similarities in relation to structure, mineralogy, alteration, geochemistry and regional setting.

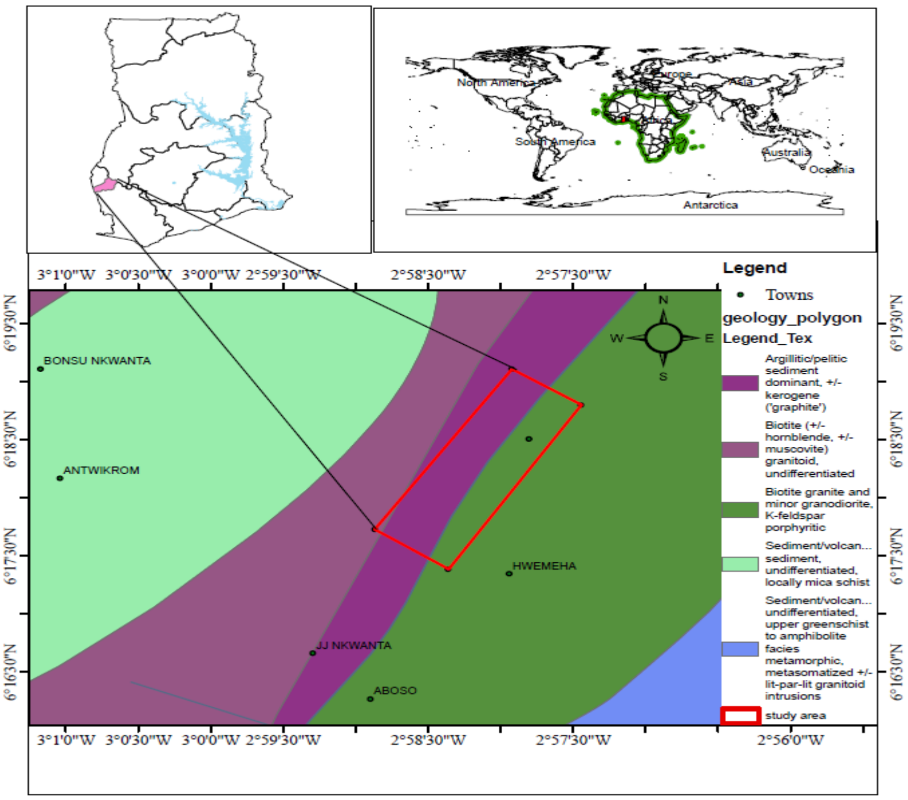

Fig. 1 Study area

The Sefwi belt, also known as Sefwi-Bibiani Belt is a fairly typical Birimian volcanic belt of considerable width (40-60 km) and lateral extent (Griffis et. al., 2002). It is predominantly of extensive belt-type diorite intrusive complexes, mafic volcanic and metasedimentary rocks, some of these host considerable auriferous deposits as in Newmont's Mine along the north-western corridor of the belt. Griffis et. al., (2002) had the Sefwi belt broken down into four geographic regions; the North Bibiani (NE margin), North Goaso area (NW), Enchi district (SE) and SW margin referred to as Juabeso-Bia-west area.

2.2 Data Acquisition, Processing and Enhancement

The ground magnetic and geoelectric data were collected by the Newmont mine geophysics team during its gold prospecting campaign in 2010. The study was conducted along a 3 km NE-SW traverse line and 1-km long cross-lines (sampling points) across the strike of the regional structural trend. The survey was conducted along sixty profile lines covering about 3 km^2 area. The surveyed grid was partitioned into blocks at 1 km^2 in order to enhance and speed up the data acquisition.

2.2.1 Magnetic survey metadata

Geometrics 859 magnetometer was used for magnetic acquisition to obtain the lateral variation of magnetic susceptibility of the project. All preprocessing corrections such as data validation, cleaning from all cultural and other undesirable noises, diurnal removal, micro-leveling were carried out. Removal of geomagnetic reference field from the data was also done after tying-in the base-rover readings. The International Geomagnetic Reference Field (IGRF) was used for this purpose. The data is further gridded following Briggs (1974) and O'Connell et. al., (2005) algorithm concepts.

Post enhancement techniques (Brodie, 2002; Milligan and Gunn, 1997) were applied to the Total Magnetic intensity anomaly. Generally, the goal is to enhance the anomaly of interest and carefully retrieve information of the magnetisation sources or location. Oasis in-built MAGMAP tool possesses a powerful mathematical imaging technique that supports the application of two dimensional Fast Fourier Transform filters to gridded data. Among these post-enhancement techniques is the upward continuity, (Kellogg et. al., 1953) which attenuates surficial noise and aid in the extraction of lineament from textural variation in the observed data.
Reduced-to-pole (Baranov, 1957 and Baranov and Naudy, 1964) enabled the transformation of the observed magnetic anomalies at a given locations into anomalies that would appear to have been taken at the North Pole.
The TMI which represent anomalies taken at the equator was standardised using the Reduced-to-Pole algorithm (Eqn. 1).

$$L(\theta)\,\frac{[Sin(I)-i.Cos(I).Cos(D-\theta)]^2\times(-Cos^2(D-\theta))}{[Sin^2(I\alpha+Cos^2(D-\theta)]\times[Sin^2(I)+Cos^2(I).Cos^2(D-\theta)]} \quad (1)$$

where I is the geomagnetic inclination (computed from projected –longitude/latitude data), D is geomagnetic declination (computed from projected –longitude/latitude data) and Iα is amplitude inclination correction which is never less than I. This algorithm was proposed by Baranov (1957) and Baranov and Naudy (1964) and was primarily meant to simplify the shape of the anomaly. The pole-dipole inversion model is based on the smoothness-constrained least-squares method (de Groot-Hedlin and Constable, 1990; Sasaki, 1992 and Loke, 2003) given in equation 2 and 3.

$$(\boldsymbol{J^TJ} + \boldsymbol{\lambda F})\Delta\boldsymbol{q_k} = \boldsymbol{J_g^T} - \boldsymbol{\lambda F_{qk}} \quad (2)$$

$$\boldsymbol{F} = \propto_x \boldsymbol{C_x^T C_x} + \propto_z \boldsymbol{C_x^T C_x} \quad (3)$$

Cx and *Cz* are the horizontal and vertical roughness filters respectively. *J* and J^T is the Jacobian matrix of partial derivative and its transpose vector and λ is the damping factor. Finally, *g* and *q* represent data misfit vector and model change vector respectively
Reduced to magnetic pole filter transforms an observed magnetic anomaly at any given location into the anomaly that would appear to have been taken at the North Pole. It reverses the amplitudes of the TMI.

Tilt derivative (Miller and Singh, 1994 and Verduzco et, al., 2004) and first vertical derivative extremely useful in mapping out mineral exploration targets as well as shallow basement structures. Also, it further illuminated textural features and better defined lateral extents of magnetic source.

2.2.2 Electrical survey

Geoelectric (IP/Resistivity) surveys were carried out on the same survey grid using an Elrec Iris equipment. The instrument was connected to a series of potential electrodes of copper in copper sulphate solution. The IP effect is measured in a time-domain. A total of 4 958 data points were acquired and processed using Geosoft Oasis Montaj.
The data was gridded using Grid and Image tool in Geosoft and subjected to a minimum curvature surface algorithm. Two pole-dipole profiles at the

northern and central portions of the study area (L 21500 and L 22700) to investigate 2-dimensional geo-electrical depth section (Fig. 2). The pole-dipole data were processed from apparent pseudo-section chargeability and resistivity sections and modeled using the Res2dinv (Loke, 2003) software tool. Surveying with the pole–dipole and pole–pole and arrays is fast and mostly find application in reconnaissance or grass-root exploration phase. It is also capable of investigation at deeper depth and able to produce excellent lateral resolution of steeply dipping features, with high signal amplitude (Dentith and Mudge 2014). The theory model behind the inversion program is based on the smoothness-constrained least-squares method (deGroot-Hedlin and Constable 1990; Sasaki 1992; Loke et. al., 2003).

3 Results and Discussion

3.1 Resistivity/ Chargeability and magnetic anomalies

The interpretation of magnetic and electrical geophysical anomalies was based largely on four indicative spatial or exploration guides (1) shear zones (2) favorable host rock units with fracture arrays, stockwork or brecciated zones (3) hydrothermal alterations and (4) strongly deformed or faults zones. The contrast in magnetic susceptibility and resistivity/chargeability were mapped as anomalous zones for interpretation, which are mostly related to various volcanic-clastic and belt-type intrusives. The interpretation were based on qualitative and quantitative (IP/resistivity inversion) terms.

3.1.1 Magnetic anomalies and pole-dipole

Magnetic signatures are presented in Fig.s 2-5 which depict the susceptibility contrast in magnetic rock forming minerals, and these are related to crustal features. The Total Magnetic Intensity (TMI) in Fig. 2 shows a varying magnetic intensities from -323.t nT to 88.9 nT which are depicted in colour-shaded scale of blues and reds. The magnetic high and low values are represented by mafic volcanoclastic (blue to green) and felsic volcanoclastic/ intrusive (pink to red) units. RTP anomalous map is presented in Fig. 3.

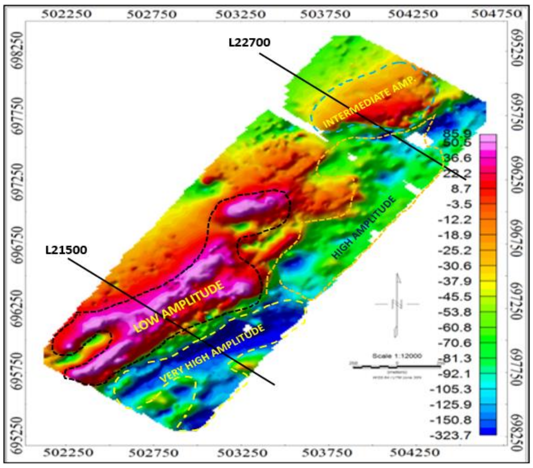

Fig. 2 Total Magnetic Intensity (TMI) Grid Map Showing Pole-Dipole Section Profiles

The magnetic signature was also grouped further into very low (-2.0 to -34 nT), fairly smooth positive (10 to 90 nT) and high positive (95 to 180 nT) susceptibilities. These are the Belt-type granitoid (GR), mainly hornblende dominated, granodiorite and diorite. Basement Birimian meta-sedimentary rocks (BS) mainly of phyllites, greywackes, schists and tuffs. Intermediate Birimian series (BV), mainly meta-volcanic rocks and volcanoclastics. These units generally trends NE-SW direction. The Belt type intrusive unit was further classified into three distinct groups as GR1, GR2 and GR3 due to ranges in susceptibilities in Fig. 3.

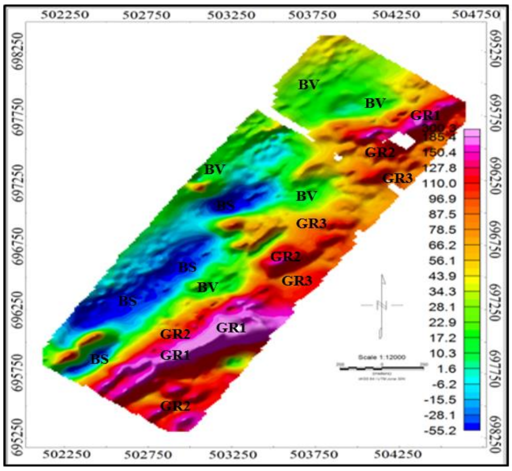

Fig. 3 Reduced-to-Pole Anomaly Showing Interpreted Lithological Units

3.1.2 Structural interpretation

Structural interpretation was based on extraction of lineation from the tilt derivative (Fig. 4), resistivity and 1 VD signatures (Fig. 5). In this work, lineaments were grouped into shear zones (extensional vein systems) and fractures (foliations and cleavages). It was observed that, the structural features trend NE-SW in the linked 1VD/tilt derivative anomalies. However, the tilt derivative showed an erratic feature indicating high degree of structural deformation, D1 (yellow lines) and D2 (white lines) which may be related to shearing (Figs. 4 and 5). Foliations, D1 were largely extracted from the 1VD anomaly (Fig. 5), whereas shear (extensional), D2 (white lines) and foliation, D1 (yellow lines) came from the tilt derivative (Fig. 4).

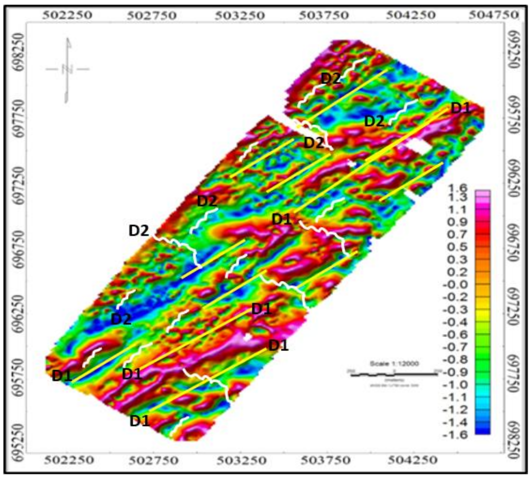

Fig. 4 Tilt Derivative Anomaly Showing Structural Lineament

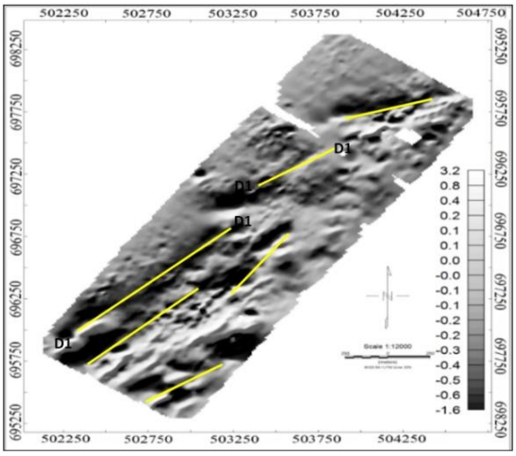

Fig. 5 1 VD Anomaly and Structural Lineament

These structures were grouped into boudins and boudinage, ductile shear zones and schistocity and generally crosscut the first generation deformations, D1. From the linked lineation map, therefore, it can be concluded that the area of interest is a favourable mineralisation prospectivity zone.

3.1.3 IP (Resistivity and Chargeability) and Pole-dipole signatures

The plotted pseudo-sections represent apparent information (Fig. 6). However, upon inversion with Res2dinv (Loke 2003), the data was inverted to real resistivity and chargeability 2D sections (Fig. 7). Real dips were recognised in section. They were helpful in showing the direction and plunge to plan drill hole orientation and planned depths to intercept potential target zones (Fig 6. b and c).

Pole-dipole geoelectrical inversion model features up to 200 m below surface topography. The sections revealed all the big breaks in the competent rocks (granitoids /volcanics). These fractured networks in competent rocks serve as conduit for hydrothermal fluids which is worth targeting. The southern section (Fig. 6) showed a major conductive structure sandwiched between two major intrusive inferred fault zone plunges at 45 degrees and at an approximate width of 200 m. The depth of this highly conductive zone is estimated at 200 m and likely at a deeper depth. Main chargeable units (Fig. 6 b and 7 b) was inferred as granitoid intrusive with sulphide alteration and also coincided well with the high resistive packages.

This major conductive units may be interpreted as conduits for hydrothermal fluid and therefore highly favourable zone to test for gold mineralization in a definitive exploration campaign. Several minor faults were inferred at low-high resistive boundaries though such minor faults are not widespread yet they play crucial role in the recognition of favourable mineralisation potential. There were several minor inferred faults at low-high resistive boundary for both profile sections.

The results indicate intense anomalies that suggest magnetic alteration of different lithological units and a set of conjugate lineaments and faults that may strongly control the mineralisation in the study area. The tilt derivative of the reduced-to-pole signature resolves the separation between anomalies, providing vital information on the faulting. The resistivity image resolved the contact between rock formations. The modelled IP-chargeability sections shows coincident low chargeability with low resistivity shown to be close to the surface. Furthermore, it is observed that the chargeability increases with depth, suggesting development of disseminated sulphide. High chargeability is restricted to sheared and silicified belt granitoid intrusives. There was a strong correlation between modelled resistivity-chargeability anomalies and the inferred magnetic structures. They provide strong geophysical target for drilling.

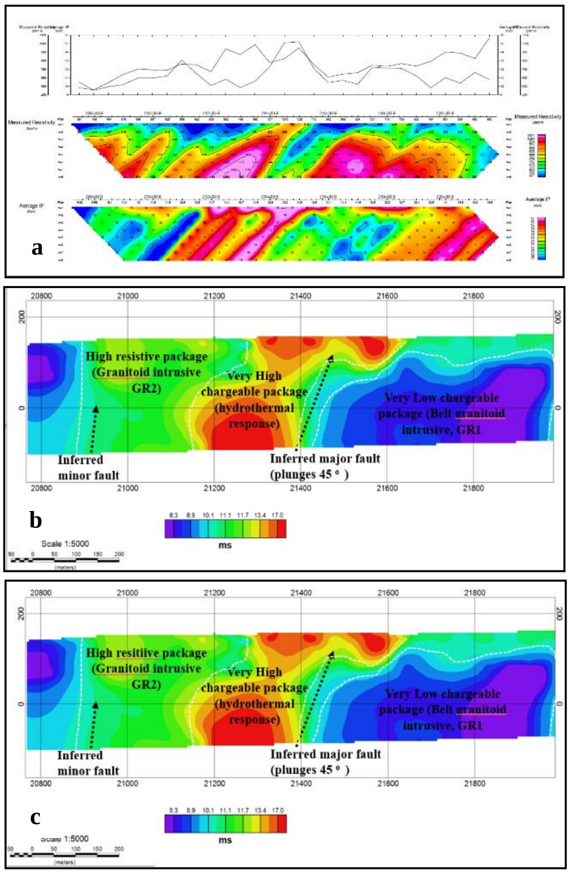

Fig. 6 (a) Pole-Dipole Pseudo-Section, (b) Resistivity and (c) Chargeability Model Inversions. Section L21500 South

3.3 Mineral Prospectivity Map

The interpreted prospectivity map (Fig. 8) is the result of mapping all structural trends obtained from the geophysical anomalies and existing geological dataset. The interpreted map serves as a highly prospectivity map of the study area. The map exhibits alteration zones, lineaments and fault elements trending NE–SW. These are clearly displayed in all the anomalous maps. Also the interpretation of the geophysical data indicated that these trends might be associated with wall rock alteration zones and have been preliminary interpreted to be related to hydrothermal sources. The interpreted geological map produced from this study comprises of NE-SW trend with a litho-structural configuration of Birimian meta-volcano-clastic rocks and belt granitoid units. The target included two main clusters and minor anomalies with an aggregate strike length of 3 km. Geological interpretation carried out on section lines 21500 and 22700 revealed steeply dipping major fault, trending NE-SW and passing through the center of the study area. This suggests that the contacts are structurally controlled and thus potential site for mineralisation. There is an interplay of structural patterns (lineation and shearing) and may be interpreted as post thrust deformation (D2) events. Also, major thrust fault may be characterised by D3 deformational event and could be an interesting site for localisation of gold.

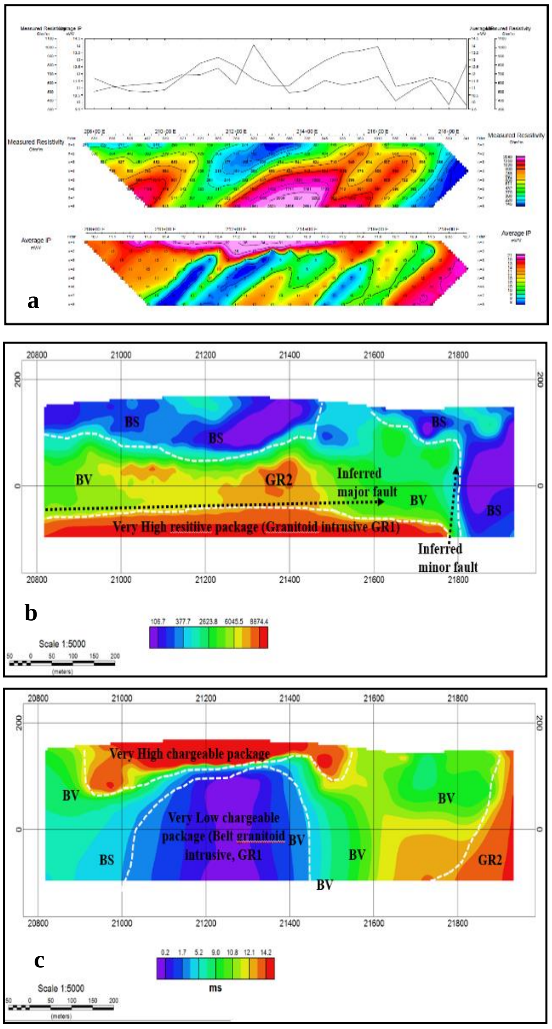

Fig. 7 (a) Pole-Dipole Pseudo-Section, (b) Resistivity and (c) Chargeability Model Inversions. Section L22700 North

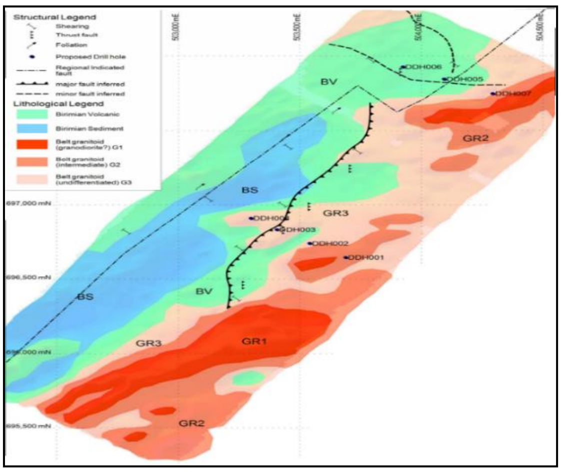

Fig. 8 Mineral Prospectivity Map Showing Structural Features and Proposed Drill

4 Conclusions and Recommendations

The study has been very effective in delineating the major geological features in the region, mapping a wide range of lithologies, and delineating regional and minor structures. The detailed map helped in mapping out three major lithological units; Birimian meta-sedimentary rocks, Birimian meta-volcanic rocks and Belt-type granitoid. These geological formations were seen to trend in the NE-SW direction with a lot of structural deformation that correspond to the D1 and D2 syn or post deformational stages. Belts of deformed volcanic, volcaniclastic and intrusive igneous rocks are separated by ‘troughs’ containing volcanic sequences and sedimentary unit. Ground magnetic truthing contributed in mapping litho-structural trends as well as textural features related to lineaments. IP anomaly map focused on defining alteration patterns of resistive-conductive boundaries which gives a unique interpretation of indicative of deep structures (good fluid conduits).

Integration of geophysical, structural datasets was key in high grade target and providing a preliminary interpretation on stratigraphy and structural orientations. The results of resistivity and IP inversions of pole-dipole data indicated that there are conductive and chargeable bodies at depths ranging from 50 to 200 m. However, the paper proposes radiometric survey to aid in the comprehension of hydrothermal alteration features. Furthermore, deep trenches should be undertaken within the highly prospective areas to reduce the subjectivity of the model.

Finally, it is recommended that this exploration model be tested with proposed diamond drill boreholes (north and south section of the pole dipole profiles) to ascertain the structural configuration and conductive and resistive anomalous trends.

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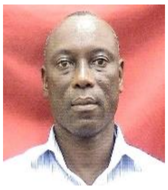

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