Journal of Environment and Earth Science
ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online)
Vol.8, No.3, 2018

Preliminary Investigation of the Geologic Controls of Graphite Mineralization and Exploration Potential of the Wa-Lawra Belt: Implications for Kambale Graphite Deposit

Emmanuel Daanoba Sunkari[1*] Musah Saeed Zango[2]
1.Department of Geological Engineering, Faculty of Engineering, Niğde Ömer Halisdemir University, 51240, Niğde, Turkey
2.Department of Earth and Environmental Sciences, Faculty of Applied Sciences, University for Development Studies, P.O. Box 24, Navrongo, Ghana

Abstract
The Kambale graphite deposit is located within the Wa - Lawra greenstone belt in NW Ghana. Historical records, recent exploration, unpublished material and accessible surface and subsurface exposures provide a valuable preliminary case study of the deposit. Examination of three transversal trenches and re-logging of eleven Rotary Air Blast (RAB) drill holes in the western part of the deposit reveal moderately to intensely sheared metasedimentary rocks of the lower Birimian formation such as mica schist, graphitic schist, quartzite, and a few pegmatite intrusions. Optical microscopic studies show that the deposit occasionally occurs in a complex mineral paragenesis of quartz ± calcite ± hornblende ± magnetite ± pyrrhotite ± rutile ± chalcocite ± graphite and other gangue minerals, often found around the boundaries of large magnesian ferrohornblende minerals, which tend to form quartz crystals. The Kambale deposit is characterized by numerous faults and shears, associated with brittle-ductile deformation at the NE part of the main shear with fewer faults and shears at the southern and western zones, generally trending E-W between 150˚ and 320˚, dipping in NE-SW direction at an average of 060˚. The rocks have undergone medium-high grade metamorphism under high T/medium P facies typically estimated as (~600-750˚C, 5.0–8.0 kbar), in amphibolite-granulite facies. The genesis of the flake graphite in Kambale is believed to be as a result of the high grade metamorphism, where deep-seated CO_2-rich fluid phase of crustal origin invaded the metamorphosed rocks. The intensity of the pore fluid pressures aided in the genesis of the graphite by hydraulic fracturing of the underlying rocks under regional syntectonic deformation.
Keywords: geologic controls, graphite, trench mapping, rotary air blast, graphitic schist, Wa-Lawra greenstone belt, Kambale, NW Ghana

1. Introduction

Graphite is an economic mineral which appears dark grey to black with metallic luster that mostly occurs as flakes due to the sheet-like arrangement of the atoms in its structure and because it is composed almost entirely of crystalline carbon (Bullock and Morgan, 2015). However, apart from the flake form, graphite also occurs as vein or lump graphite and as amorphous or crystalline graphite (Beyssac and Rumble, 2014). Its unique physical and chemical properties make it the major component of most industrial products and developing technologies like semi-conductors, fuel cells, lithium-ion batteries, aircraft wings, nuclear, wind and solar power (Luque et al., 2012; Rosing-Schow et al., 2017). Therefore considering the rarity of graphite, its remarkable physical and chemical properties as well as its increasing importance in high technology applications, it has been declared a strategic mineral by both the United States and the European Union (European Commission, 2014).

Today, China has the largest reserves and production capacity, producing about 80% of the world's graphite with Brazil, Canada, India, North Korea and European countries closely following China in terms of production capacity (Beyssac and Rumble, 2014). Nevertheless, Chinese graphite is declining in quality as easily mined surface oxide deposits are being depleted. Costs of production are increasing as mines become deeper. Costs are also under considerable pressure from tightening labor and environmental standards. The majority of Chinese graphite mines is small and operates seasonally. Mines located in far northern China stop during the severe winter months (Wilde et al., 1999). These measures are creating supply concerns for the rest of the world.

The formation of graphite is termed "graphitization", which depicts in-situ metamorphism of organic matter (Crespo et al., 2004). The mineral may also form epigenetically within veins or as an overgrowth on pre-existing graphite. Graphite may form in rocks that have undergone low-grade metamorphism but mostly in rocks that have undergone higher degrees of metamorphism (Beyssac et al., 2002). Flake graphite usually forms in high-grade schists, gneisses, quartzites, and a wide range of granulite facies rocks. It may also occur in metamorphosed carbonate rocks, though these occurrences are currently of little economic significance in the global front. Flake graphite deposits are mostly sandwiched between metasedimentary strata, where the individual beds are usually thicker than 30m over a large areal extent. On a regional scale, the ore bodies appear to be tabular, however they can be lenticular as irregular bodies within the zones of curvature (hinge zones) of most folds. Economic graphite deposits of flake form have been geochronologically constrained to Archean or

Late Proterozoic ages of evolution (Mitchell, 1992).

The discovery of a number of wide flake graphite rich horizons in North West Ghana within the Proterozoic Wa-Lawra greenstone belt by Castle Minerals Limited, presents a significant and rapidly emerging opportunity for Ghana considering the economic potential of the mineral. Mineralized zones up to 50m true width have been reported from drilling activities in the Kambale graphite prospect. Based on trenching, mapping and interpretation of geophysical data, the zones have at least 1km strike extents. The discovery of the graphite was serendipitous as it was first discovered by Russian geologists whilst prospecting for manganese in the early 1960's. Following this, the exploration for the graphite deposit in the area involved trenching and drilling of 25 holes to a maximum depth of 20m. The Wa-Lawra belt-type of graphite occurrence features complicated graphitic and quartz mica schist commonly associated with extensive metamorphism of carbonaceous shale with some quartz veins running through the ore body. The coexistence of the carbonate rocks and graphite schist probably implies that the schist initially represented organic-rich sediment, which was converted to graphite during granulite facies metamorphism (Rantitsch et al., 2004).

Although, dozens of information are available on the regional perspective of the occurrence of the graphite deposit in the Wa-Lawra belt, only limited attention has been given to the geology of this world class deposit. This has led to the many failed exploration attempts by Castle Minerals Limited in the area. Early studies were only comprehensive on reporting the occurrence of the deposit, but did not adequately define the controls of mineralization or ways to optimize future mining or exploration. Besides, surface geological mapping could not be sufficient to explain the controls and nature of mineralization in the area.

In the present study, we present the geologic controls triggering the graphite occurrence in Kambale in the Wa-Lawra Birimian greenstone belt of Ghana by re-logging of drill chips obtained from Rotary Air Blast (RAB) drilling programs, outlining the petrology of the deposit and examination of three old transversal trenches in the area. This helped in producing the first litho-structural map of the area which clearly defined the fault systems and lithologies. The study is based mainly on field mapping and sampling including information from unpublished reports.

2. Study Area and Geological Setting

Kambale is in the Northwestern part of Ghana within the Wa Municipality and stands as one of the prospective regions for base metal mineralization and other ore deposits where presently graphite is being explored from alluvial deposits by Castle Minerals Limited (Fig. 1). The study area encompasses some suburbs of the municipality such as Wa-Sombo, Mangu, Nakore, Kambalekori and some parts of Kpaguri.

It lies in the Wa-Lawra Birimian greenstone belt, which is the only N-S trending belt in Ghana (Kesse, 1985). The belt represents the southern peripheral of the mega Boromo belt in Burkina Faso (Baratoux et al., 2011). It is mainly composed of metavolcanic, pyroclastic and metasedimentary rocks (Fig. 1). The metavolcanic rocks are of basaltic and gabbroic compositions and most have now been altered to various schists (Arhin and Nude, 2009; Block et al., 2015). The metasedimentary rocks consist of tuff, carbonaceous phyllites, tuffaceous phyllites, cherts and manganiferous rocks (Amponsah et al., 2015). Leube et al. (1990) reported the intrusion of hornblende-rich ('belt') and mica–rich ('basin') granitoids. The belt-type granitoids in this area tend to be closely associated with the metavolcanic rocks whereas the basin-type granitoids tend to border the volcanic belt and are in the metasedimentary units (Leube et al., 1990). The belt-type granitoids are unfoliated, however the basin-type granitoids are strongly foliated to gneissic units. Rocks are generally isoclinally folded, with dips usually greater than 50°; the general foliation within the rocks is N-NNE to S-SSW. Sheared and brecciated quartz veins (up to 3m thick and 100 to 400m in length) are extensively developed in the southwestern part of the area. The quartz veining is associated mostly with the metasedimentary rocks, but there are also minor veins in the metavolcanic rocks and granitoids. These veins are usually concordant with the foliation, especially in the central part of the area. The volcanics and pyroclastic flows in the belt were emplaced between 2.2 Ga to 2.16 Ga (Barratoux et al., 2011). However, detrital zircon geochronological dating of the volcano-sedimentary rocks in the Wa-Lawra belt yielded ages older than 2.14 Ga (Barratoux et al., 2011). Syn-tectonic to late kinematic granitoid intrusion in the belt occurred around ~2.15-2.1 Ga (Amponsah et al., 2016).

Most of the volcanic suites and sediments at the western part of the belt have been metamorphosed under greenschist facies conditions with metamorphic mineral assemblage of chlorite, calcite and epidote. Contrary, the granitoids and para-ortho gneisses that outcrop in the eastern part are affected by amphibolite facies metamorphism characterized by metamorphic mineral assemblage of garnet, plagioclase, clinopyroxene and hornblende (Block et al., 2015). Other parts of the belt around the Wa domain where Kambale is located are mostly composed of metasedimentary rocks which have been metamorphosed to amphibolite-granulite facies. The belt has been affected by polyphase deformational episodes with a predominant N-S shortening under variable metamorphic facies (Barratoux et al., 2011).

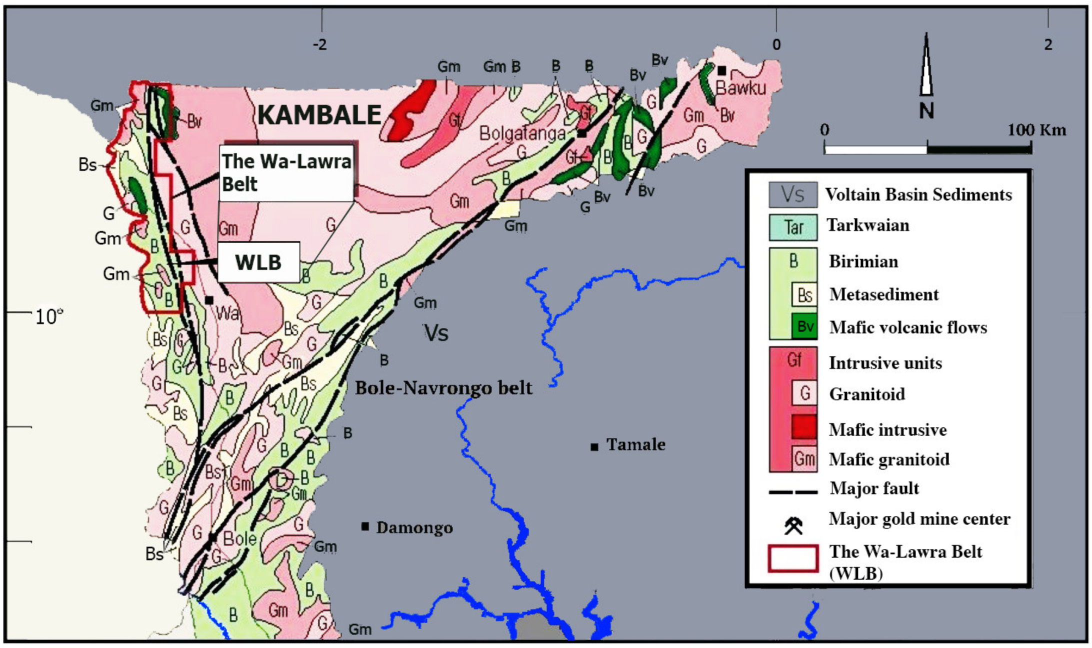

Figure 1. Geological map of the Wa-Lawra Belt where Kambale is located (modified from Amponsah et al., 2015)

3. Materials and Methods

3.1 Data Gathering and Preparation

In order to have first-hand information on the regional geology, mineralization and previous exploration activities in the area, data preparation, preliminary pre-processing and interpretation of datasets including relevant spatial exploration data and associated non-spatial data as well as reports on the various drilling activities in the area were executed. These data regarding the research in previous works elsewhere especially on graphite exploration were accessed from the internet whilst others were directly taken from Castle Minerals Limited.

Variable levels of weathering in the Kambale prospect dictated the use of small isolated occurrences of good outcrops for sample collection and mapping. Samples for detailed analysis were taken from RAB drill chips, where fresh unweathered specimens are available. Generally, the field work was based on; trench mapping and re-logging of drill chips. The strike and dips (line of zero dip) of the various structures observed in the rocks were taken and the data plotted using rose diagram.

Trenches which are a quick, cheap way of obtaining lithological and structural information in many terranes were used in achieving the objectives of this study. They served as an excellent adjunct to the previous RAB drilling programs in Kambale and the structural data that was obtained from the trenches complemented the lithological information obtained from the drill cuttings. The three transversal trenches used in this study are located at areas with the graphite deposit at shallow depths (Fig. 2) close to 10m and were subsequently mapped geologically.

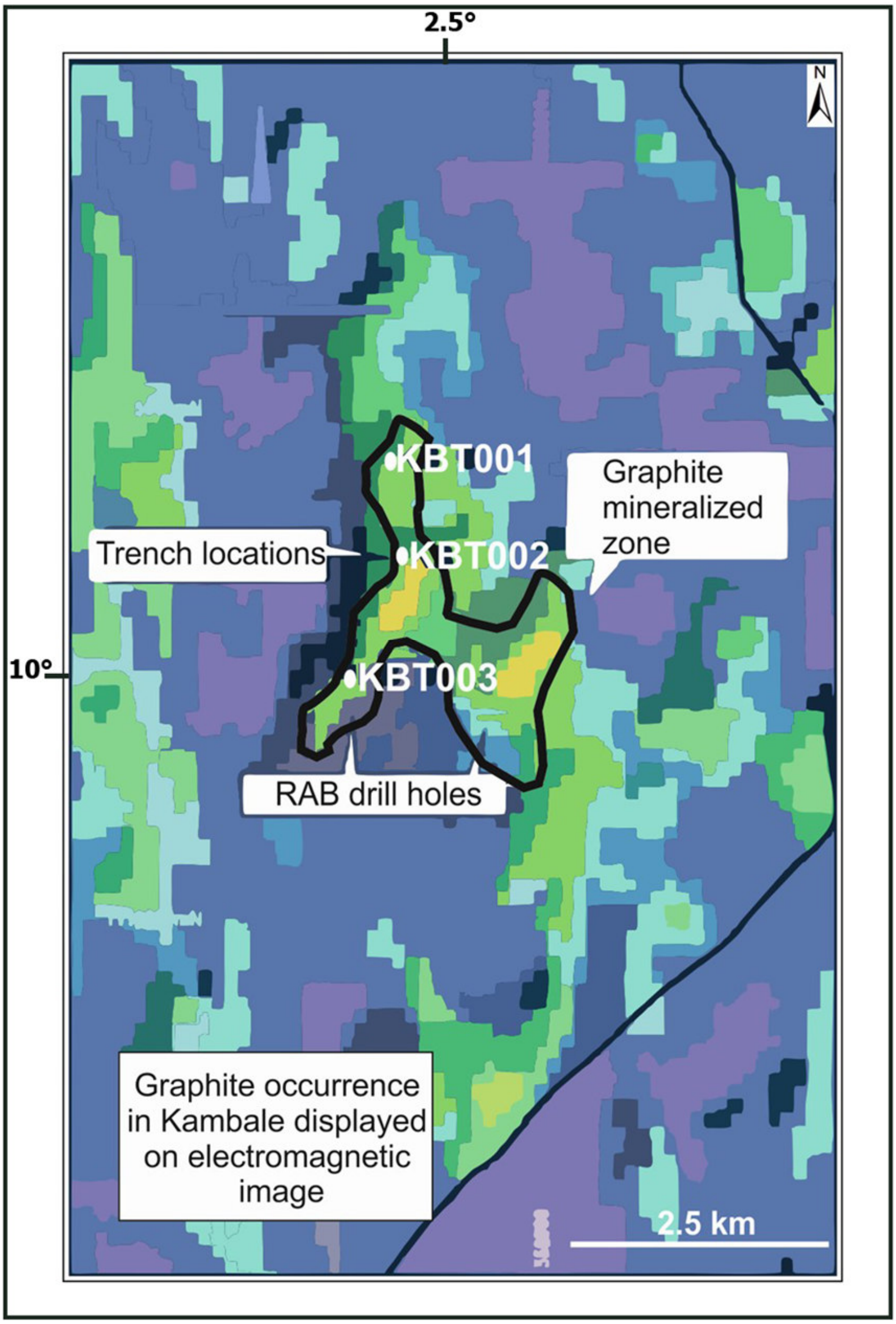

Figure 2. Location of historic trenches under this study and RAB drill traverses over regional electromagnetic image. The area circled black is the graphite prospect in Kambale, KBT001, KBT002 and KBT003 are the trenches used in this study (modified from Castle ASX Release, 2012)

The transversal trenches were each 12m deep having a length of 32m with a common width of 1.5m (Fig. 3a). The field sheet of the area was used as a base map at a scale of 1:50 000 and all structures were then mapped through observation and measurement. GPS coordinates of structures and lithological units were also taken. Data on structures (faults) basically dips and strikes were measured and recorded. The data obtained of all lithologies in the trenches was transformed into a single stratigraphic log (Fig. 4a).

Figure 3. a) Old trenches in Kambale prepared for mapping. The arrow shows graphitic schist zone encountered on the wall of the trench, b) Field view of steeply dipping sheared graphitic schist in Kambale. The arrows indicate the prevalent dip of the rock. Note the steepness of the dip and the dark gray to black color of the outcrop, the hammer is 32cm long, c) RAB drill chip samples at Kambale

Subsequently, eleven (11) RAB drill holes were re-logged to know the rock types found in the area and those associated with the graphite occurrence since rocks are not more exposed in the project area. During the geological logging of the well cuttings, close attention was paid to features that may be related to the graphite mineralization in the area. The rock type, its dominant minerals, colour and texture were noted. These were all transformed into a single stratigraphic section and correlated with the stratigraphic section produced from the trench mapping data (Fig. 4b).

3.2 Data Analysis

The data collected from the field, basically dip and strike of structures including lithological units were first plotted on the Wa field sheet manually. ArcGIS 10.2 software was then used to digitize the map indicating clearly the fault system, rock types, mineralized zones and shear zones. The faults observed in the lithological units were analyzed using a rose plot.

Mineralogical and textural relations of four (4) thin sections of graphitic schist and mica schist were investigated using optical microscopy, complemented by back-scattered electron (BSE) images obtained with a JEOL JSM 6360LV scanning electron microscope (SEM) equipped with a silicon drift detector analysis system, and presented in Fig. 5a, b.

4. Results

4.1 Field Observations, Trenching and Drill Chip Logging

In Kambale, extensive occurrence of the graphite deposit is associated with the NE part of the prospect commonly hosted in weathered to sheared graphitic schist with minor occurrences in mica schist (Fig. 7). The occurrence stretches from Wa-Sombo, Kambalikori to Nakore in the south (Fig. 7). The trenches exposed moderately to intensely sheared metasedimentary rocks of the lower Birimian formation, in close proximity to the contact of the unconformably overlying moderately weathered metavolcanic rocks (Fig. 4a). These rocks are overprinted with weak to moderate ferricrate or lateritic cover above, weak to strong pervasive biotite, and locally strong foliation with selective silicification (Fig. 4a). Sericitic alteration is present in discrete bands or beds which may represent more felsic precursors (dikes or pegmatites).

Most of the altered lithologies host quartz veins at a percentage of 1 to 5%. Massive schist bands and lenses up to 20cm wide occur within some intensely sheared zones (Fig. 3b). The data obtained from the trench mapping was plotted on the field sheet of Wa to produce the first litho-structural map of the area as shown in Figure 7. The graphitic samples obtained during RAB drilling appear to be greasy and dark grey in color (Fig. 3c). Results from re-logging of the eleven (11) RAB drill holes are summarized in a stratigraphic section (Fig. 4b). The data suggests that the dominant rock types hosting the graphite deposit is graphitic schist and mica schist.

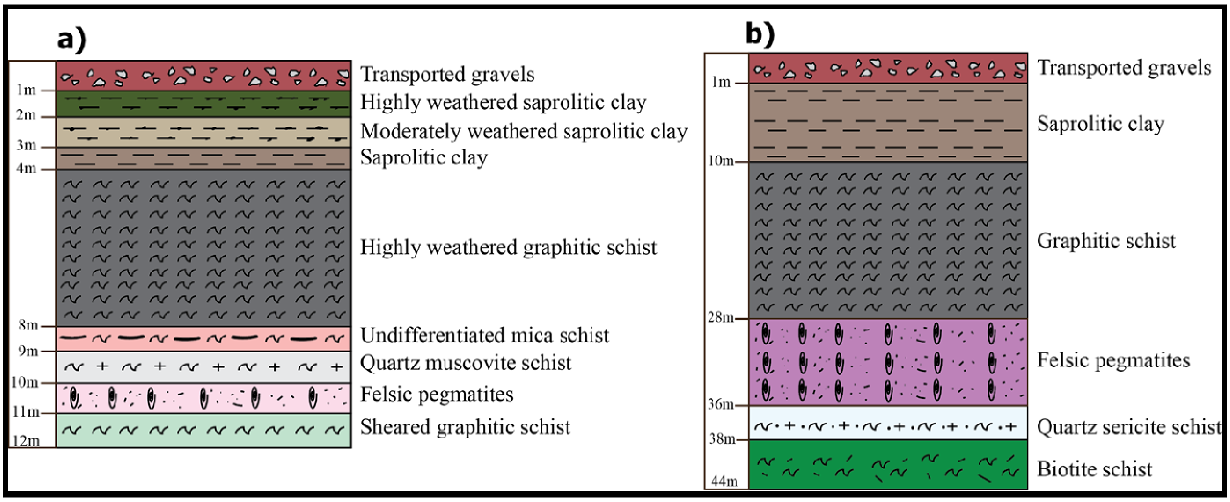

Figure 4. a) Stratigraphy of the investigated trenches, b) Stratigraphic section produced from the drill-hole data

4.2 Structural Data

The area is dominated by dip-slip faults that are characterized by E-W, NW-SE and NE-SW trends (Fig. 8).

4.3 Mineralogy and Paragenesis

The Kambale deposit is interpreted to be a flake graphite deposit from floatation recovery tests and is composed of pure aggregates of graphite though there are some quartz inclusions (Fig. 5a). Optical microscopic studies of graphitic schist show that the deposit occasionally occurs in a complex mineral paragenesis of quartz ± calcite ± hornblende ± magnetite ± pyrrhotite ± rutile ± chalcocite ± graphite and other gangue minerals (Table 1). They were often found around the boundaries of large magnesian ferrohornblende minerals which tend to form quartz crystals (Fig. 5b). The quartz appears milky to opalescent as a result of the presence of rutile needles (Fig. 5c), implying that the terrane may have undergone regional type of metamorphism characterized by amphibolite-granulite facies. The magnesian ferrohornblende minerals are associated with the graphite in the area in view of the manganese mineralization that had hitherto been explored by Russian geologists. Petrographic examination of the mica schist in the area showed similar mineral associations with graphite (quartz ± biotite ± hornblende ± pyrrhotite ± chalcocite ± graphite) though the coarser parts tend to contain lesser or lack calcite magnetite and rutile (Fig. 5c, d).

Table 1. Host rock mineralogy from three locations of the study area

Rock type	Kambale	Nakore	Wa-Sombo
Mica schist	Qtz-Bt-Hbl-Mgt-Pyrt-Chalc-Gr	Qtz-Bt-Ms-Chalc-Gr	Qtz-Bt-Hbl-Pyrt-Chalc-Gr
Graphitic schist	Qtz-Cal-Hbl-Mgt-Pyrt-Rt-Chalc-Gr		Qtz-Cal-Hbl-Mgt-Chalc-Gr

Qtz-Quartz, Bt-Biotite, Ms-Muscovite, Hbl-Hornblende, Mgt-Magnetite, Pyrt-Pyrrhotite, Chalc-Chalcocite, Cal-Calcite, Rt-Rutile, Gr-Graphite

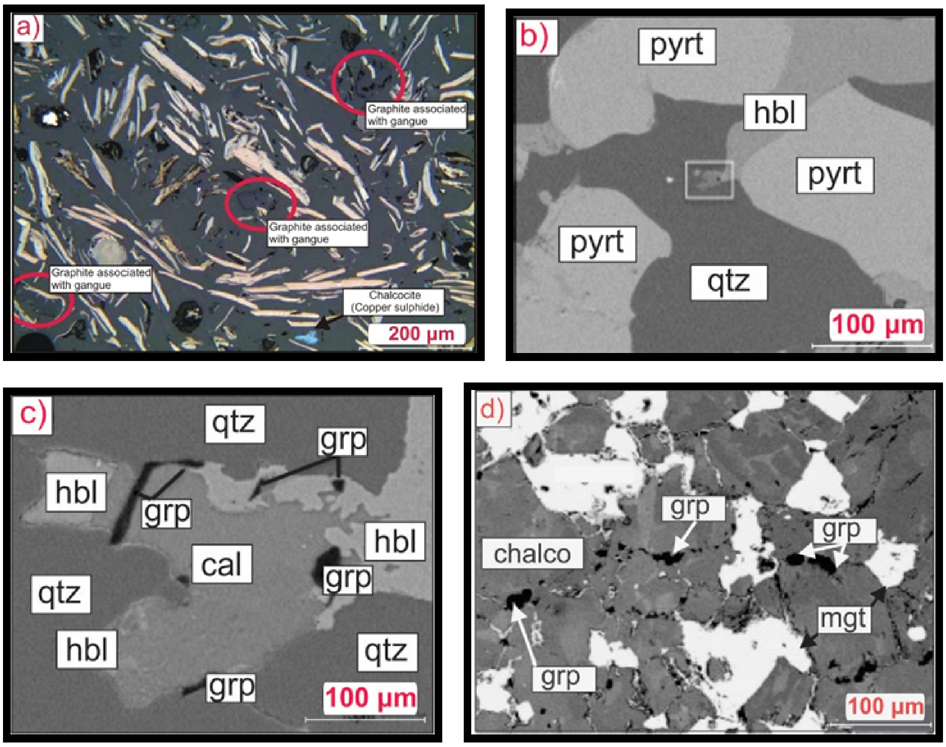

Figure 5. Backscatter images of subhedral to euhedral graphite in Kambale a) Polished section of fresh sample flotation concentrate showing predominantly liberated flakes of grey graphite (100 - 250 micron) in association with gangue minerals, b) graphite displaying textural relations with quartz-qtz, pyrrhotite-pyrt and hornblende-hbl, c) quartz-qtz, hornblende-hbl and calcite-cal in contact with graphite-grp at the crystal boundaries, d) graphite-grp showing association with chalcocite-chalco and magnetite-mgt. These minerals associated with graphite are common in hydrothermal deposits

5. Discussion

5.1 Litho-Structural Setting and Ore Body Characteristics

Graphite mineralization in Kambale shows affinity with graphitic schists as the host rocks from the subsurface data obtained from the trench mapping and drill-holes. The data obtained from the trenches and the drill-holes complement each other considering the similarity in stratigraphy of the area (Fig. 4a, b). The RAB drill data revealed that anytime graphitic schists were encountered, there was the presence of abundant graphite tracers, further corroborating the conclusion that the graphite deposit is hosted in graphitic schist even though there are a few traces of mica schists, which also have a potential influence on the graphite mineralization. The drill cross-section produced from the most graphitized drill-holes suggests that the deeper the drill-hole the more likely it is to largely intersect the graphite ore body though it could be reached at shallow depths about 10m (Fig. 6). However, the amount of graphite that can be reached by shallow drilling is not enough to quantify the tonnage and the prevailing structures of the deposit. This suggests that an oriented diamond drilling in the area would enhance complete understanding of the structures prevailing in Kambale. Also, manganeferrous rocks are encountered just a few meters in the ferruginized zone (Fig. 6), where laterization is the dominant alteration supporting the earlier exploration for manganese in the area by the Russian geologists. One of the trenches under examination is located in close proximity to the RAB drill-holes (Fig. 6). The presence of graphite in the metasedimentary rocks including graphitic schist and mica schist was likely formed hydrothermally. The hydrothermal fluids are interpreted to be metamorphic in origin or may be associated with magmatism, however there exists no isotopic data to confirm this with certainty.

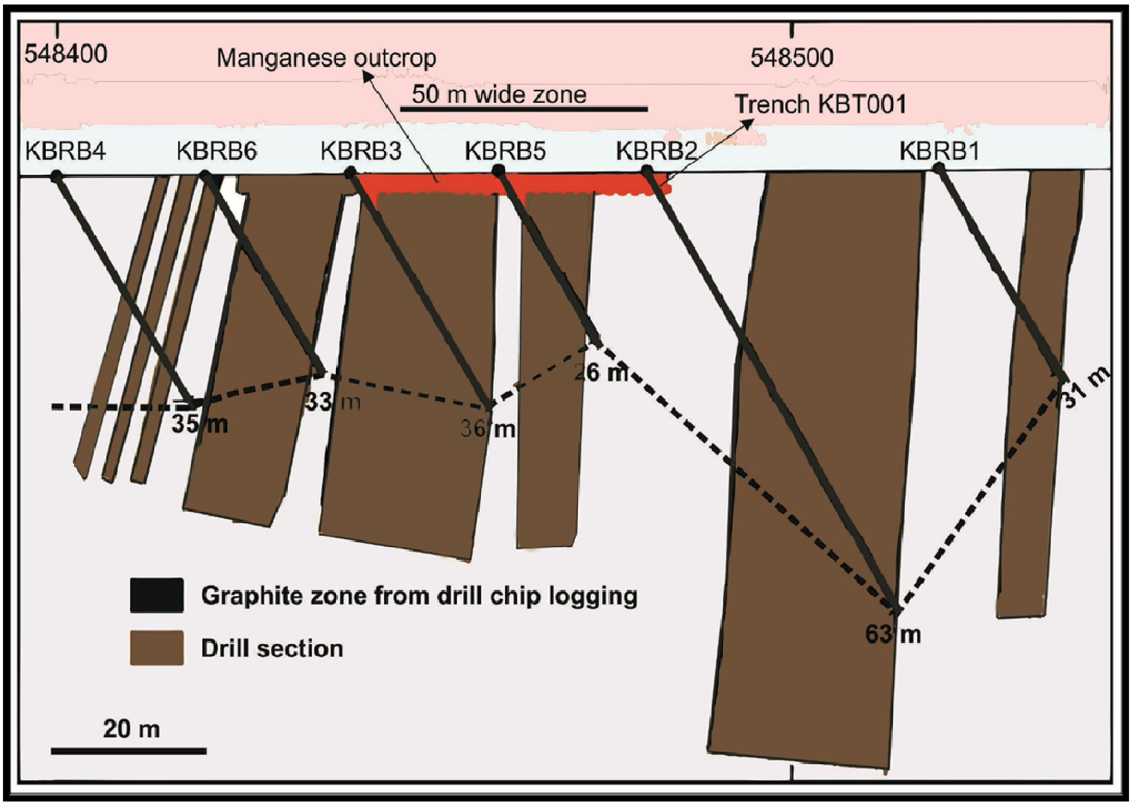

Figure 6. Rotary Air Blast drill-hole section based on the most graphitized holes along 1112140mN

In the litho-structural map, evidence from the trench mapping projected to the surface has shown that the area has been subjected to high degree of brittle and ductile deformation and faulting mostly in the graphitic schist zone (Fig. 7). It would be reiterated that much of the faults are found at the eastern walls of the trenches, most of which are dip-slip and a few of them being strike-slip. The faults in the area are generally stretching E-W between 150˚ and 320˚ at an average of 185˚, dipping NE-SW at an average of 060˚ (Fig. 8). These structural mechanisms indicate the masking effect of the Pan-African orogeny in the area. The dominant E-W trend coincides with the schist belts in the Birimian of Ghana, suggesting poly-cyclic metamorphism in the area.

Moreover, the cluster of faults on the NE segment corresponds to the distribution of mineralization in the area. The denser the fault population, the broader the mineralization. The dip-slip faults probably led to thrusting of the footwall over the hanging wall. They may have produced bends in the structure. Bends in faults are interpreted to be dilation sites which aid in the accumulation of large volumes of mineralizing fluids (e.g., Tripp and Vearncombe, 2004; Wang et al., 2013; Helmy and Zoheir, 2015). At the southern and western parts of the area, fewer faults were observed (Fig. 7), indicating that permeability was weaker in those areas during the period of placement of the mineralization. In other words, less deformation in those areas resulted in low permeability further causing narrow ore zone and for that matter the truncation of mineralization towards those areas (Kim et al., 2015; Sundarrajan et al., 2017).

The dominant syn-mineralization movement direction on faults and shears in the Kambale deposit appears to be dextral reverse-slip, consistent with an E–W to NE–SW shortening of the Wa-Lawra greenstone belt (Block et al., 2015). If the same regional forces had been active during post-mineralization faulting, the offset of ore zones would have resulted in movement towards the south and depth on the opposite side of the late Kambale shear parallel fault. Therefore continuation of the main lode would be present in the foot-wall sequence between the Nakore and Kambale shear to the south of the main lode at a depth. Mineralization is largely confined to the NE dipping dip-slip faults. Mineralization is also associated with the main Kambale Shear Zone (KSZ) and wall rock alteration products. In the southern part of the area, the footwall strikes generally N-S. The clear KSZ contact begins from the southern zone. Some veins were also observed in the field and the orientations of the quartz veins are related to mineralization. The veins are commonly found at the western zone. The extensional veins tend to be sub-vertical, they occur throughout the hanging wall and perpendicular to the shear vein. The Kambale footwall fault and hanging wall veins resulted in the deformation of the rocks between them, hence making them permeable to hydrothermal graphite bearing fluids. Jogs and fractures in the direction of the controlling faults within the KSZ influenced hydrothermal ore deposition by creating dilational zones. The fractures acted as conduits for the transportation of the fluid.

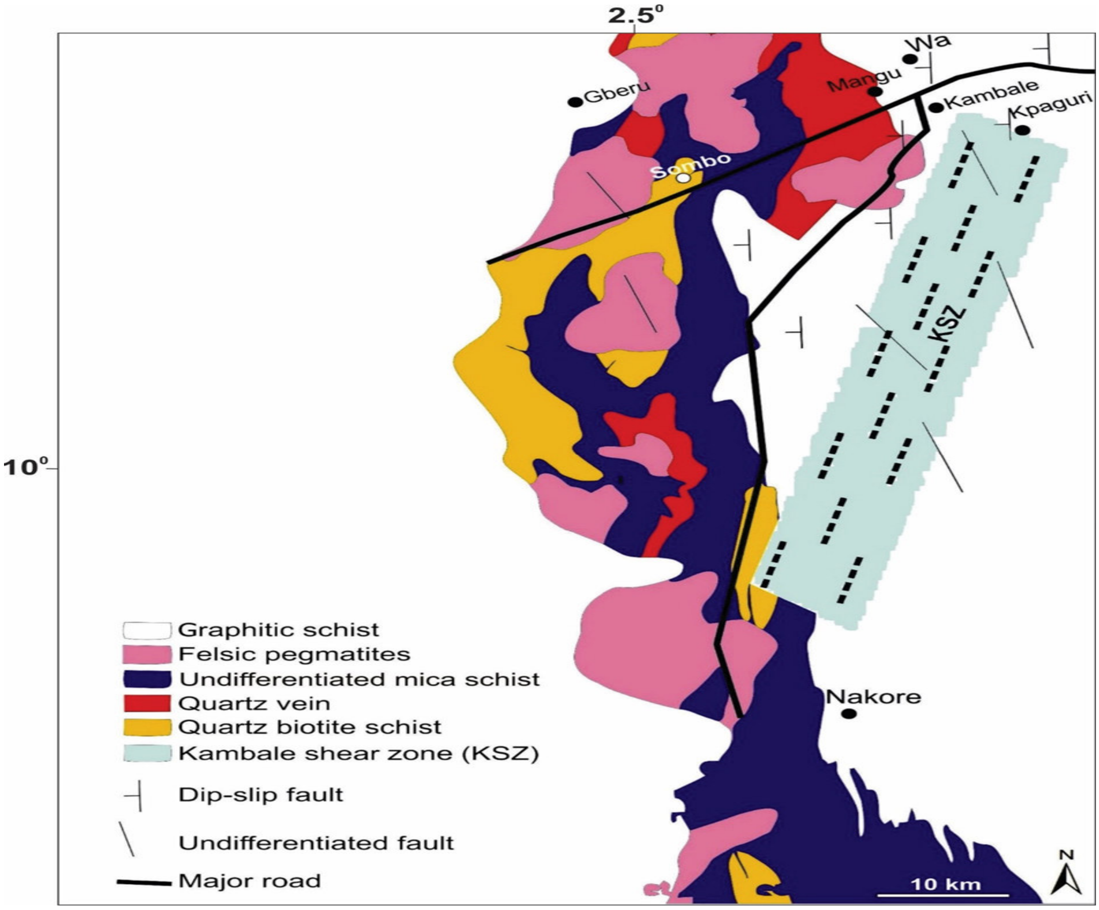

Figure 7. First litho-structural map of Kambale based on data obtained from the field. Mineralization is associated with the Kambale Shear Zone (KSZ) overlain mainly by graphitic schist

According to Allibone et al. (2002), rock permeability is dramatically influenced by rock deformation. This seems to corroborate the fact that active structures under a wide range of crustal conditions have higher permeability and maintain reduced fluid pressures to draw fluid into them. Hence, the more concentrated the deformation e.g., faults and shear zones, the more intensive will be the fluid flow. The observation of rock inclusions preserved in the metasedimentary rocks in the study area suggests the presence of an early deformation phase D1. The D1 phase of deformation is defined by a penetrative fabric S1 that developed throughout northwestern Ghana, and is directly associated with shear zones and large-scale folds (Block et al., 2016). On a regional scale, S1 trails in the Wa domain are parallel to the E–W axial surface of km-scale folds and shear zones. In most of the schist units in Kambale, S1 defines an arcuate geometry, elongated E-W (Fig. 8) and consistently oblique when correlated with the N-S orientation of the Wa-Lawra belt. The north-dipping KSZ represents the tectonic boundary between low-grade and high-grade metasedimentary rocks within the Wa domain of the Wa-Lawra belt. It is interpreted to be an extensional detachment in contact with other domains of the Wa-Lawra belt. The D2 event shows no strong fabric in proximity to the KSZ and adjacent shear zones, hence no overprinting relationships can be observed between D1 and D2 structures in Kambale. Therefore, shallow-dipping high-strain contact between various rocks in Kambale and the formation of graphite may be as a result of D2 deformation than D1, which stretches NW-SE and is associated with the Kambale mega-shear zone which largely affected all the litho-units (Fig. 8).

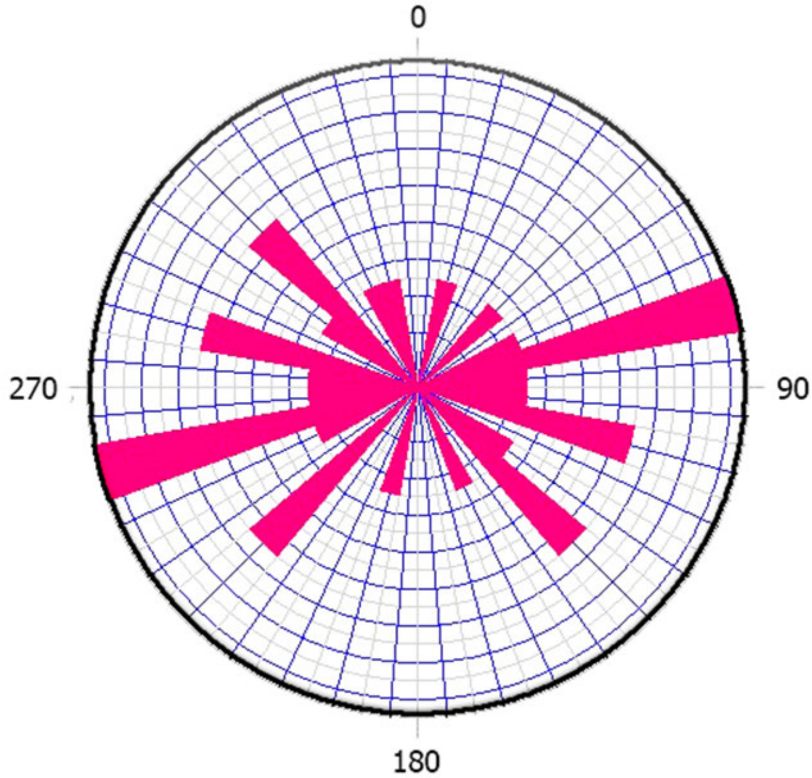

Figure 8. Rose diagram showing maximum deformation and fault trends in Kambale. The faults are mainly dip-slip faults that are characterized by E-W, NW-SE and NE-SW trends

5.2 Metamorphism and Graphite Formation

The metasedimentary rocks in Kambale are locally intruded by igneous rocks such as felsic pegmatites (Fig. 7). A regional metamorphic study based on petrological and geochronological constraints by Block et al. (2015) suggests that the rocks in the area have undergone medium-high grade metamorphism under high T/medium P facies typically estimated as (~600-750˚C, 5.0–8.0 kbar), which corresponds to a high apparent geothermal gradient (~30˚C/km). The high-temperature, medium pressure (HT–MP) rock assemblages formed in the amphibolite-granulite facies (Block et al., 2015). The timing of the amphibolite-granulite facies metamorphic overprinting in the area is constrained by in-situ U–Pb dating of monazite crystallization at 2.13 Ga (Block et al., 2015). It is presumed that the graphite deposit formed under such HT-MP amphibolite-granulite facies conditions where the CO_2 phase became dominant and flushed out the H_2O as a CO_2 rich fluid (Glassley, 1982).

Considering such conditions of metamorphism, the porosity of the host rocks decreases and the fluid pressure approaches that of the rock pressure (Pf=Pt) (Katz, 1987). However, the density difference between the fluid phase and the rock may potentially redirect fluid transportation via the surface of the earth. Such impermeable conditions are conducive enough to permit the high pore pressures develop effective stresses that make the rocks more brittle. This decreases their tensional strength and stimulates hydraulic fracturing and crack growth. At this point, the fluids freely migrate into the opened fractures and cracks until the fluid pressures are re-equilibrated. Any drop in the pressure of the fracture will result in the precipitation of SiO_2, whilst the CO_2-rich fluid phases will increase the pore pressures causing further hydraulic fracturing in the SiO_2 saturated fracture. The CO_2-rich fluid phases will precipitate graphite after filling the fracture under optimum conditions (Glassley, 1982; Katz, 1987). These interpretations are however constrained by the non-availability of isotopic data.

Therefore evolution of the flake graphite in Kambale is believed to be as a result of the high grade metamorphism, where deep-seated CO_2-rich fluid phase of crustal origin invaded the metamorphosed rocks. The intensity of the pore fluid pressures aided in the genesis of the graphite by hydraulic fracturing of the underlying rocks under regional syntectonic deformation. The petrographic features of the flake graphite in Kambale suggest a complex history of crack seal growth as seen in the subparallel quartz crystals. The rutile inclusions in the graphite is interpreted to be a late stage exsolution event which speared the crystal boundaries of the quartz grains and the cracks. The little occurrence of pyrrhotite and chalcocite in the flake graphite may be as a result of the widespread abundance of graphite sulphide-rich schist in Kambale. In such rocks, pyrrhotite is the most common phase and is formed by the transition of pyrite to pyrrhotite by desulphidization reaction;

$$2\ FeS_2 + 2\ FeO + C = 4\ FeS + CO_2$$

The prevalence of CO_2-rich fluid phase in the rocks however inhibits this reaction and results in the pyrite-graphite assemblage.

5.3 Hydrothermal Transport of Graphite

Hydrothermal fluids have the tendency of dissolving carbon and transporting it in the form of CO_2 as can be inferred from the above equation. During metamorphism of carbonate and organic sediments, the transported carbon is usually released (Rumble, 2014). The graphite in Kambale may have formed from metamorphic fluids derived from metasedimentary rocks as discussed earlier on in the previous sections. Significant enrichment of hydrothermal graphite is mainly observed in shear zones cross-cutting host rocks as in Kambale. These shear zones are usually zones of permeability and conductivity and tend to be conduits for carbon-rich fluid phases. Considering minor occurrence of the hydrothermal graphite in metaigneous rocks such as pegmatites and quartz veins and the widespread abundance in carbon-bearing metasedimentary rocks such as graphitic schist and mica schist in Kambale, the graphite might have migrated from a local source into the KSZ.

Again, hydration of the wall-rocks in the passage of hydrothermal alteration coupled with local pressure fluctuation in the KSZ can be invoked for the deposition of the flake graphite in Kambale. The fluids responsible for the mineralization appear to have been reduced juxtaposed to the reduced nature of the hydrothermally altered wall-rocks in Kambale. In all, the genetic model developed for the flake graphite mineralization in Kambale can be described in three steps;

(1) initial graphite formed by graphitization of organic matter in carbon-rich sediments, during prograde metamorphism (Fig. 9a).
(2) formation of the main Kambale Shear Zone (KSZ) associated with later folding, caused by shearing in the metasedimentary host rocks. The shear zones served as conduits for the passage of metamorphic fluids, which may have sifted carbon from the graphitic metasedimentary rocks (Fig. 9b).
(3) precipitation of the graphite from carbon-rich hydrothermal fluids, within the KSZ and the proximal host rocks, by hydration of the wall-rocks causing carbon-saturation. The graphite developed anastomosing structures draping fragments of the host rocks in the KSZ during retrograde metamorphism (Fig. 9c).

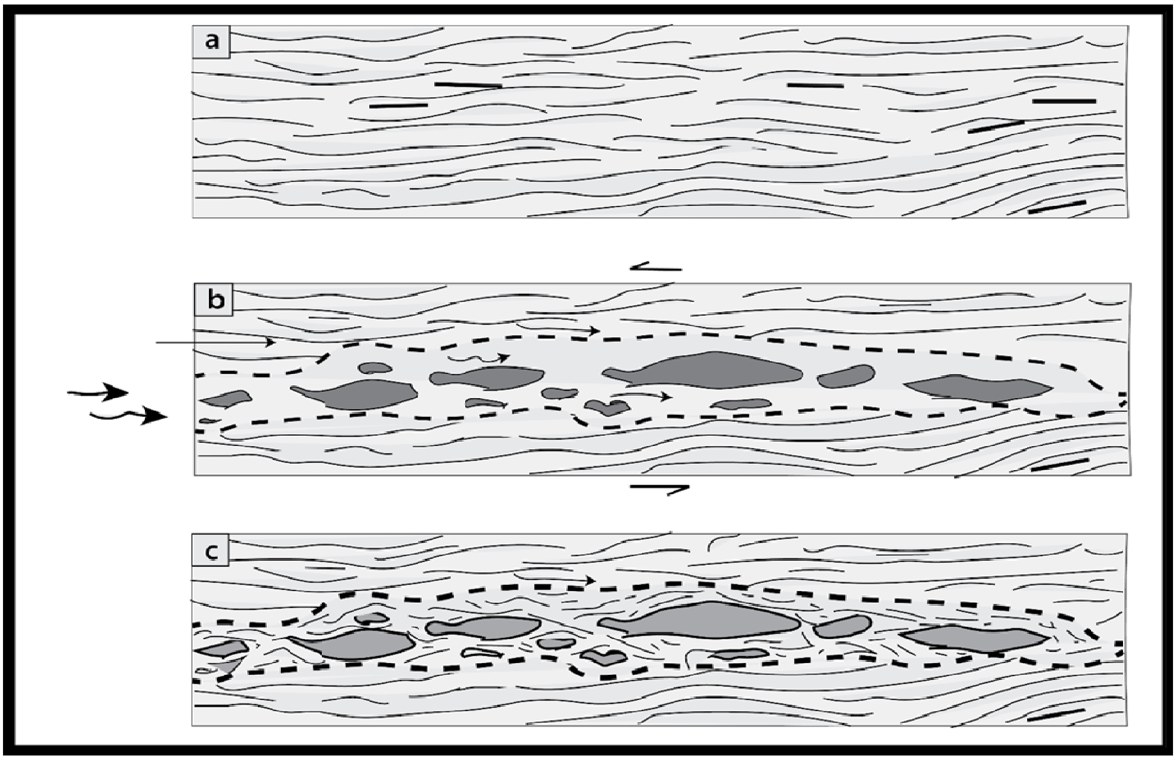

Figure 9. Three-stage model describing the genesis of graphite within graphitic schist in Kambale a) The graphitic schist contains in-situ graphite formed by graphitization of organic matter during prograde metamorphism, b) Shearing during folding forms the Kambale Shear Zone (KSZ) with fragments of graphitic schist. The KSZ serves as a conduit for carbon-rich hydrothermal fluids, c) Graphite is precipitated within the KSZ forming anastomosing structures that drape around the graphitic schist fragments

6. Conclusions

The geologic controls on graphite mineralization in Kambale, NW Ghana were investigated by means of trench mapping, petrology and re-logging of eleven (11) RAB drill-holes. The following conclusions are drawn from the study;

- The area is underlain by metasedimentary rocks such as graphitic schist, mica schist, quartzites and manganiferous rocks, which are overprinted with weak to moderate ferricrate or lateritic cover above, weak to strong pervasive biotite.
- The rock type accommodating the graphite mineralization is graphitic schist and to a lesser extent, mica schist.
- The Kambale deposit is characterised by numerous faults and shears, associated with brittle and ductile deformation at the NE part of the main Kambale Shear Zone (KSZ).
- The deposit is structurally controlled by dip-slip faults and shears stretching generally E-W between 150˚ to 320˚, dipping NE-SW at an average of 060˚, which provide good dilational sites for mineralizing fluids accumulation. Hence, structures (faults, shears) have outright control over graphite mineralization in the Kambale deposit.
- Optical microscopic studies show that the deposit occasionally occurs in a complex mineral paragenesis of quartz ± hornblende ± magnetite ± pyrrhotite ± rutile ± chalcocite ± graphite and other gangue minerals.
- The rocks have undergone medium-high grade metamorphism under high T/medium P facies typically estimated as (~600-750˚C, 5.0–8.0 kbar), which corresponds to a high apparent geothermal gradient (~30˚C/km) in amphibolite-granulite facies.
- Flake graphite formation in Kambale is believed to be as a result of the high grade metamorphism in the presence of deep-seated CO_2-rich fluid phase of crustal origin.
- The intensity of the pore fluid pressures aided in the genesis of the graphite by hydraulic fracturing of the rocks under regional syntectonic deformation.

Future research is aimed at using stable isotope geochemistry and fluid inclusions to better constrain the genesis of the deposit.

Acknowledgements

The authors wish to thank the exploration geologists at Castle Minerals Limited for their unreserved support rendered during the period of the research. Particularly the Exploration Supervisor, Mr. Edward Nii Mills is duly acknowledged for his assistance in the field. We sincerely acknowledge the University for Development Studies, Navrongo Campus for the opportunity within the Department of Earth and Environmental Sciences to conduct this research. Oguzcan Karagoz is acknowledged for his contribution to the first draft of this paper. The first author also wishes to thank the Scientific and Technological Research Council of Turkey (TÜBİTAK) for their continuous support during the time of writing this research as a fellow of TÜBİTAK BIDEB 2215 Graduate Scholarship Program for International Students.

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