-RESEARCH PAPER-

International Journal of Mining and Geo-Engineering

IJMGE

IJMGE 57-3 (2023) 275-281

DOI: 10.22059/IJMGE.2023.354348.595026

Structural interpretation of the Mangochi-Makanjira area (Southern Malawi) from an aeromagnetic analysis: Implications for gold exploration

Joshua Chisambi [a, *]

[a] 1 Department of Mining Engineering, School of Engineering, Malawi University of Business and Applied Sciences, Blantyre, Malawi.

Article History:

Received: 25 January 2023.
Revised: 14 May 2023.
Accepted: 22 May 2023.

ABSTRACT

Malawi's geology has not been mapped in detail and there are no detailed geological and structural assessments in relation to gold mineralization. Mangochi-Makanjira area in southern Malawi is endowed with abundant gold mineral resources but there is a scarcity of precise knowledge on the structures that control primary mineralization. This study used aeromagnetic data to provide a structural framework of the Makanjira area and delineated potential areas for further gold exploration. Many analytic approaches were applied to the aeromagnetic data, including reduction to the pole, Euler deconvolution, Tilt, and Vertical Derivatives filtering. Euler deconvolution was used to determine the depth of magnetic sources. Geophysical data interpretations identify the dominant linear trends present in the area to be faults, dykes, and deep-level basement shear zones as structures responsible for fluid flow and gold mineralization in the area. Gold in this area is structurally controlled by N-S structures that were derived during the Pan-African orogeny and it is during this event that the area got mineralized. These fractures and faults served as channel ways for hydrothermal solutions, resulting in the emplacement of gold mineralization within the fractures. Mineralization occurs from the surface and goes deep and ranges in depth from 0.5 km to 2.4 km. In order to further gold exploration, these structures should be highly considered.

Keywords: *Gold mineralization, Makanjira, Aeromagnetic anomaly, mineral exploration.*

1. Introduction

Gold is a highly valued and sought-after metal due to its economic importance. It is used in various industries, including jewelry, electronics, and finance. Additionally, it serves as a store of value and a hedge against inflation, and it can be used as collateral to borrow money. In recent years, the demand for gold has increased in the developing world, where it is seen as a means to contribute to wealth and economic growth. This increase has led to a rise in gold mining activity globally and the development of new technologies to extract gold more efficiently and sustainably [1]. Many African countries possess abundant natural resources, including gold, which have played a significant role in their economies for centuries. The mining industry has traditionally been one of the most important sectors in many African countries, providing jobs, revenue, and other economic benefits. According to published literature, there is evidence that organized gold mining in Africa dates back to the Middle Ages. Certain African nations, such as the Republic of Ghana and Mali, historically served as important centers of trans-Saharan gold commercial routes. In recent times, Africa continues to play a significant role in the global gold mining industry, with an estimated 30% of the world's gold coming from mines located in Africa. This is due to the abundance of gold deposits in the continent and the increasing global demand for metal [2][1].

Gold holds high value due to its economic significance, serving various industries such as jewelry, electronics, and finance. It also acts as a store of value, a hedge against inflation, and collateral for borrowing. Recently, gold demand has surged in the developing world, seen as a means to foster wealth and economic growth. This surge led to increased global gold mining activity and the development of more efficient and sustainable extraction technologies [1]. Many African nations possess abundant natural resources, including gold, which historically played pivotal roles in their economies. The mining sector traditionally stood as a key sector, offering employment, revenue, and economic benefits. Published literature suggests organized gold mining in Africa dating back to the Middle Ages. Certain African nations, such as the Republic of Ghana and Mali, historically served as central hubs in trans-Saharan gold trade routes. Africa continues to exert a significant influence on the global gold mining industry today, contributing approximately 30% of the world's gold production. This is attributed to abundant gold deposits on the continent and growing global demand for the metal [2][1].

In contrast to many emerging African nations where natural resources have historically driven economic growth, Malawi stands apart. The country has long relied heavily on rain-fed agriculture, which makes up one-third of its gross domestic product and employs about 80 percent of the population. However, persistent droughts have hindered agriculture's ability to significantly contribute to Malawi's economic growth [3].

The country's economic performance has suffered due to agriculture's limited role. To address this and diversify the economy, the government is actively exploring alternatives, with a focus on the mining industry as a potential source of economic growth. Currently, mining contributes only about 10 percent to the nation's gross domestic product. Therefore, the government is promoting investments in mining and encouraging the exploration and development of mineral resources within the country. These steps could diversify the economy and boost foreign exchange earnings [3].

Despite the fact that the mining industry currently contributes only a small fraction of Malawi's GDP, the nation possesses abundant mineral

---

* Corresponding author: *E-mail address:* jchisambi@poly.ac.mw (J. Chisambi).

resources. These resources, if sustainably explored and developed, hold the potential to expand the country's economy. Gold, in particular, is one of the minerals that Malawi boasts in abundance. The Geological Survey of Malawi first documented gold in 1908, and since then, numerous additional discoveries have been recorded across various locations within the country.

Although the presence of gold deposits throughout Malawi is proven, the absence of substantial large-scale gold mining operations can be attributed to the absence of comprehensive surveys and detailed geological and structural studies on gold mineralization. Previous research on gold in Malawi is limited, but available information suggests that the history of gold mining in the country dates back to the early 1900s and is characterized by a complex and controversial past [4].

One of Malawi's known gold discoveries is in the Makanjira region, which has attracted significant attention. According to Bloomfield [5], the Geological Survey of Malawi first found gold in the Mangochi-Makanjila region in 1936 during a reconnaissance survey. In 1937, a more detailed investigation was conducted, revealing that the gold-bearing veins were too thin and scattered to support large-scale commercial gold mining in the area. Since then, no further research has been carried out, resulting in limited knowledge about gold mineralization characteristics. Currently, small-scale artisanal miners are the only ones extracting gold in the area, mainly focusing on placer deposits.

This research aims to understand the nature of gold mineralization and the controlling structures in the area. Identifying geological structures is essential as they are often associated with the formation and concentration of mineral deposits [6]–[8]. The study also seeks to identify potential locations for future gold exploration. This research will not only deepen our understanding of the structural factors influencing gold mineralization but will also guide future gold exploration in this area and similar gold occurrence sites in Malawi.

2. Regional Geology

Malawi's geological history is intricate and marked by the presence of three major orogenic belts: the Ubendian Belt, the Irumide Belt, and the Mozambique Belt. These belts formed due to the collision of tectonic plates and exhibit distinct rock types and structures that originated during specific periods. The Ubendian Belt, the oldest among them, formed approximately 2200-1800 million years ago, whereas the Irumide Belt and Mozambique Belt are comparatively younger, with origins around 1050-950 million years ago and 800-500 million years ago, respectively [9]–[11].

The Ubendian orogeny signifies the collision and amalgamation of the Tanzanian craton and the Bangweulu block. The Tanzanian craton is an ancient, stable landmass at the core of the East African continent, while the Bangweulu block is a smaller landmass that collided with the craton during this orogenic event. This collision led to the deformation and metamorphism of rocks in the region, giving rise to the Ubendian Belt. This belt is distinguished by a complex sequence of metasedimentary rocks such as quartzite, schist, and gneiss [12]-[13], resulting in NW-SE trending structures, primarily in the northern regions of Malawi [14].

The Irumide orogeny gave rise to the Irumide Belt, which extends in a NE-SW direction, spanning from Zambia through central and southern Malawi, and into the northern region of Mozambique. This belt is believed to have formed during the collision of the East African craton and the Damaran terrane, leading to the deformation and metamorphism of rocks in this area. The Irumide Belt trends NE-SW [15]–[18] and is further divided by crustal-scale shear zones into several sub-provinces, including the Irumide sensu stricto, the Southern Irumide, the Unango, and the Nampula.

The Nampula province underwent extensive reworking during the Late Neoproterozoic Kuunga orogeny, resulting in the formation of the ENE-WSW-trending Lurio Belt (Figure 1; [19], [20]).

The Mozambique Belt resulted from the Pan African Orogeny, which occurred approximately 800-500 Ma. During this orogeny, the belt experienced high temperatures and pressures, with peak metamorphic conditions reaching 750-800°C and 12-13 kbar. This was followed by retrogression at lower temperatures and pressures, approximately 550-700°C and 5-8 kbar, leading to the formation of rocks with amphibolite facies characteristics. The tectonic activity and metamorphism during the Pan African orogeny also caused significant overprinting and reactivation of older structures inherited from previous orogenic episodes, such as the Ubendian, Irumide, and Kuunga events. This resulted in the development of predominantly north-south trending structures and fabrics [14], [22], [23].

3. Materials and Methods

Geophysics is a commonly employed method for identifying structures in mineral exploration. In this study, we utilized aeromagnetic anomaly data provided by the Geological Survey of Malawi (GSM). Sanders Geophysics collected these data for GSM between 2012 and 2013 as part of the World Bank's Malawi Governance and Growth Support Project (MGGSP), which aimed to facilitate the exploration of Malawi's mineral resources.

The aeromagnetic survey was conducted at an altitude of 80 meters, employing a 3*-Scintrex CS3 Cesium Vapour Magnetometer. Flight lines were oriented in a NE-SW direction, perpendicular to regional structural trends, and spaced 200 meters apart. Additionally, tie lines extending over 2000 meters were included. The collected data underwent correction for transient magnetic variation effects, and the influence of the International Geomagnetic Reference Field (IGRF 2005 model) was removed. It is essential to note that all subsequent data interpretations rely on this IGRF-corrected aeromagnetic anomaly data.

The total magnetic intensity (TMI) map of the study area was generated using a minimum curvature gridding technique with 50-meter intervals. Subsequently, a reduced to pole (RTP) filter was applied to the TMI grid to produce the RTP anomaly map, effectively correcting the asymmetry linked to low-latitude anomalies [24].

The RTP TMI grid underwent processing with Tilt Derivative (TD) and Analytical Signal Amplitude (ASA) techniques. These processes were applied to enhance and clarify the subsurface structures and lithologic boundaries [25]–[30].

The Euler deconvolution technique was employed to estimate the depth of magnetic sources across the study area. This method defines the geometry of magnetic bodies through structural indices (SI) and relies on the Euler homogeneous equation (1) [31].

$$(x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} = N(B - T) \tag{1}$$

where (x_0, y_0, z_0) is the location of the observed magnetic source at (x, y, z), $\frac{\partial T}{\partial x} \frac{\partial T}{\partial y}$ and $\frac{\partial T}{\partial z}$ are derivatives of the magnetic field in the directions of x, y, and z respectively. B is the regional value of the total field. The degree of homogeneity N is construed as a structural index [32].

The structural index, SI, characterizes the rate of anomaly attenuation at the observation point and is influenced by the properties of the field source. For the calculation of Euler deconvolution solutions, the RTP aeromagnetic data was utilized along with structural indices (SI) of 0, 0.5, 1, 2, and 3, while employing a window size of 10 × 10. Here, "A window size of 10 × 10" signifies a squared window with dimensions of 10 times the cell size, equivalent to 500 meters (10×cell size).

3.1. Field mapping

Field studies were carried out to augment and confirm the geophysical investigation of the study area. During field mapping, the team identified rock mineralogy using a hand lens and observed and recorded rock texture based on characteristics such as grain size, shape, and sorting. Additionally, the team noted the color of the rocks since it can indicate mineral content and alteration. Geological structures like faults, folds, and joints were carefully observed and recorded. These observations are crucial because they provide valuable clues about the geological history of the area and help assess the potential for mineralization.

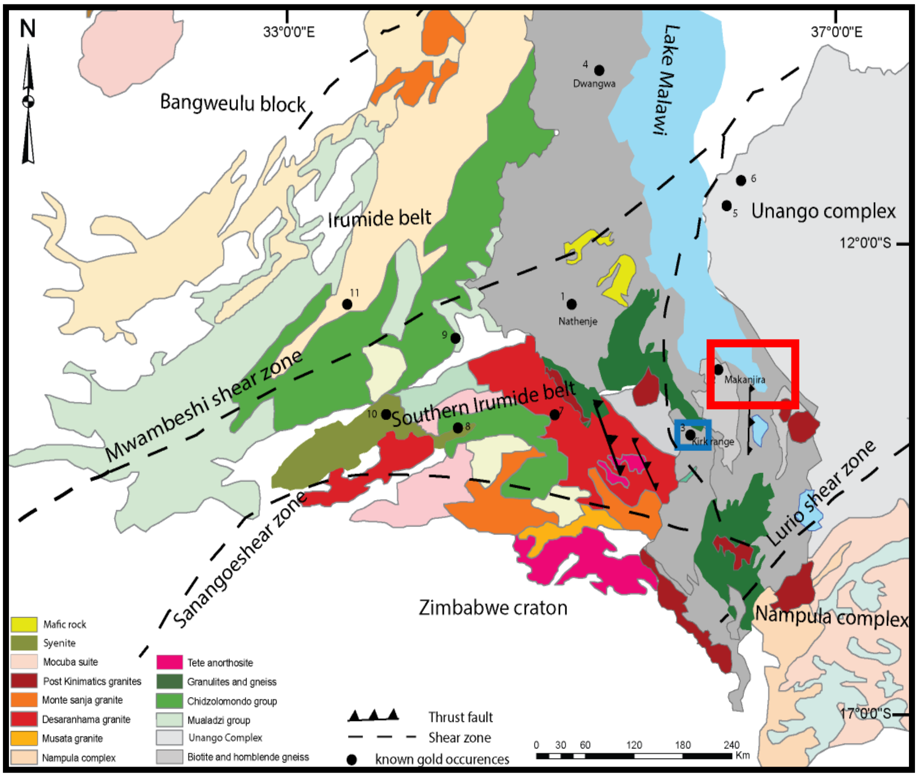

Figure 1. Regional geological map. Our study area is shown in the red rectangle.

Major lithological units were sampled for subsequent thin and thick section mineralogical analyses. The team used a Nikon Eclipse E 200 polarizing microscope in both reflected and transmitted light at the laboratories of Malawi University of Business and Applied Sciences to further characterize the mineralogy and distribution of gold.

4. Results and Discussion

Figure 2 illustrates the analyzed magnetic data. In the TMI map, magnetic high values are evident in the northern, central, southwestern, and southeastern regions of the study area, depicted in red and magenta colors. These high values exhibit amplitudes ranging from 35 to 247 nT. Additionally, these magnetic high-value anomalies predominantly align in north-south and east-west directions and are correlated with granitic gneiss lithologies.

Conversely, the study area exhibits low magnetic values, primarily situated in the western to central areas, indicated by deep blue colors. These low magnetic anomalies display amplitude values ranging from -360 to -131 nT and are associated with biotite gneiss lithologies. They tend to trend in a NE-SW direction.

Additionally, the TMI map reveals linear and folded magnetic anomalies within various parts of the study area. Figure 2 illustrates that the axial planes of the folds and the trend of the linear structures are in the N-S direction. The orientation of this trend coincides with the N-S structural trend of the Pan African orogeny that affected this area, indicating that these structures developed during the shortening of the Pan African orogeny.

This study is supported by evidence from prior observations, e.g., authors in [33] share our interpretation and have indicated that Pan-African tectonism and high-grade metamorphism caused significant overprinting and reactivation of older structures inherited from the Ubendian, Irumide, and Kuunga orogenic episodes that affected Malawi, resulting in predominantly N-S trending structures and fabrics development.

Additional analysis highlights the pronounced N-S fabric in the magnetic data. The aeromagnetic expression of the folds suggests their tight to isoclinal nature. These folds are also visible and confirmed in the Google Earth image of the study area, oriented in the N-S direction (Figure 3a). Ground geological mapping provided strong evidence of these structures. It confirmed that the major lithologies in the area are highly deformed, primarily consisting of N-S trending gneissic rocks subjected to amphibolite-granulite facies metamorphism. Garnet, as an indicator mineral of high-grade metamorphism, is mineralogically present (Figure 3h). These findings suggest that, in general, these lithological units exhibit intense deformation, resulting in the development of diverse fabrics and structures (Figure 3b, c).

Therefore, during the Pan-African orogeny, the basement complex rocks in the study area underwent polyphase deformation, including both ductile and brittle processes, leading to the formation of these folds.

Turning now to the evidence on Tilt Derivative and Vertical Derivative data, it is apparent that dominant linear trends are present in the area (Fig. 2 c, d). These linear trends are interpreted to be faults, dykes, and deep-level basement shear zones and their distribution may render critical insights into the structures responsible for fluid flow and gold mineralization in the area. An implication of this is the possibility that these fractures and faults served as channel ways of hydrothermal solutions, resulting in the emplacement of gold within the fractures. It is suggested that the area underwent crustal deformation, which resulted in the creation of these structures, which we interpret as having an important role in gold mineralization. The evidence from this study denotes that deep-seated basement faults mainly govern the structural style in the area and the N-S and E-W are the predominant trends of the basement faults. The analyzed structures are shown in Figure 4.

Considering that the N-S magnetic signatures align closely with the tectonic trends associated with the Pan-African orogeny, it is thus interpreted that this N-S structural imprint was initiated during the Pan-African orogeny.

The circular feature observed on the western side (see Fig. 4) in the aeromagnetic data is connected to granite intrusions. This intrusion

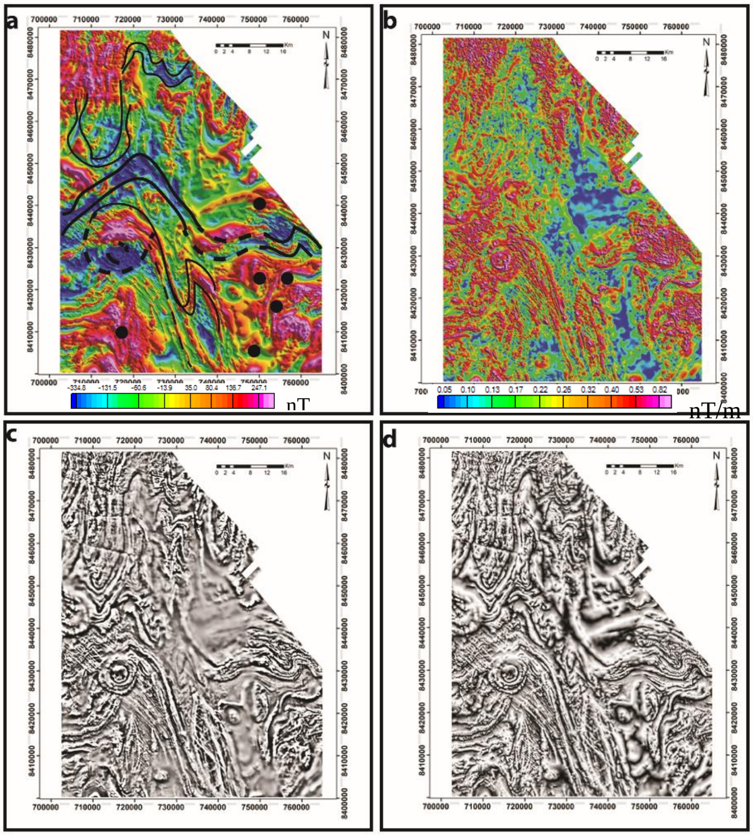

Figure 2. Analysed airborne geophysical data showing geological structures. The area is highly deformed (a)Reduced to the Pole Total Magnetic Intensity grid, black dots are gold occurrences in the study area. (b)Analytical signal grid (c)Vertical derivative grid (d)Tilt derivative grid.

exhibits a circular or nearly circular shape, and the processes related to gold mineralization in the study area are interpreted to be associated with it. The intrusions seem to have played a significant role in the gold mineralization processes by potentially serving as heat sources. They may have created fractures within the invaded rocks, thereby establishing pathways for hydrothermal solutions that led to the gold mineralization. Field evidence supports the presence of several magmatic suites that have intruded the basement lithologies within the area (refer to Fig. 5). These intrusions, such as the Mangochi granites, could have exploited the pre-existing structures in the basement rocks, functioning as heat sources. The intricate interplay between a crystallizing and cooling pluton, the circulation of fluids, and the influence of country rock collectively govern the connection between granitic rocks and the mineralization process.

These findings indicate that mineralizing fluid flow in the broader region predominantly followed north-south-oriented regional structures. Notably, within the Makanjira area, gold was introduced into the N-S trending structures during the Pan-African orogeny. These N-S trending structures hold promise for future gold exploration. During this orogenic event, ore-rich fluids were generated through metamorphic devolatilization associated with the orogeny and possibly magmatic events. These fluids were then transported from deeper crustal sources to favorable depositional environments within the upper crust.

Local people engage in alluvial gold mining in the area. Figure 3d displays some of the artisanal gold mining activities. Several of these deposits align with known faults (Fig. 4), suggesting a relationship between the emplacement of the gold mineralization and the faults. Hence, mineralization can be linked to the structures. A clear correlation exists between artisanal gold mining and N-S trending lineaments. This suggests possible structurally controlled gold mineralization. We envision that the pan-African orogenic event created fractures in the basement rocks, thereby establishing channels for the hydrothermal solution responsible for the mineralization.

The petrological and mineralogical analysis of the mineralized rocks reveals that gold mineralization is found within quartz veins and is closely associated with pyrite and chalcopyrite (see Fig. 3). Pyrite, chalcopyrite, and gold constitute the primary sulphide minerals in this assemblage. Pyrite is the dominant sulphide mineral and is the first to appear in the paragenetic sequence, comprising approximately 70% of the total sulphide population. Much of the older pyrite has undergone replacement by new, distinct euhedral to subhedral pyrite grains. Paragenetically, pyrite is gradually being replaced by chalcopyrite. Gold is also found in association with the biotite schist wall rock. The presence of gold is predominantly observed along or in close proximity to linear structures, implying that gold mineralization in Makanjira is influenced by geological structures.

The Euler deconvolution operation was applied to the magnetic data in order to determine the positions and corresponding depth estimates of magnetic anomalies with geological origins (refer to Fig. 4). This depth estimation technique is commonly utilized because it does not rely on a specific geological model. The map effectively displays the distribution of magnetic sources, both deep-seated and near-surface, within the studied area. The solutions align quite well with linear structures, primarily trending in the north-south (N-S) direction. Consequently, any gold exploration efforts conducted by the Malawi Geological Survey or other investors should concentrate on these structural features. The depths of these solutions range from 0.5 km to 2.4 km, indicating that mineralization is not only near the surface but also extends to greater depths. These structures predominantly follow a north-south (N-S) orientation, likely influenced by the Pan-African Orogeny.

Figure 3: **(a)** Google Earth image of the study area indicating folded lithologies oriented in the N-S direction. (b, c) Folded lithologies in the study area were found during ground truthing. (d) artisanal miners panning gold. (e, f, g) ore minerals comprised of pyrite, Chalcopyrite, and gold are seen under a petrographic microscope. (h) The thin section comprised of garnet as an indicator of high-grade metamorphism in the rocks of the study area.

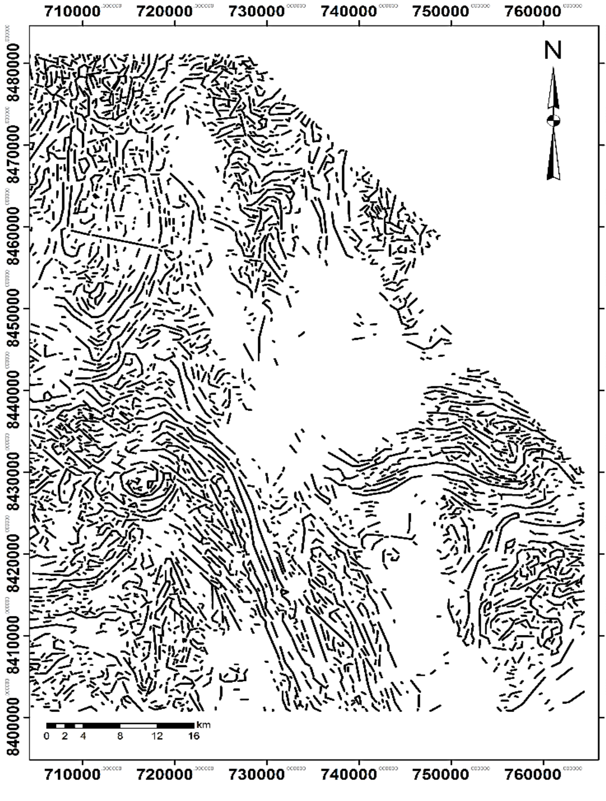

Figure 4. Structures delineated from the magnetic data that have affected the study area. These structures may have acted as conduits for gold mineralization. The major trends of the structures are depicted in the rose diagram as N-S and E-W.

Figure 5: *Granitic intrusion that intruded the basement rocks evidence of heat source in the study area.*

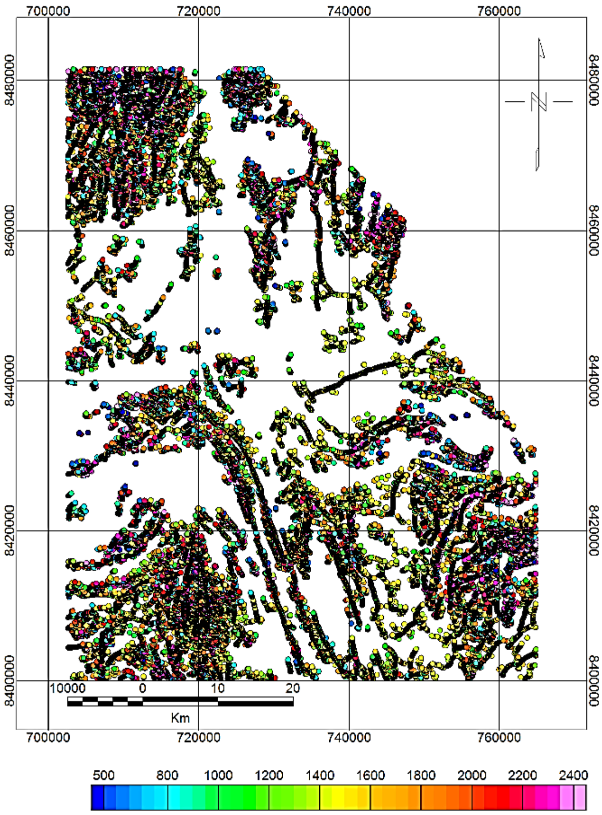

Figure 6*. Euler depth solutions depict most of the structures in the study area.*

5. Conclusions

The findings of this study offer valuable insights into the nature of gold mineralization, the structural framework of the Mangochi-Makanjira area, and identify potential areas for future gold exploration. Generally, the study has revealed that gold mineralization in this region is primarily influenced by north-south (N-S) structural features that originated during the Pan-African orogeny, marking the period of mineralization for this area.

In this research, areas characterized by a significant prevalence of extensive lineaments and high lineament density, all trending in the N-S direction (associated with Pan-African structures), represent promising targets for further gold exploration. Consequently, both the Malawi Geological Survey and other potential investors interested in gold exploration should concentrate their efforts on these specific structural features. Mineralization is observed from the surface and extends to considerable depths, ranging from 0.5 km to 2.4 km.

Conflicts of Interest

The researcher declares no conflict of interest

Funding Statement Acknowledgments

This research did not receive any funding however I would like to thank the Geological Survey of Malawi for providing data used in the research. The study was carried out as part of the employment of the authors at the Malawi University of Business and Applied Sciences and the Geological Survey of Malawi.

REFERENCES

[1] A. Kumah, "Sustainability and gold mining in the developing world.," J Clean Prod, vol. 14, 2006, [Online]. Available: https://doi.org/10.1016/j.jclepro.2004.08.007.

[2] K. Amponsah-tawiah, "The Mining Industry in Ghana : A Blessing or a Curse.," International Journal of Business and Social Sciences, 2(12), 62–69., 2011.

[3] Ministry of Mining, "Mines And Minerals Policy Of Malawi.," 2013.

[4] G. S. Carter, "The Geology and Mineral Resources Of Malawi." Government print, Zomba, Malawi, 1973.

[5] K. Bloomfield and M.S. Garson, "The Geology of the Kirk Range-Lisungwe Valley Area. Ministry of Natural Resources. Geological Survey Department. Bulletin No.17.," The Government Printer, Zomba. Malawi, 1965.

[6] F. Khalifani, A. Bahroudi, S. Barak, and M. Abedi, "An integrated Fuzzy AHP-VIKOR method for gold potential mapping in Saqez prospecting zone, Iran," Earth Observation and Geomatics Engineering, vol. 3, no. 1, pp. 21–33, 2019, doi: 10.22059/eoge.2019.263180.1027.

[7] F. Mami Khalifani, A. Bahroudi, F. Aliyari, M. Abedi, M. Yousefi, and M. Mohammadpour, "Generation of an efficient structural evidence layer for mineral exploration targeting," Journal of African Earth Sciences, vol. 160, no. August, 2019, doi: 10.1016/j.jafrearsci.2019.103609.

[8] M. Mohammadpour, A. Bahroudi, and M. Abedi, "Automatic Lineament Extraction Method in Mineral Exploration Using CANNY Algorithm and Hough Transform," Geotectonics, vol. 54, no. 3, pp. 366–382, 2020, doi: 10.1134/S0016852120030085.

[9] B. De Waele, J. Liegeois, A. A. Nemchin, and F. Tembo, "Isotopic and geochemical evidence of proterozoic episodic crustal reworking within the irumide belt of south-central Africa , the southern metacratonic boundary of an Archaean Bangweulu Craton," Precambrian Res, vol. 148, pp. 225–256, 2006, doi: 10.1016/j.precamres.2006.05.006.

[10] B. De Waele, I. C. W. Fitzsimons, F. Tembo, and B. Mapani, "The geochronological framework of the Irumide Belt : A prolonged crustal history along the margin of the Bangweulu Craton," Am J Sci, no. February, 2009, doi: 10.2475/02.2009.03.

[11] B. De Waele, A. B. Kampunzu, and F. Tembo, "The Mesoproterozoic Irumide belt of Zambia," Journal of African Earth Sciences, vol. 46, pp. 36–70, 2006, doi: 10.1016/j.jafrearsci.2006.01.018.

[12] N. Boniface, V. Schenk, and P. Appel, "Mesoproterozoic high-grade metamorphism in pelitic rocks of the northwestern Ubendian Belt : Implication for the extension of the Kibaran intra-continental basins to Tanzania," Precambrian Res, vol. 249, pp. 215–228, 2014, doi: 10.1016/j.precamres.2014.05.010.

[13] R. B. McConnell, Outline of the geology of Ufipa and Ubende. Bulletin of Geological Survey of Tanganyika. 1950.

[14] U. Ring, A. Kröner, and T. Toulkeridis, "Palaeoproterozoic granulite-facies meta-morphism and granitoid intrusions in the Ubendian-Usagaran Orogen ofnorthern Malawi, east-central Africa.," Precambrian Reserch., vol. 85, 27–51., 1997.

[15] E. H. Ackermann, "Ein neuer Faltengürtel in Nordrhodesien und seine tektonische Stellung im Afrikanischen Grundgebirge.," Geologische Rundschau, vol. 38, 24–39, 1950.

[16] E. H. Ackermann and A. Forster, "Grundzuge der Stratigraphie und Struktur des Irumide Orogen.," 21st International Geological Congress,. pp. 182–192, 1960.

[17] J. Chisambi, T. Haundi, and G. Tsokonombwe, "Geologic structures associated with gold mineralization in the Kirk Range area in Southern Malawi," Open Geosciences, vol. 13, no. 1, pp. 1345–1357, 2021, doi: 10.1515/geo-2020-0304.

[18] J. Chisambi and B. von der Heyden, "Primary gold mineralization in the lisungwe valley area, kirk range, southern Malawi," South African Journal of Geology, vol. 122, no. 4, pp. 505–518, 2019, doi: 10.25131/sajg.122.0039.

[19] B. Bingen et al., "Geochronology of the Precambrian crust in the Mozambique belt in NE Mozambique , and implications for Gondwana assembly," Precambrian Res, vol. 170, pp. 231–255, 2009, doi: 10.1016/j.precamres.2009.01.005.

[20] R. Boyd et al., "The Geology and Geochemistry of The East African Orogen In Northeastern Mozambique," Geological Society of South Africa, vol. 113, pp. 87–129, 2010, doi: 10.2113/gssajg.113.1.87.

[21] R. Boyd et al., "The Geology and Geochemistry of The East African Orogen In Northeastern Mozambique," Geological Society of South Africa, vol. 113, pp. 87–129, 2010, doi: 10.2113/gssajg.113.1.87.

[22] B. De Waele, I. C. W. Fitzsimons, F. Tembo, and B. Mapani, "The geochronological framework of the Irumide Belt : A prolonged crustal history along the margin of the Bangweulu Craton," Am J Sci, no. February, 2009, doi: 10.2475/02.2009.03.

[23] H. Sommer and A. Kröner, "Lithos Ultra-high temperature granulite-facies metamorphic rocks from the Mozambique belt of SW Tanzania AR," Lithos, vol. 170–171, pp. 117–143, 2013, doi: 10.1016/j.lithos.2013.02.014.

[24] R. J. Blakely, Potential Theory in Gravity and Magnetic Applications. Cambridge, England.: Cambridge University Press, 1996. doi: https://doi.org/10.1017/CBO9780511549816.

[25] A. Ates, F. Bilim, A. Buyuksarac, and Ö. Bektas, "A tectonic interpretation of the Marmara Sea, NW Turkey from geophysical data," Earth, Planets and Space, vol. 60, no. 3, pp. 169–177, 2008, doi: 10.1186/BF03352780.

[26] A. Ateş, A. Büyüksaraç, F. Bilim, Ö. Bektaş, Ç. Şendur, and G. Komanovali, "Spatial correlation of the aeromagnetic anomalies and seismogenic faults in the Marmara region, NW Turkey," Tectonophysics, vol. 478, no. 1–2, pp. 135–142, 2009, doi: 10.1016/j.tecto.2008.09.025.

[27] K. Rozimant, A. Büyüksaraç, and Ö. Bektaş, "Interpretation of magnetic anomalies and estimation of depth of magnetic

crust in Slovakia," Pure Appl Geophys, vol. 166, no. 3, pp. 471–484, 2009, doi: 10.1007/s00024-009-0447-8.

[28] Y. L. Ekinci, A. Büyüksaraç, Ö. Bektaş, and C. Ertekin, "Geophysical Investigation of Mount Nemrut Stratovolcano (Bitlis, Eastern Turkey) Through Aeromagnetic Anomaly Analyses," Pure Appl Geophys, vol. 177, no. 7, pp. 3243–3264, 2020, doi: 10.1007/s00024-020-02432-0.

[29] A. Ates, F. Bilim, A. Buyuksarac, A. Aydemir, O. Bektas, and Y. Aslan, "Crustal Structure of Turkey from Aeromagnetic, Gravity and Deep Seismic Reflection Data," Surv Geophys, vol. 33, no. 5, pp. 869–885, 2012, doi: 10.1007/s10712-012-9195-x.

[30] A. Büyüksaraç, D. Jordanova, A. Ateş, and V. Karloukovski, "Interpretation of the gravity and magnetic anomalies of the Cappadocia region, Central Turkey," Pure Appl Geophys, vol. 162, no. 11, pp. 2197–2213, 2005, doi: 10.1007/s00024-005-2712-9.

[31] A. B. Reid, J. M. Allsop, H. Granser, A. J. Millett, and I. W. Somerton, "Magnetic interpretation in three dimensions using Euler deconvolution," Geophysics, vol. 55, no. 1, pp. 80–91, Feb. 2012, doi: 10.1190/1.1442774.

[32] A.B. Reid, J.M. Allsop, H. Granser, A.J. Millett, &I.W. Somerton, "Magnetic interpretation i n three dimensions using Euler deconvolution," Geophysics, vol. v 55, 80-9, 1990.

[33] U. Ring, A. Kröner, and T. Toulkeridis, "Palaeoproterozoic granulite-facies meta-morphism and granitoid intrusions in the Ubendian-Usagaran Orogen ofnorthern Malawi, east-central Africa.," Precambrian Reserch., vol. 85, 27–51., 1997.