Research Article

Joshua Chisambi*, Tiyamike Haundi, and Gift Tsokonombwe

Geologic structures associated with gold mineralization in the Kirk Range area in Southern Malawi

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Abstract: In this contribution, we use a newly acquired high-resolution airborne geophysical data set and field geological investigations in the Kirk Range area in southern Malawi to understand structures that control gold mineralization. Gold in this area is alluvial, mined by artisanal miners and detailed information regarding the structures controlling primary mineralization remains sparse. Structural interpretations are afforded by in-depth investigation of airborne magnetic and radiometric data, which are then supported by ground geological mapping and by microscopic observations using X-ray computed tomography (XCT) and optical microscopy. The results show that the Kirk Range displays extensive faulting and shearing with a NE–SW trend as the prevalent structural grain of the region. Gold mineralization is hosted in NE–SW trending structures. The wall rock alteration associated with gold mineralization results in a pronounced K/Th anomaly, which is suggested as an important radiometric guide for future exploration efforts. Exploration in the Kirk Range region should focus on the NE–SW structures, which represent potential conduits for fluid flow.

Keywords: magnetic data, radiometric data, gold mineralization, Kirk Range

1 Introduction

Geological structures play a significant role in mineral exploration. They act as conduits for mineralizing hydrothermal fluids [1]. As such, they play a major role in the formation of mineralized systems; however, sometimes they may not be apparently recognized from the ground mapping of surface geology [1,2]. When such is the case, geophysical methods, particularly high-resolution magnetic and gravity methods, are usually used to map the concealed geological structures that might be directly related to mineralization [3,14]. These methods are extensively used worldwide as a base for geological interpretations because they play an important role in delineating geological features like faults, folds, shear zones and other areas favourable for mineralization [4–9]. These structures are significant in the exploration and localization of mineralized zones [10–12]. This is evidenced by the fact that most significant mineral deposits are spatially associated with crustal scale structures. High global demand for mineral commodities has led to the increasing application of geophysical technologies to a wide variety of ore deposits [13]. An understanding of the basic geologic characteristics of ore deposits is crucial to evaluating known deposits and delineating prospective areas of mineralization [14]. For example, in their study, Elkhateeb and Abdellatif [15] used aeromagnetic and aeroradiometric methods to determine the possible location of gold mineralization by structure delineation, mapping lithology and hydrothermal alteration zones and were able to locate probable gold mineralization zones. Similarly, Yousif et al. [16] integrated aeromagnetic, Landsat ETM + and airborne radiometric data to map the distributions of the favourable areas for archaic orogenic-gold mineralization and their relation with lithology and structure. By using airborne gamma-ray spectrometric and aeromagnetic data, they were able to construct lithological and structural maps that were used in identifying favourable areas for archaic orogenic-gold mineralization. Their findings suggest that geological and

* **Corresponding author: Joshua Chisambi**, Department of Mining Engineering, Malawi University of Business and Applied Sciences, Blantyre, Malawi, e-mail: jchisambi@poly.ac.mw, jjchisambi@gmail.com

Tiyamike Haundi, Gift Tsokonombwe: Department of Mining Engineering, Malawi University of Business and Applied Sciences, Blantyre, Malawi

structural maps play a crucial role in mineral prospecting and exploration as they allow delineation of ore-bearing host rocks and also structures associated with mineralization [17]. Furthermore, Assran *et al.* [18] successfully used aeromagnetic data to detect prospective areas for gold mineralization using image analysis technique in Eastern Desert, Egypt. Similar findings have also been demonstrated by Elkhateeb and Abdellatif [15], who used aeromagnetic and aeroradiometric methods to determine possible locations of gold mineralization by delineating structures, mapping lithology and hydrothermal alteration zones. Several other studies [19–27] have also been conducted in mapping surface geology and delineation of potential mineralized zones using aeromagnetic and gamma ray spectrometry data and have shown to be successful.

Although airborne magnetic and gamma-ray data have been used to map out the surface geology and structures related to ore deposit mineralization in several studies across the world, it is not the case with Malawi, a country in sub-Saharan Africa. Malawi is one of the poorest countries in the world. Due to a lack of finances, the geology of Malawi has not been studied well, and the existing geological map dates back to 1965 [28]. Mapping was done by traditional geological mapping approaches and most lithological units and structures were missed due to thick forest covers at that time. This has contributed to scanty mineral resource data for Malawi.

In a bid to uncover the true mineral potential for the country, the Malawi government has recently acquired high-resolution airborne geophysical data. These data comprise magnetic, radiometric and gravity covering the whole country. The data are new and have not been used in mineral exploration. In this study, we use these newly acquired airborne geophysical data to characterize the major structural controls of gold mineralization in the Kirk Range, southern Malawi, and map hydrothermal alteration zones associated with gold mineralization. The Kirk Range is one of the well-known gold occurrences in Malawi [28]. Gold in this area is mined by artisanal miners and mostly it is alluvial. Though the Kirk Range consists of several occurrences of alluvial gold workings, detailed information regarding the structures controlling primary mineralization remains sparse. This present study would help in improving our knowledge about structural controls of gold mineralization and provide a reference for further gold prospecting in this area and for studying other similar gold occurrence areas in Malawi.

This is the first study to use these new data and will help in identifying geological environments favorable for gold mineralization for future exploration efforts in the area.

2 Regional geology

The geology of the Kirk Range, and indeed the whole of Malawi, has not been well constrained, with the existing geological map dating back to 1965 [28]. The geology of Malawi is underlain by Precambrian to lower Paleozoic high-grade metamorphic para- and orthogneisses and schists commonly referred to as Malawi basement complex rocks [29]. These rocks have been subjected to high-grade metamorphism and polyphase deformation [30,31] and a prolonged structural and metamorphic history. They are associated with three major orogenic events (Ubendian, Irumide, and Mozambiquean) [32].

The Ubendian belt is characterized by NW-SE trending structures and was first described by McConnell [33]. It was formed during the Palaeoproterozoic Ubendian Orogeny between 2,200 and 1,800 Ma [34]. The rocks of the Ubendian belt are characterized by sequences of medium- to high-grade metamorphic supracrustal gneisses and schist that were intruded by various plutonic igneous rocks [35]. The rocks experienced peak metamorphic conditions of 750–850°C at 18 kbar and recorded high-pressure granulite facies conditions [36]. The Ubendian belt rocks were structurally overprinted during the Mesoproterozoic (Irumide) and Neoproterozoic (East African/Pan-African) orogenies. These later events extensively altered the internal architecture of the belt and partly obscured the Palaeoproterozoic history.

Mesoproterozoic Irumide orogeny is a northeast-trending orogenic belt. It is marked by a rapid increase in metamorphic grade from greenschist facies conditions to granulite facies conditions. The Irumide Belt was first described by [37] and [38]; it trends in the NE–SW direction and is subdivided by crustal-scale shear zones into the Irumide s.s., the Southern Irumide, the Unango subprovince, and the Nampula subprovince with a general trend of NE–SW [39,40].

The Pan African Orogeny occurred roughly at 800–500 Ma [41], forming the Mozambique Belt [42]. The Pan African Orogeny [41] was the last major orogenic event that shaped the overall geology of Malawi and resulted in significant overprinting of older orogenic features from the Ubendian- and Irumide orogenies [43]. The Pan African Orogeny created N–S trending structures and reactivated older pre-existing structures. Peak conditions for the orogenic event were suggested to be 750–800°C at roughly 12–13 kbar and subsequent amphibolite facies retrogression occurred at 550–700°C at 5–8 kbar [32]. The regional geological map is shown in Figure 1.

Figure 1: Structural architecture of the Precambrian geology of Malawi.

2.1 Local geology

The Kirk Range lies between latitudes 15.30 and 15.31°S and the longitudes 34.82 and 34.85°E, approximately 40 km northwest of Blantyre city in Malawi. The area is characterized by NE trending gneissic rocks that underwent amphibolite facies metamorphism. These lithological units have experienced multiple episodes of folding and fracturing. The Manondo-Choma thrust fault separates a moderately steep southeasterly dipping hanging-wall, from highly deformed and isoclinal folded lithologies in the footwall. Biotite schists in the footwall of the

Manondo-Choma thrust are the host rocks for gold mineralization. Mineralization is associated with sulphide mineral assemblages dominated mainly by pyrite, pyrrhotite and chalcopyrite, and gold is associated with pyrite [44,45]. The local geological map for the Kirk Range is shown in Figure 2.

3 Methods

3.1 Airborne geophysical data

Between 2013 and 2014, a high-resolution geophysical survey was conducted by Sander Geophysics Limited (SGL) under the auspices of the World Banks Mining Governance and Growth Support Project (MGGSP) in Malawi. Airborne geophysical data were collected over the entire country using a Cessna Grand Caravan 208B's aircraft at 250 m line spacing and 60 m ground clearance. The aircraft was equipped with a high-resolution airborne magnetometer and radiometer. The survey was conducted with survey traverse lines-oriented northeast-southwest at N45°E, with orthogonal control lines spaced at 5,000 m. The airborne magnetic data were corrected for the IGRF using the IGRF model from 2010.

The collected data included magnetic anomaly measurements, gravity and gamma-ray spectrometric measurements of potassium (K), thorium (Th) and uranium (U) signals [46].

3.2 Magnetic data processing

All geophysical data were subsequently processed using Geosoft Oasis Montaj software [47]. Specifically, the original data lines were gridded using a minimum curvature gridding method [48] and a 50 m grid cell size to provide smoothed spatial continuity across the area of interest.

Magnetic anomalies usually have complex shapes due to the variation of the earth's magnetic field at the point of measurement. To resolve this, a reduction of the total magnetic field to the pole (RTP) was applied using the reduction to the pole (RTP) algorithm [49]. RTP positions the anomalies are more directly over their causative bodies, and hence, make interpretation easier [50]. The resulting grids were further filtered to enhance any high-intensity magnetic bodies and structures. The applied filters included the analytical signal [51], first vertical derivative [52,53] and tilt derivative [54]. The analytical signal was used to delineate the edges of the magnetic

Figure 2: Geological map of the Kirk Range area, after Chisambi and von der Heyden (2019).

anomalies. Tilt- and first vertical derivatives enhance linear geological features, such as faults and dykes, and provide an excellent base for structural interpretation [55]. Geological features were then extracted from the processed images using visual image interpretation techniques [56].

3.3 Radiometric data processing

Single-band (K, Th, U) pseudo colour and ternary images derived from the radiometric data were used to confirm the mapped surface geology and structures [57]. The single-band potassium (K), thorium (Th), uranium (U) pseudo color images were used for interpretation because they show areas where a particular radio-element can be directly correlated with the geochemical properties of the surface lithology and regolith. Gamma-ray channels (bands) were displayed as ternary colour composite images allowing for the interpretation of three channels of data using an additive mix of the primary colors (red-green-blue) of the computer. The ternary map was produced by assigning Th grid to green, K grid to red and U grid to blue in order to qualitatively interpret various lithologies and compare them with the ground-based measurements. This image helped in highlighting different lithological units.

Additionally, K/Th radioactive element ratio maps were generated in Oasis Montage using the grid math algorithm to enhance subtle features that may not have been obvious in the original grids [58].

3.4 Field mapping and petrography

The geophysical results were ground-truthed during the mapping campaign. Major lithological units were mapped and sampled for subsequent thin and thick section mineralogical analyses using a Nikon Eclipse E 200 polarizing microscope in reflected and transmitted light.

3.5 High-resolution X-ray computed tomography (XCT)

In order to understand the distribution of gold mineralization in mineralized drill core samples, a segment of the core sample (45 mm diameter and 15 cm length) was scanned using the Electric Phoenix VTomeX L240 micro XCT scanner system at the Central Analytical Facility (CAF), Stellenbosch University (South Africa). The XCT

facility is described in more detail in ref. [59]. To optimize the scanning of gold-sulphide ores, the scanning parameters were set to 100 kV, 100 μ A, and the X-ray beam was filtered using a 0.5 mm Cu filter. Images were acquired using a dwell time of 500 ms. Each scan took about 4 h and the resulting model had a voxel size of 35 μ m.

4 Results and discussions

The aeromagnetic data are presented in Figure 3. The total magnetic intensity map shows high-amplitude, long-wavelength anomalies in the northeastern side and central parts of the study area that trend in the NE–SW direction. These high magnetic anomalies suggest deeper magnetic sources. On the surface, the NE-striking, magnetic highs in the northeastern side correlate with biotite gneiss rocks, biotite schist, granitic gneiss and quartzite schist units. Similar amplitude anomalies are found on the eastern side and southwestern side where they correlate with exposures of granitic gneiss and biotite schist. The longer wavelength anomalies associated with these units indicate deeper underlying magnetic sources attributed to intrusive bodies that may have acted as the heat source for gold mineralization. The magnetic low in the northwestern, southeastern and central sides correlate with charnockitic gneiss, feldspathic gneiss and muscovite schist units. These rocks are highly altered in the field and the low magnetic signatures may indicate that hydrothermal alteration has caused significant changes in rock magnetism in these units.

The aeromagnetic data allow for the identification of dominant linear trends in the greater Kirk Range (Figure 3). These linear features are interpreted to represent faults and deep-level basement shear zones. From the aeromagnetic data, it is seen that the Kirk Range displays extensive faulting and shearing. The rose diagram in Figure 3e presents a compilation of the orientations of the linear features and shows that the NE–SW is the prevalent structural grain of the region. From magnetics, it can be deduced that these major fractures may have acted as a conduit system for mineralizing hydrothermal fluids and played a fundamental role in gold mineralization.

The NE–SW trending faults and shear zones are better revealed in the tilt derivative and vertical derivative maps (Figure 3c and d). The central part of the Kirk Range area is marked by an increase in visibility of shallow structural features. Comparison of the first vertical derivative map and tilt derivative map (Figure 3c and d), with the total field map (Figure 3a), shows a marked increase in

Figure 3: Airborne geophysical data of the Kirk Range area with interpreted linear structures overlain on it. (a) Total magnetic intensity image, (b) analytic signal, (c) tilt derivative image and (d) vertical derivative, black dots gold mines, brown dots, gold occurrences. (e) Rose diagram depicting the dominant orientation of the structures in the study area to be a NE-SW trend.

Figure 4: Ground evidence indicating the presence of faulting and shearing augmenting found in airborne magnetics. (a) Sheared Biotite schist rock, (b) biotite gneiss rock that has been faulted, (c) thin section of the biotite gneiss rock showing grain size reduction due to shearing, and (d and e) shear sense indicators obtained from the sheared part in (c).

visibility of structural features, especially in the central and NE part. These structures are interpreted to have acted as potential fluid pathways for hydrothermal fluids. Most of the structures were verified during the ground geological mapping, and ground field mapping evidence indicates the presence of numerous faulting and shearing (Figure 4) at different locations in the area oriented in the NE–SW direction, an orientation that is similar to the orientation found in the aeromagnetic data.

In the field, the shear structures exhibit a dextral sense of movement. Additionally, we examined some of the rock units under a microscope and thin section examination of the lithological units in the area indicates mylonitic texture and sigmoidal structures a feature common in ductile shear zones (Figure 4c–e). These indicate that the area must have undergone crustal deformation that produced these shear structures, which we interpret to have played a vital role in gold

mineralization. The shear structures acted as the conduits for the mineralizing hydrothermal fluids and are the same linear structures depicted in the magnetic data in Figure 3. Orogenic gold mineralization is known to occur in areas of structural complexity near major shear zones that form conduits for mineralizing fluids. Geophysical evidence in this study indicates that the geology of the Kirk Range is associated with these NE–SW trending regional structures/faults [45].

In addition, in this study area, there are two historical gold mines, namely the Breeze Au mine and the Phalula Au mine. The location of these old gold mines mostly occurs along these NE–SW structures identified on the airborne geophysical data (Figure 3a and b). Furthermore, most gold occurrences (Figure 3a and b) in the Kirk Range are spatially occurring along these structures as well. Therefore, the spatial relation in the location of the historical gold mines and gold occurrences with the structures indicates that there is a high correlation, signifying that these structures (shear zones and faults) must have acted as potential fluid pathways for hydrothermal fluids.

We can further say that the Kirk Range must have undergone a pronounced tectonic activity, probably during the Pan-African orogenic cycle, which resulted in the development of these NE–SW trending structures and we consider these structures to be prospective for gold [43]. Our interpretation of aeromagnetic data, therefore, reveals crustal-scale lineaments that are important for understanding mineralization in this area. These crustal scale lineaments were used as conduits for mineralizing hydrothermal fluids and are closely associated with mineralization.

4.1 Gamma-ray spectrometry data

To augment the aeromagnetic interpretation, we used the gamma-ray spectrometry data to map out lithological variations and alterations. It is a well-known fact that hydrothermal alteration anomalies provide evidence of fluid/rock interaction of hot acidic hydrothermal fluids' proximity to mineralization and the surrounding rocks. Evidently, recognizing and mapping out alteration areas is very important in mineral exploration because they act as a guide to mineralization [60]. Practical application of gamma-ray spectrometry in mapping hydrothermal alteration has been demonstrated in a wide variety of geologic settings [60]. For example, potassium alteration in the form of sericite is commonly associated with many types of base metal and gold deposits [60].

In our study area, the K radiometric map (Figure 5a) shows high K values in the west and southeastern side of the study area indicating the dominance of K. These high K values are associated with biotite schist, feldspathic gneiss, muscovite schist and biotite gneiss. The north and northeastern side of the survey area are associated with low K values. These lower values of K in the N and NE of the survey area are associated with quartzite gneiss and Charnockites. Some linear patterns are also recognized, inferring the presence of geological discontinuities or local fault-oriented NE–SW.

The total count map in Figure 5b shows the lowest total count concentration level in the north, which is associated with Charnockitic gneiss and quartzite gneiss. The moderate concentration levels in the southern and central parts of the study area are related to Biotite gneiss and schist. The high-level concentration in the central and southern areas is associated with biotite schist, granitic gneiss and feldspathic gneiss.

The lowest concentration level in the Th contour map (Figure 5c) in the north is related to Charnockitic gneiss. The highest level in the central and southern part is associated with granitic gneiss and biotite schist while the moderate level is related to Biotite gneiss.

The U map (Figure 5d) shows a high level of uranium concentration in the west and this is associated with biotite gneiss and schist. The low uranium concentration in the north is related to Charnockitic gneiss. The moderate level in the east is associated with amphibolite gneiss.

The K/Th ratio map is shown in Figure 5e and is of great importance for searching signatures associated with hydrothermal alteration zones. A high K concentration and low Th concentration indicate an alteration in many ore deposits. In the figure, the areas that have been affected by hydrothermal alteration are revealed in red to pink colors. These hydrothermally altered areas are found in the central part and a bit of the southern part of the study area. These areas are associated with biotite schist, biotite gneiss and charnockite gneiss. The areas showing low K/Th values are not altered. Most of the hydrothermal alteration zones are trending towards the NE–SW direction, which is the same trend that the structures identified on the aeromagnetic data are following. Accordingly, the NE–SW trend seems to be the most identified trend both from aeromagnetic and aero radiometric interpretation. This indicates that this trend is very significant and plays an effective role in the geological frame of the study area.

We also see that the location of the structures and historical gold mines occur along the area where there is hydrothermal alteration. Thus, hydrothermal alteration zones in the Kirk Range and associated gold mineralization are

Figure 5: Radiometric data: (a) K map, (b) total count map, (c) Th map, (d) Ur map, (e) K/Th ratio map. The ratio map indicates the high concentration of K (red colour) and this suggests a low concentration of Th. (f) Ternary image.

strongly linked to NE–SW trending structures. Field evidence from ground geological mapping reveals that the area is hydrothermally altered and the alteration is mainly associated with sericitization (Figure 6), signifying the alteration assemblages mapped in the radiometric data to be true.

The ternary image was made by assigning gamma-ray channels (bands) as colour composite using an additive mix of the primary colors (red–green–blue) of the computer. We assigned Th grid to green, K grid to red and U grid to blue in order to qualitatively interpret the various lithologies. This image helped in highlighting different lithological units from which lithological contrasts were interpreted.

Some areas within the map show a high level of concentration for all the three radioactive elements K, Th and U, and are characterized by white color. These areas are

associated with granitic gneiss. The dark area in the north represents the low concentration of all the radioactive elements and is associated with the charnockitic gneiss rocks. The red color represents a high concentration of K but low concentrations of Th and U and is associated with biotite gneiss and schist lithological units, while the green color corresponds to regions of high Th, low K, and U associated with quartzite schist.

4.2 Gold mineralization

A critical inspection of this newly acquired airborne geophysical data has shown that the Kirk Range area is highly faulted. The predominant tectonic trend is NE–SW. Also, a number of hydrothermally altered zones are mapped

Figure 6: Hydrothermal alteration identified on the ground. This alteration augments the alteration assemblages found in airborne radio-metric data.

from the K/Th ratio map (Figure 5). These zones are spatially highly correlated with structures identified in magnetics data and are interpreted that they served as channel pathways for migrating hydrothermal fluids that contemporaneously led to gold mineralization. Most gold occurrences and the location of Breeze and Phalula mines in the area are spatially correlated with these structures.

We analysed core samples that were drilled near the Breeze gold mine along the NE–SW trending shear structure. Drilling intersections along these structures at the Breeze mine reveal the presence of gold mineralization (Figure 7). These drill cores were scanned with an X-ray computed tomography (XCT) at Stellenbosch University in South Africa. XCT works based on density contrast.

Figure 7: XCT scanned drill core. The mineralized drill hole was drilled along the NE–SW trending structures that were identified in magnetic data. This drill hole was drilled at the Breeze mine. The yellow colour indicates sulphides, the dark colour indicates the silicate matrix and warm colours indicate gold grains (blue: small gold grains and red: large gold grains).

Figure 8: Thin section images showing gold grains (in yellow) from the Kirk Range area. The thin sections were made from the drill core sample from Figure 7. This proves that the dense gold mineral seen in XCT is indeed gold.

Gold being the densest mineral exhibits a high attenuation coefficient in XCT. Sulphides (yellow colour in XCT) exhibit subvertical veins parallel to the foliation. Foliation and dominant lithologies in the area trend in the NE–SW direction.

Gold mineralization in the core samples is associated with sulphides, an indication that mineralization is related to these NE–SW structures.

Thin section examination of the drill core samples reveals predominant gold mineralization (Figure 8). Gold mineralization is associated with sulphide mineral assemblages dominated mainly by pyrite, pyrrhotite and chalcopyrite. Gold is present both as free Au in wall rock and in association with pyrite. Pilot drilling has shown that gold is found in these NE–SW trending structures indicating that these structures must therefore be considered to have acted as conduits for mineralizing hydrothermal fluids. Therefore, in the greater Kirk Range area, mineralizing fluid flow is interpreted to have been directed predominantly along the NE–SW trending regional structures, gold was introduced in these NE–SW trending shear zone and the NE–SW trending structures appear to be prospective for future gold exploration efforts.

5 Conclusion

This study has interpreted the newly acquired airborne geophysical data set of the Kirk Range, southern Malawi, with an aim of characterizing the major structures controlling gold mineralization. The Kirk Range area is dominated by NE–SW trending structures and gold mineralization is associated with these NE–SW structures. The identified structures acted as fluid pathways for hydrothermal fluids that contemporaneously altered the wall rocks and lead to gold mineralization and they appear to be prospective for future gold exploration efforts. This study has only looked at the Kirk Range area; however, there are other areas with gold occurrences in Malawi. It is therefore recommended that future studies should look at these other areas and check if they share similar structural controls of gold mineralization. This study acts as a reference point or a guide to mineral exploration campaigns searching for gold in Malawi.

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