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Trace Elements Geochemistry of In Situ Regolith Materials and Their Implication on Gold Mineralization and Exploration Targeting, Dodoma Region, East Africa

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Abstract

The central Dodoma region of Tanzania is one of the regions defined by the Tanzania Craton (TC). Although the Craton gold mineralization has been well explored and hosts most of the gold deposits in the country, the understanding of the mineralization potential of the Dodoma region is still an enigma. This study using trace elements geochemistry of soil samples aims basically at providing information for future exploration works in the region by delineating the possible mineralized zones, the pathfinder elements, and the lithological facies to target. Generally, there is an anomalous spatial distribution of a probable Cu-Au deposit in the N, NE, S, and SE parts of the region and are prospective areas worth exploring for gold from the Gaussian variogram models. The multivariate statistics shows that Cu, Pb, Zn, and Fe are the main pathfinder elements while searching for Au mineralization in the region. The gold deposit is most probably a Cu-Au porphyry type, although VMS type of Au deposit cannot be precluded in the area. The mineralization in the area is largely associated with tonalitic orthogenesis, tonalities, granodiorite, and granitic rocks with Cr-Ni-Co-V forming elemental association. This elemental association is similar to other gold bearing greenstone belts. The style of mineralization in the Dodoma region is similar to other gold deposits within the TC; hence, successful exploration methods in these ancient gold deposits like Geita and Kahama gold deposits can be adopted in the event of any further exploration exercise in the central Dodoma region.

Keywords Trace elements · In situ Regolith · Gold mineralization · Bed rock mapping · Dodoma · East Africa

1 Introduction

A spectrum of trace elements has proven to be suitable indicators of gold (Au) mineralization, e.g., Pb, Ag, Zn, Bi, Se, Sb, As, Cu, and Hg [35, 55]. The geochemistry of trace element can be used as the best indicator for Au mineralization during gold exploration [48]. However, much attention is required from sampling to analysis chain when applying geochemistry of trace elements in mineral exploration because it is usually associated with poor results which can lead into wrong conclusions [21, 35]. Gold has both physical and chemical resistant properties which cause it to occur in native and particulate forms. The use of trace elements geochemistry in mineral exploration has been extensive across the globe [15–17, 32, 33, 35–37, 44, 48, 54], especially for Au. This has been an important exploration method in mineral prospecting and in delineating anomalous mineralized zones as well as suitable in showing the spatial distribution of mineralization. The technique can be best utilized in Greenfield or less explored areas as well as in Brownfields to improve the existing reserve. The multivariate statistical approaches like principal component analysis (PCA), factor analysis (FA), and hierarchical cluster analysis (HCA) have been effectively used and extensively in constraining Au mineralization deposits [33, 34, 36, 37, 48, 53] using soil and stream sediments samples. This is done in order to

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reduce the dimensionality of exploration geochemistry data and predicting the main process and pathfinder elements which control mineralization. Trace element geochemical exploration is as such a suitable preliminary investigation method for identifying prospects for detailed exploration targeting [15, 51, 54].

The Singida gold province, e.g., Geita belts, Geita-Kahama areas, Saza, and Mbeya areas [23, 25, 26, 28, 39, 41, 49, 50] of the Tanzania Craton (TC), as well as the southern part of the TC, thus Lake Victoria areas as well as Lake Nyanza region and East Lake Victoria supper terrains according to Koegelenberg et al. [25], are famous for their Au mineralization [12, 13, 26, 27, 40, 42]. The Dodoma region, also of the TC, has however been less studied regarding its gold mineralization and spatial distribution. The TC of East Africa like other Au mineralized greenstone belts in Africa is composed principally of granitic rocks together with their metamorphosed counterparts consisting of granitoids, granodiorites, granitic gneisses, and metasediments [3, 26, 28]. The TC has been classified by Clifford [19] into three systems of Dodoma, Nyanzian, and the Kavirondian. The Craton is surrounded in the east and west by the Mozambique and Ubendian young Proterozoic greenstone belts [19], respectively. Majority of the gold mineralization in the TC of East Africa is hosted by the several kilometers long (~30 km) and wide greenstone Nyanzian system and the western Ubendian schist, gneiss, and quartzite Proterozoic terrain [14]. Leverage to the TC, Tanzania is the 4th largest Au producer in Africa according to Tanzania Chamber of Minerals and Energy [45]. Kabete et al. [26] also indicated that the Craton hosts one of the world-class gold deposits. For the lack of exploration data on the central Dodoma system of the TC, elucidation of mineralization zones and patterns within the region is very difficult if not impossible. This region is mineralized although there is no empirical scientific data to support this assertion. The presence of artisanal mining activities within the region is a good evidence to support this assertion. The aim of this study therefore is to (i) identify the most probable mineralized zones for follow-up exploration exercise, (ii) identify the target elements (pathfinders) in the search for Au in the area, and (iii) decipher the possible lithological controls of the mineralization within the Dodoma region. This study seeks to achieve the aforementioned aims using trace elements geochemical data of 103 soil samples, multivariate statistical approaches of PCA, FA, and HCA. Krigging interpolation/prediction maps (Gaussian variogram models) using ArcMap version 10.4 will also be generated together with statistical approaches. This work is basically a guide for future/further exploration works like drilling, so as to allow resource estimation within the region. Also, with the understanding of the spatial distribution and the possible controls of mineralization in the area, the time spent on exploration will be reduced and the exploration risk and cost within the central Dodoma region assessed.

2 Local Geology

The Central Dodoma system [19] comprises migmatitic gneisses of mainly sedimentary origin and granitoid belts with narrow greenschist to amphibolite facies greenstone and schist belt. Zircon U–Pb dating from fuchsitic quartzites [26] indicated an age of 3604 Ma. Granitoids intruded sedimentary rocks at about 2850 to 2660 Ma and later on covered by volcanic rocks, e.g., Mazoka Greenstone Belt. The Dodoma system also has observations of granodioritic orthogneisses (Fig. 1) with quartz – plagioclase – minor K feldspar – biotite ± hornblende as the mineral assemblage [26, 47]. There are also the presence of chlorite schist, homblende schist, biotite gneisses, homblende gneisses, and pyroxene gneisses. There is the presence of fault rocks like cataclasites as well within the regional geology of the Dodoma region [18]. These rocks were later overprinted by greenschist to amphibolites facies metamorphism processes with the area generally experiencing a low–medium grade metamorphism with a local structure of almost northeast–southwest. The granitic rocks are dominantly intrusive in the area. Unlike the coterminous eastern Pan–African Mozambique Belt as well as the Paleoproterozoic Usagaran, Ubendian, and the Ruwenzori Belts at the south to NW fringes of the TC with fewer prospects for hydrothermal Au mineralization, the TC has a greenschist metamorphic facies with high gold mineralization potential that is hydrothermally controlled [25]. The minerals defining other hydrothermally controlled Au mineralization within the TC like the Sukumaland Greenstone Belt [30] are sericite, chlorite, epidote, carbonate, and silica. This mineralogical suite is common for almost all greenstone belts. The Dodoma region of the TC is a greenstone belt and hence has the aforementioned minerals together with other sulfide and phyllosilicates [30]. These sulfides and phylllosilicates often oxidize to form Fe-oxide/hydroxide and other clay minerals when exposed/near surface [5, 30].

3 Materials and Methods

3.1 Data Acquisition, Processing, and Analysis

3.1.1 Geochemical Sampling and Analysis

Broadly, regolith profile has been grouped into three zones/horizons of A, B, and C. The A horizon is rich in humus and other organic matter, the B horizon is enriched with trace elements together with clay, and C horizon is

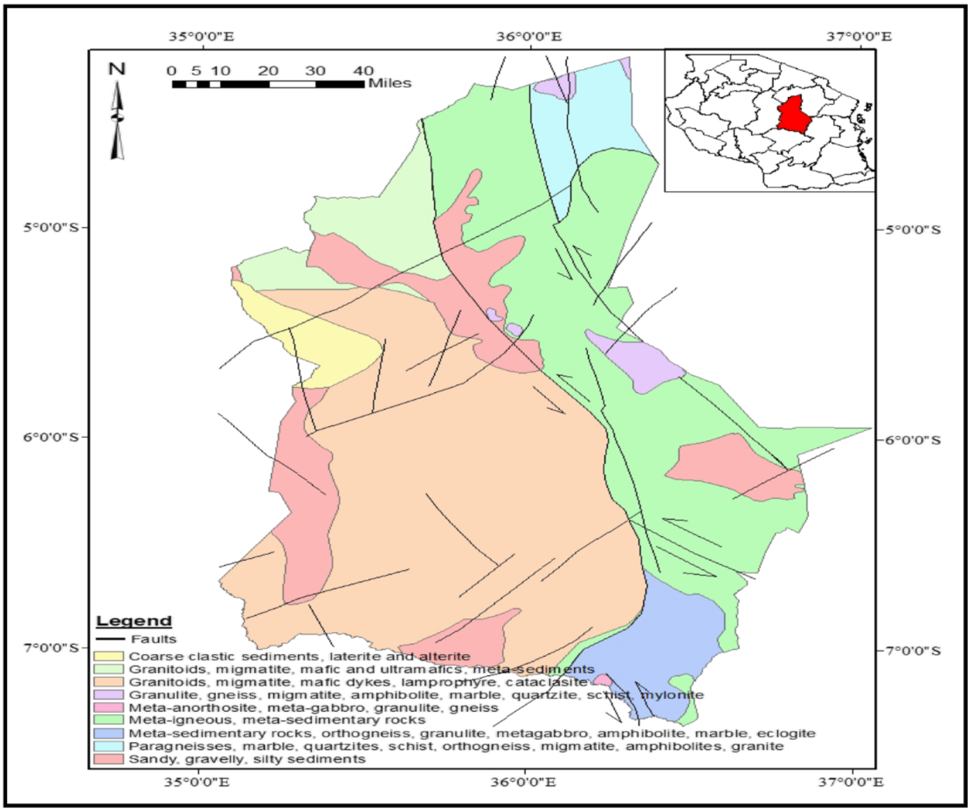

Fig. 1 The geological map of the study area, Dodoma region, Tanzania

sparsely weathered with bedrock fragments [48]. The presence of trace elements within the B horizon of the regolith profile makes it a suitable zone to sample from during soil sampling for geochemical exploration purposes [8, 24]. A total of 150 samples including, thus, 103 samples and 47 duplicate samples for quality control checks were collected from predefined sample points on the QDS 162 topographical sheet for Dodoma areas (Luatu and Mvumi) from the B horizon, thus from 60 cm depth. The collected samples were sieved in the field to < 2 mm micron before been transported to the Geological Survey of Tanzania (GST) sample preparation rooms where the samples were later sieved to < 75 mm micron fraction. The samples were prepared in two clean rooms at the GST following four main steps. Five grams of each sample was taken to the Canadian Acme Laboratory (CAL) for ICP-MS analyses where the samples were subjected to a HF-HNO_3-$HClO_4$ acid digestion and the prepared samples were digested to complete dryness with an acid solution of (2:2:1:1) H_2O-HF-$HClO_4$-HNO_3 25 g of each sample to the Canadian Geological Survey CGS Laboratory for XRF analyses and 30 g of each sample to the Geo-analysis Laboratory (GL) of Henan in PR of China for gold-platinum-palladium analyses. Fifty percent HCl was added to the residue and heated using a mixing hot block. After cooling, the solutions were transferred to test tubes and brought to volume using dilute HCl and sample splits of 0.25 g were analyzed. A twelve (12)-gram-milled sample material and three (3)-gram Lico wax were mixed and pressed into a powder briquette by a hydraulic press with the applied pressure at 25 ton. The pellets were analyzed by a PANalytical Magic-X Fast simultaneous X-ray fluorescence spectrometer equipped with Rh-tube.

For the gold-platinum-palladium analyses at the GL of Henan in People's Republic of China, a 10 g of sample was decomposed with aqua regia and pre-concentrated with thiourea resin and subsequently ashed, resulting in a residue. This residue was dissolved by aqua regia and Pt, Pd, and Au were analyzed by ICP-MS. The detection limits were between 0.001–0.01% and 0.002–2 ppm for the oxides and the traces elements, respectively.

To check the quality of the results obtained from these laboratories, duplicate samples were selected for the soil samples. A total of 47 duplicate samples were collected and inserted as blind samples and analyzed together with the other samples accordingly. In general, most of the results of the original samples and the duplicate samples were repeatable with minor differences. However, few samples produced more random results and plot as outliers for the majority of elements. These outliers were produced in both the analytical techniques ICP-MS and XRF. Therefore, it is certain to conclude that the original error was produced by the subsampling process and the quality of the analytical data is generally good.

3.1.2 Statistical Approaches and Data Processing

Statistical summary of raw and transformed data was generated using Microsoft excel as well as Spearman correlation of the data so as to ascertain the relation and possible association between two elements without their units of measurements influence. To explore the normality of the data, since most geochemical data are usually not normally distributed, box and whisker plots together with Q-Q (quantile–quantile) plots were initially used to assess the normality of the data. According to Sadeghi et al. [37], three forms of data transformations have been proposed when it comes to identifying the spatial distribution and mapping of pathfinder elements during geochemical exploration, thus centered log-ratio (clr) and additive log-ratio (alr) both by Aitchison [2] and isometric log-ratio (ilr) by Egozcue et al. [20]. Although there is a variation in views as to which method is suitable, [16] indicated that either the clr or ilr is effective in the transformation of in situ soil geochemical exploration data, in order to make the data suitable in elucidating anomalous zones and elemental associations as well as pathfinder elements suitable for targeting mineralization. Hence, the data was transformed by applying the clr method using Eq. 1, before multivariate statistical analytical approaches; thus, PCA, FA, and HCA were applied. Using interpolation by kriging, Gaussian variogram models for anomalous areas of Cu, Pb, Zn, Fe, Mg, Au, Ni, and Co were generated following the procedure of Sunkari et al. [43, 44].

$$\mathrm{clr}(x) = (\log(x1/g(x)), \ \ldots, \ \log(xN/g(x))) \tag{1}$$

4 Results and Discussion

4.1 Geochemistry

The trace element concentrations of the untransformed data are shown in Table 1, with Ni, Mn, Sr, V, Cr, Ba, Zr, and Rb having average concentration values ranging between 49.7 and 571.5 ppm. La and Li have concentration average values ranging between 28.7 and 38.5 ppm, whereas Sc, Nb, Y, Al, and Co are with average values less 20, within the range between 11.7 and 15.6 ppm. Zn has 33.0–125.0 ppm with average value of 54.5 ppm. Cu also has 3.0–89.6 ppm with average value of 28.7 ppm, while Pb has concentration values in the range of 8.3 ppm to 53.3 ppm and average value of 22.4 ppm. As is with values ranging between 0.0 and 113.0 ppm and an average value of 3.2 ppm, Ag has a maximum value of 0.3 ppm while Au has minimum and maximum values of 0.5 ppb and 31.6 ppb, respectively, with average value of 3.3 ppb. With average concentrations between 1 and 10 ppm are Fe, K, and Hf with the oxides Ca, Mg, Ti, and Na having average concentration values less 1 ppm (Table 1).

4.2 Geostatistics Analysis

4.2.1 Spearman's Correlation

From the correlation matrix (Table 2), the relation between possible pathfinder elements and the relationship between other trace elements and their implication on the underlying geology is inferred. Cu significantly correlates with Ni (r = 0.81), Co (r = 0.85), Fe (r = 0.74), V (r = 0.74), Cr (r = 0.84), Mg (r = 0.50), Ti (r = 0.65), and Sc (r = 0.78) and then with Au although not so high but it is worthy because of the often usage of Cu as a pathfinder element in search for Au, and has Cu – Au correlation value of r = 0.42. The suit of elements/metals, thus, Ni, Co, Fe, V, Cr, Mg, Ti, and Sc are mostly associated with mafic–ultra mafic rocks [1, 17, 20, 37, 38, 46]. This elemental association is indicative of metavolcanics and volcanic/basaltic rock controls on the occurrence of the metal Cu and on Au to an extent within the area. These rocks and their metamorphic progeny are the main dominant rock suite in the area under consideration according to Thomas et al. [47]. Due to the unstable nature of the mineralogy of these mafic–ultramafic rocks, they easily weather on exposure to water, air, and temperature; their weathered elements like Ni, Zn, Mn, V, Cr, and Ni are not mobile with effect of weathering or metamorphism [1, 6, 7, 46] and hence their high concentration levels as observed in their average values (Table 1). Pb positively and significantly correlates with Sr (r = 0.54), K (r = 0.65), Zr (r = 0.58), and Rb (r = 0.74). These trace elements are mostly enriched in felsic rocks, thus granitoids, and are also mobile during weathering and metamorphism; this mobility effect often affects their concentration levels in regolith materials [9, 31]. Their significant correlation with Pb can be attributed to the possibility that Pb and for that matter Au within the area is being sourced or controlled to some extent by the granitic rocks in the area. This interpretation has been given to similar element association by Sadeghi et al. [37]. Although their concentration levels are often modified by weathering and metamorphic processes, the observed high levels of Sr, Ba, Zr, and Rb (Table 1) could be accounted for by the in situ (untransported) nature of the weathered materials sampled for the study, hence, the samples still maintaining the elemental fingerprints of the underlying lithology (most probably). Also, Zn strongly correlates with Mn (r = 0.53), Au (r = 0.57), La (r = 0.60), Mg (r = 0.71), and Y (r = 0.53) (Table 2). Zn as a pathfinder element for Au with this element suite could be explained by the source of the Zn and by extension Au, to be largely from mafic igneous rocks (strong correlation with Mn and Mg) [37], with some minor

Table 1 Statistical summary of untransformed data and centered log-ratio (clr) transformed data without units of measurements influence

	Min	Max	Mean	Median	Skew	Std	Kurt	Sample var	No. of samples
Statistical summary of untransformed data									
Cu	3.0	89.6	28.7	27.0	1.4	12.2	5.2	194.1	103.0
Pb	8.3	53.3	22.4	20.2	1.5	8.9	2.4	93.5	103.0
Zn	33.0	125.0	54.5	50.0	1.7	15.0	5.0	322.6	103.0
Ag	0.0	0.3	0.0	0.0	2.6	0.1	7.3	0.5	103.0
Ni	10.2	162.7	49.7	44.5	1.2	26.1	2.6	817.0	103.0
Co	5.0	48.3	15.6	14.7	1.9	5.8	9.1	45.4	103.0
Mn	147.0	1384.0	388.6	331.0	1.9	190.1	6.8	46,501.0	103.0
Fe	1.0	7.2	3.2	3.0	0.9	1.1	1.7	1.5	103.0
As	0.0	113.0	3.2	1.0	9.9	11.1	100.1	313.1	103.0
Au	0.5	31.6	3.3	1.9	4.4	4.2	24.0	27.9	103.0
Sr	26.0	505.0	123.6	91.0	1.7	89.7	3.1	9243.5	103.0
V	22.0	198.0	68.0	62.0	1.4	30.4	3.1	1128.8	103.0
Ca	0.1	2.3	0.6	0.4	1.8	0.5	3.2	0.3	103.0
La	7.0	138.5	29.6	24.3	3.0	17.7	14.5	417.1	103.0
Cr	20.0	425.0	92.2	87.0	2.9	51.7	16.7	3706.7	103.0
Mg	0.1	1.5	0.4	0.3	2.2	0.3	5.6	0.3	103.0
Ba	263.0	1355.0	571.5	529.0	1.3	204.2	2.2	52,564.2	103.0
Ti	0.2	0.9	0.4	0.4	0.9	0.1	1.4	0.0	103.0
Al	5.9	14.6	10.1	9.7	0.4	1.9	−0.4	6.2	103.0
Na	0.1	2.5	0.7	0.5	1.2	0.6	0.9	0.3	103.0
K	0.8	3.7	1.8	1.7	0.6	0.6	−0.2	0.4	103.0
Zr	50.0	436.3	116.6	96.5	2.7	58.0	10.4	4379.5	103.0
Y	6.0	44.1	14.2	12.4	1.9	6.0	5.9	45.0	103.0
Nb	7.6	33.2	13.4	12.6	1.9	3.9	6.4	20.9	103.0
Sc	3.0	25.0	11.7	11.0	0.7	5.0	0.1	28.4	103.0
Li	13.0	89.3	38.5	36.3	1.3	14.2	2.7	247.2	103.0
Rb	41.1	270.4	107.5	95.8	1.6	36.6	3.8	1778.6	103.0
Hf	1.5	13.6	3.6	3.0	2.5	1.9	8.5	4.7	103.0
Statistical summary of clr transformed data									
Cu	0.1	3.2	1.0	1.0	1.4	0.4	5.2	0.2	103
Pb	0.4	2.4	1.0	0.9	1.5	0.4	2.4	0.2	103
Zn	0.6	2.3	1.0	0.9	1.7	0.3	5.0	0.1	103
Ag	0.2	3.3	1.0	0.9	1.2	0.5	2.6	0.3	103
Ni	0.3	3.1	1.0	1.0	1.9	0.4	9.1	0.1	103
Co	0.4	3.6	1.0	0.9	1.9	0.5	6.8	0.2	103
Mn	0.3	2.3	1.0	1.0	0.9	0.4	1.7	0.1	103
Fe	0.0	51.4	1.5	0.5	9.9	5.0	100.1	25.5	103
As	0.2	10.5	1.1	0.6	4.4	1.4	24.0	1.9	103
Au	0.2	4.2	1.0	0.8	1.7	0.7	3.1	0.6	103
Sr	0.3	3.0	1.0	0.9	1.4	0.5	3.1	0.2	103
V	0.2	3.9	1.0	0.7	1.8	0.8	3.2	0.7	103
Ca	0.2	4.8	1.0	0.8	3.0	0.6	14.5	0.4	103
La	0.2	4.7	1.0	1.0	2.9	0.6	16.7	0.3	103
Cr	0.3	3.8	1.0	0.8	2.2	0.6	5.6	0.4	103
Mg	0.5	2.4	1.0	0.9	1.3	0.4	2.2	0.1	103
Ba	0.4	2.3	1.1	1.0	0.9	0.3	1.4	0.1	103
Ti	0.6	1.5	1.0	1.0	0.4	0.2	−0.4	0.0	103
Al	0.1	3.6	0.9	0.7	1.2	0.8	0.9	0.7	103
Na	0.4	2.1	1.0	0.9	0.6	0.3	−0.2	0.1	103
K	0.4	3.8	1.0	0.8	2.7	0.5	10.4	0.3	103

Table 1 (continued)

	Min	Max	Mean	Median	Skew	Std	Kurt	Sample var	No. of samples
Zr	0.4	3.2	1.0	0.9	1.9	0.4	5.9	0.2	103
Y	0.6	2.5	1.0	0.9	1.9	0.3	6.4	0.1	103
Nb	0.3	2.2	1.0	0.9	0.7	0.4	0.1	0.2	103
Sc	0.3	2.3	1.0	1.0	1.3	0.4	2.7	0.1	103
Li	0.4	2.5	1.0	0.9	1.6	0.3	3.8	0.1	103
Rb	0.4	3.8	1.0	0.8	2.5	0.5	8.5	0.3	103
Hf	0.4	3.8	1.0	0.8	2.5	0.5	8.5	0.3	103

mineralization being controlled by the granitic rocks with the strong correlation with Y and La. Ni correlates positively (Table 2) with Co, Mn, and Cr. Co also positively correlates and strongly with Mn, Fe, V, Cr, Mg, Ti, and Sc whereas Mn also positively correlates with Sr, V, Ca, Mg, and Y while Fe positively correlates with V, Cr, Mg, Ti, Y, and Sc (Table 2). All these strong correlations go to explain the main rocks controlling the trace elements concentrations in the area and conversely the mineralization in the area, and it can be inferred from the correlation patterns that the dominant lithology controlling the mineralization in the Dodoma region is the mafic rock suite with the granitic intrusives contributing some amount of mineralization to the area although it may be small. Au positively correlates strongly with Mg ($r=0.65$); however, although weakly, it also correlates positively with the following elements V ($r=0.40$), -Ca ($r=0.39$), Rb ($r=0.40$), Fe ($r=0.38$), Mn ($r=0.38$), Co ($r=0.33$), Cu ($r=0.42$), Pb ($r=0.42$), and Cr, Y, Sr, and Sc. This correlation and elemental association supports their possibility as pathfinder elements to Au (Cu, Fe, Mn, Cu, and Pb) while Au correlation with Mg, V, Cr, Sc, Co, Fe, and Mn could support the volcanic/basaltic and metavolcanic control on the Au mineralization in the area. Volcanogenic massive sulfide (VMS) Au deposits are strongly associated with volcanic rocks, with the correlation patterns of Au. The probable VMS Au deposit occurrence in the area cannot be precluded although further works need to be carried to understand the deposit type(s) in the Dodoma area. Also, the lateritic component in the area could be possible target for any further exploration in the area or could be hosting some amount of Au mineralization [43] within the Dodoma central region of Tanzania.

The elements of interest, thus, Cu, Zn, Pb, As, Mn, and Au and Fe in Fig. 2, show high contents of Mn. It shows the presence of outliers where the whiskers exceed the 75th quartile mark and indicating some level of skewness as well. The other elements are relatively normally distributed from the boxplots and Q-Q plots. The other points not within the normal distribution line (Q-Q plots) may be the anomalous values and maybe indication of mineralization according to Sunkari et al. [43].

4.2.2 Multivariate Statistical Analysis

FA is a suitable multivariate statistical analytical approach for exploration geochemical data in accounting for the various sources of the elements together with the target mineral, e.g., Au or Cu, and has been successfully applied in constraining trace elements geochemical data [32, 35, 37, 43]. The multivariate statistics was performed on the transformed data set. The principal component analysis (Table 3) indicates that three main components of elemental associations control the overall trace element concentration within the Dodoma area forming 77.03% of the total variance for the initial eigenvalues for the studied samples. The rotational sums of squared loadings for component 1, 2, and 3 are 39.93%, 18.61%, and 18.48%, respectively (Table 3). In Table 4, the rotated component matrix of C1, C2, and C3, thus principal component 1, 2, and 3, respectively, as well as the rotated space FA (Fig. 3), indicates the elemental constituents of the various components making up the various percentages (Table 3). Based on the eigenvalues loadings of the three components, C1 has Fe-Cu-Sc-Co-Ni-V-Cr as the elemental association, C2 has Mg-Zn-Au-Rb-Pb as its elemental association, and C3 has Ba-Sr-Ca-Mn elemental association (Table 4 and Fig. 3). Porphyry copper deposits are largely accepted to be structurally controlled, making this type of deposit hydrothermally influenced. The mineralization styles are Cu-Mo, Cu-Mo-Au, and Cu-Au. The geological terrain coupled with the elemental associations shown from the elemental correlation and the multivariate statistics could be explained by a probable Cu-Au porphyry type of mineralization within the area not precluding a possible VMS deposit occurrence. Further research, however, is required to characterize the Au deposit(s) in the Dodoma area. The probable Cu mineralization is mainly controlled by the mafic–ultramafic rocks whereas the Au is controlled both by the granitic and volcanics/metavolcanic rock suite within the area. Cr-Ni-Co, as observed in association with other pathfinder elements like Fe and Cu, has been considered as the elemental association for mineralized greenstone belts according to Billay et al. [10, 11]. The PCA and the FA categorization of the elemental associations collaborate

Table 2 Spearman's correlation matrix of the data set (italicized values are the figures considered as significant in the discussion of this paper)

	Cu	Pb	Zn	Ni	Co	Mn	Fe	As	Au	Sr	V	Ca	La	Cr	Mg	Ba	Ti	Al	Na	K	Zr	Y	Nb	Sc	Li	Rb	Hf
Cu	1.00																										
Pb	−0.20	1.00																									
Zn	0.32	0.39	1.00																								
Ni	0.81	−0.44	0.04	1.00																							
Co	0.85	−0.24	0.27	0.78	1.00																						
Mn	0.48	0.29	0.53	0.24	0.57	1.00																					
Fe	0.74	−0.03	0.48	0.57	0.70	0.59	1.00																				
As	0.05	0.05	0.09	0.02	0.07	0.24	0.15	1.00																			
Au	0.42	0.29	0.57	0.17	0.33	0.38	0.38	0.07	1.00																		
Sr	−0.04	0.54	0.46	−0.13	0.05	0.57	0.24	0.21	0.30	1.00																	
V	0.74	−0.01	0.38	0.59	0.75	0.60	0.91	0.21	0.40	0.30	1.00																
Ca	0.26	0.36	0.47	0.10	0.34	0.78	0.43	0.25	0.39	0.85	0.48	1.00															
La	−0.04	0.53	0.60	−0.21	0.00	0.38	0.23	0.09	0.34	0.40	0.16	0.36	1.00														
Cr	0.80	−0.19	0.13	0.86	0.80	0.45	0.66	0.07	0.26	0.15	0.71	0.35	−0.09	1.00													
Mg	0.50	0.29	0.71	0.31	0.52	0.73	0.68	0.24	0.65	0.65	0.69	0.77	0.48	0.49	1.00												
Ba	−0.42	0.38	0.03	−0.45	−0.33	0.08	−0.34	0.08	−0.07	0.46	−0.18	0.21	0.12	−0.29	0.00	1.00											
Ti	0.65	−0.23	0.38	0.59	0.61	0.31	0.75	−0.01	0.20	−0.03	0.63	0.12	0.13	0.59	0.36	−0.30	1.00										
Al	0.24	−0.13	0.19	0.20	0.07	−0.01	0.29	0.13	0.03	−0.08	0.05	0.06	0.13	0.07	0.00	−0.33	0.40	1.00									
Na	−0.21	0.51	0.38	−0.26	−0.15	0.40	0.13	−0.02	0.11	0.83	0.13	0.64	0.36	−0.01	0.47	0.34	−0.16	−0.12	1.00								
K	−0.45	0.67	0.17	−0.59	−0.45	0.15	−0.38	−0.06	0.11	0.32	−0.31	0.14	0.37	−0.41	0.05	0.67	−0.41	−0.31	0.39	1.00							
Zr	−0.24	0.58	0.47	−0.35	−0.23	0.29	0.08	0.00	0.10	0.47	−0.04	0.37	0.70	−0.16	0.33	0.12	−0.03	0.09	0.64	0.42	1.00						
Y	0.33	0.44	0.53	0.10	0.26	0.63	0.53	0.22	0.37	0.44	0.41	0.53	0.64	0.22	0.57	−0.02	0.33	0.31	0.34	0.17	0.41	1.00					
Nb	0.42	−0.04	0.21	0.36	0.37	0.12	0.34	−0.01	0.06	−0.16	0.25	−0.06	0.01	0.39	0.09	−0.18	0.68	0.26	−0.30	−0.22	−0.10	0.20	1.00				
Sc	0.78	−0.24	0.26	0.70	0.63	0.35	0.74	0.24	0.26	0.03	0.64	0.26	0.07	0.66	0.42	−0.45	0.70	0.59	−0.14	−0.52	−0.12	0.49	0.39	1.00			
Li	0.29	0.06	0.24	0.32	0.26	0.16	0.22	0.37	0.13	0.07	0.22	0.09	0.00	0.24	0.18	−0.12	0.28	0.26	−0.10	−0.23	−0.03	0.12	0.46	0.31	1.00		
Rb	0.02	0.74	0.42	−0.25	−0.08	0.38	0.08	0.20	0.40	0.33	0.04	0.35	0.59	−0.06	0.38	0.20	−0.03	0.17	0.26	0.65	0.48	0.57	0.15	0.06	0.18	1.00	
Hf	−0.23	0.66	0.46	−0.36	−0.24	0.32	0.06	0.00	0.14	0.50	−0.05	0.40	0.70	−0.16	0.33	0.14	−0.08	0.08	0.67	0.48	0.99	0.44	−0.12	−0.13	−0.05	0.55	1.00

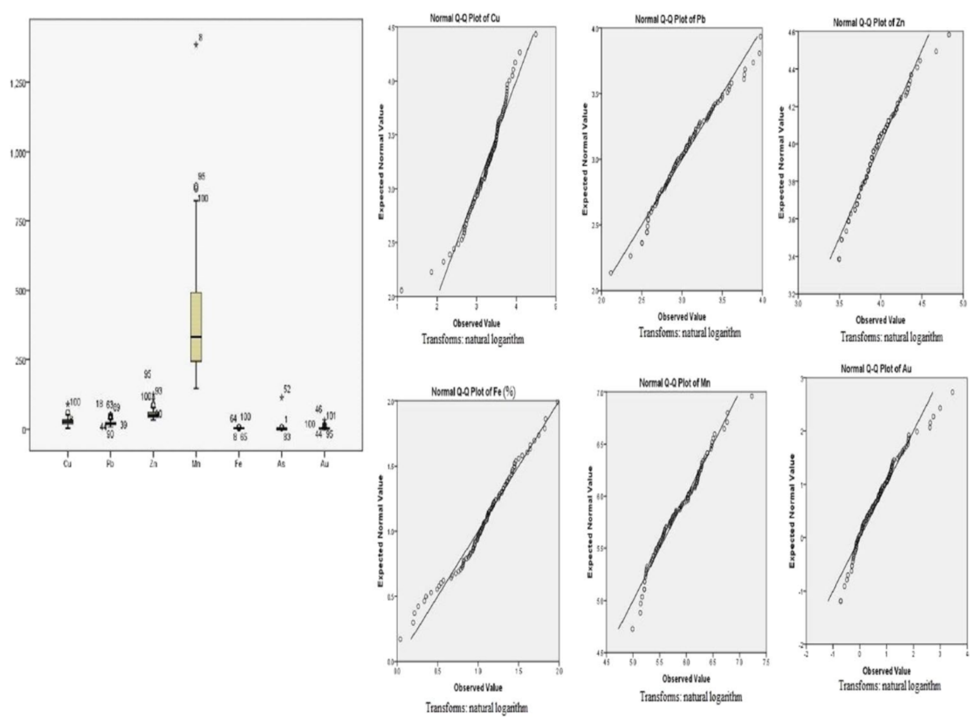

Fig. 2 Boxplots and Q-Q plots of Cu, Pb, Zn, Fe, Mn, and Au

Table 3 Extraction of principal components of the data sets

Total variance explained for the transformation data set						
Component	Initial eigen values			Rotation sums of squared loadings		
	Total	% of variance	cumulative %	Total	% of variance	Cumulative %
1	7.157	44.728	44.728	6.389	39.931	39.931
2	3.925	24.531	69.259	2.978	18.614	58.546
3	1.243	7.769	77.029	2.957	18.483	77.029

Table 4 Rotated component matrix C1, C2, and C3 components for the transformed data sets with significant positive loadings in bold fonts

Component of the transformed data			
	1	**2**	**3**
Cu	**.916**	.182	
Pb	−.356	**.688**	.370
Zn	.253	**.729**	.246
Mn	.476	.350	**.626**
Fe	**.821**	.275	.193
Au	.335	**.711**	
Sc	**.826**	.151	
Cr	**.870**		.177
Co	**.888**		.115
Ni	**.890**	−.200	−.103
Mg	.539	**.534**	.531
V	**.821**	.161	.315
Ca	.288	.311	**.823**
Rb	−.145	**.816**	.171
Sr		.301	**.889**
Ba	−.507		**.620**

and explain better the correlation patterns of these elements in Table 2.

HCA has been used over the period in assessing the variables of geochemical data rather than on the cases [22, 52]. This approach has also been used and suitable in elucidating how similar or otherwise a mineral of interest (Au, Cu, etc.) is with the other trace elements, and for that matter the suitability of the approach in identifying pathfinder elements to Au occurrence, and has been used to some extent [32, 43]. The approach, thus, HCA is also capable of defining possible areas within a target area with high Au concentrations and hence exploration targeting within a mineralized zone [32]. Using this approach on the soil samples of the Dodoma region, the main aim is to identify the possible pathfinder elements and also to support the PCA revelations on the controls of the mineralization in the area. The HCA, presented in the form of a clustering tree (dendogram) (Fig. 4), has identified 3 main clusters for the data sets. The first cluster in Fig. 4 has Cu, Pb, Zn, and Fe together with other trace elements, in the first cluster and with Au defining a unity

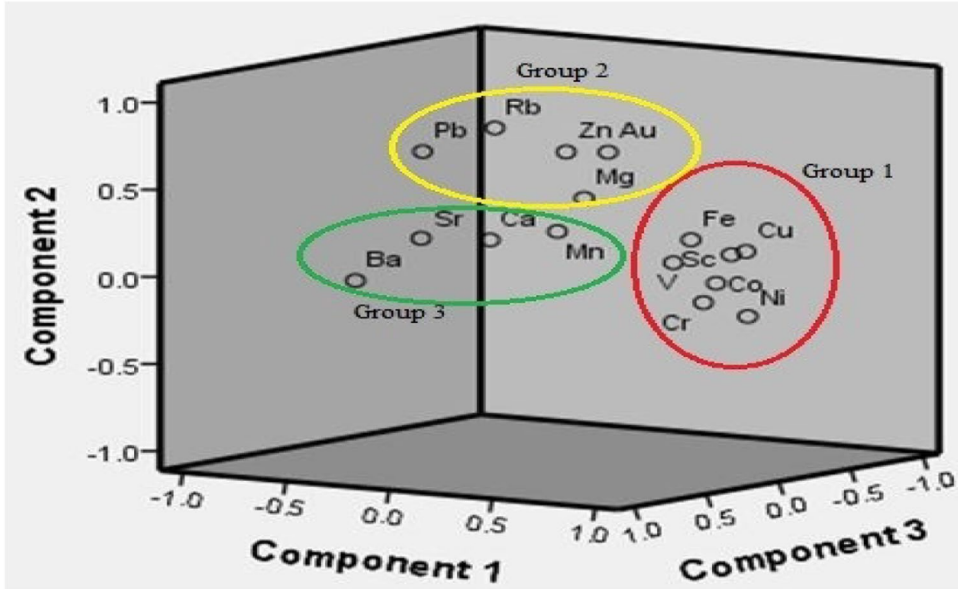

Fig. 3 Rotated in space factor analysis plots of transformed data sets

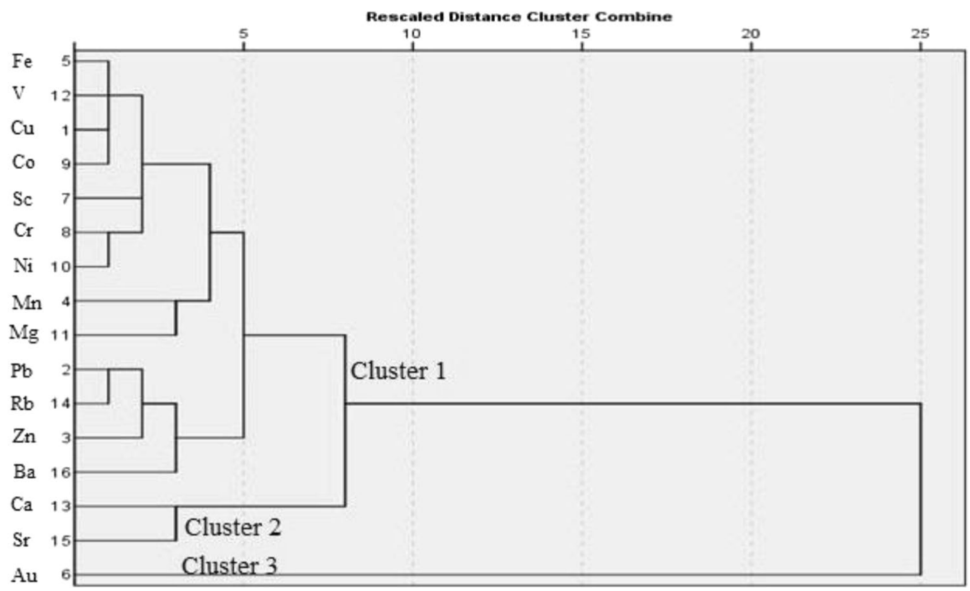

Fig. 4 Dendrograms of within groups cluster analysis clr transform data sets

cluster in cluster 3. The occurrence of the pathfinder elements with this suite of trace elements can be explained that the mineralization is strongly controlled by the volcanic and metavolcanic rock suite. Au alone in cluster 3 could also be explained by a possible Cu-Au porphyry deposit in the area and this assertion is in corroboration with that shown by the PCA (Fig. 3).

4.3 Spatial Distribution of Mineralization

The normal kriging interpolation spatial distribution maps of Cu, Ni, Fe, and Co (Fig. 5) have similar geospatial distribution. This elemental association which defines the C1 of the PCA is anomalous in the northeastern (NE), eastern (E), southeastern (SE), and southern (S) most parts of the area, with very low concentrations (green color) to the northwestern part of the area. In Fig. 6, the interpolation maps of Pb, Mg, Au, and Zn are shown. The elemental suite account for the C2 loading of the PCA and have similar geospatial distribution pattern except for Pb which is dominant in all the upper northern half of the area whereas Mg, Au, and Zn are more concentrated to the northern most and northeastern parts of the Dodoma region with very low concentrations (green color) found at the southern half for Pb and to the south, southeastern, and southwestern parts. Generally, the Dodoma region is worth exploring for a possible Cu-Au porphyry deposit type and the focus of any exploration exercise should be

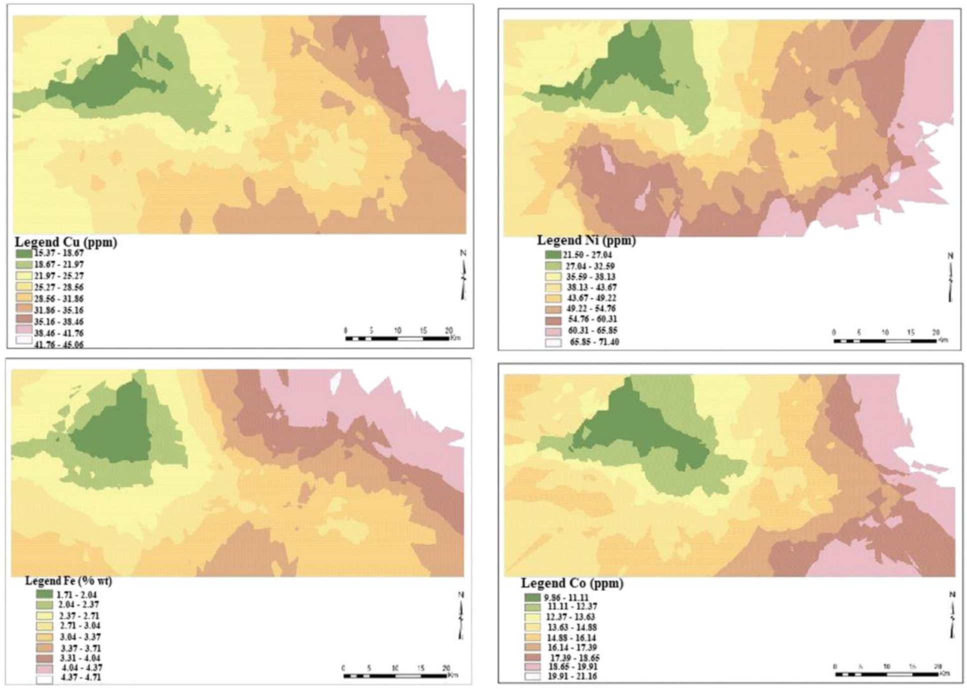

Fig. 5 Geospatial distribution maps ((Gaussian semivariogram models) of Cu, Ni, Fe, and Co of central Dodoma region generated by ordinary kriging interpolation

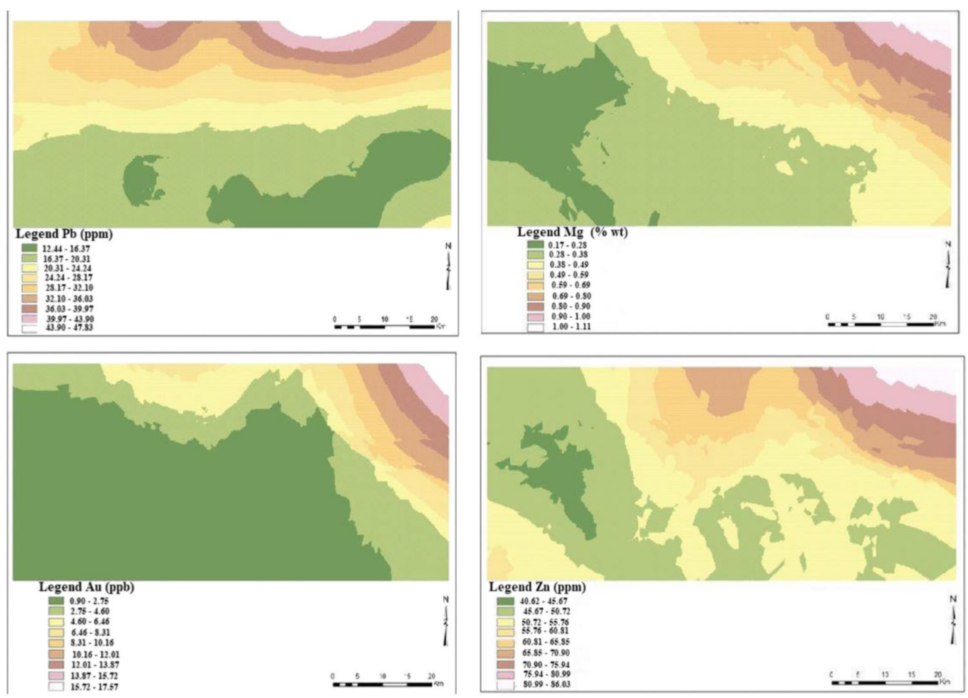

Fig. 6 The ordinary kriging interpolation spatial distribution maps of Au and other path-finder elements, Pb, Mg, and Zn (Gaussian semivariogram models)

to the northern (N), northeast (NE), southeastern (SE), and southern (S) parts.

4.4 Geological Implication

Trace elements of in situ regolith material have been effectively used to decipher the underlying rock type(s) of a mineralized area [10, 11, 17, 37, 51]. Trace elements of mafic–ultramafic (basalts, diorite, granodiorites, meta-volcanics) rocks are unequivocally distinct from their felsic (granitic and granitic gneisses) counterparts. Whereas Cr, Co, Ni, and V are observed in weathered materials of mafic–ultramafic rocks, Ca, Rb, Sr, Ba, Pb, and Y are often enriched in the weathered products of felsic rocks [4, 20, 37, 38]. This therefore makes this suite of trace elements suitable proxies in bed rock mapping using trace elements geochemistry. The Dodoma region of the TC is a greenstone belt with granodioritic intrusives and orthogneisses [19, 47]. The elemental association of Fe-Cu-Sc-Co–Ni-V-Cr indicated by the C1 (Table 4 and Fig. 3) is indicative of mafic–ultramafic bed rocks and agrees with Billay et al. [10, 11] elemental association for mineralized greenstone belts. The elemental associations of Mg-Zn-Au-Rb-Pb and Ba-Sr-Ca-Mn shown by C2 and C3 respectively in Table 4 and Fig. 3 are proxies of felsic-intermediate bed rocks within the area. This also suggests the control of the mineralization in the area by these felsic–intermediate rocks. This interpretation agrees with Sadeghi et al. [37] interpretation of soil geochemical data of the Giyani areas of South Africa.

4.5 Comparability to Other TC Mineralized Regions

Located in the Archean Geita Greenstone Belt is the longest operating Geita Hill gold deposit at the northwestern part of Tanzania [41]. The gold mineralization in the area is associated with the last stage mafic (dioritic) dykes emplacement. The mineralization in these parts of Tanzania according to Koegelenberg et al. [27] is hosted by the metasedimentary (metavolcanics inclusive) of green schist metamorphic facies within the shear zones. At the southwestern Lupa gold field, the mineralization fluid is associated with the emplacement of the granodioritic (mafic) suite and other narrow cross-cutting mafic dykes in the area [29]. Just like the Geita Greenstone Belt, the Dodoma region is part of the TC, and the Craton, in general, has reports of magmatism events due to the tectonically active nature of the area. These tectonic episodes are the most likely culprits for the suite of precious elements/metals mineralization in the TC. The elemental association of this study shows that the mineralization is largely associated with mafic–ultmafic rocks or the metavolcanics in the area. This makes the controls of the Au mineralization in the region being analogous to the mineralization style in the other Au bearing regions within the broader Tanzanian Craton.

5 Conclusion

With the aim of the study to identify potentially mineralized zones where possible follow-up exploration exercise can be undertaken, the elemental association/pathfinder elements, and also map the bed rock from soil trace elements geochemistry, the following conclusions can be drawn from the study.

- There is anomalous concentration of a possible Cu-Au porphyry deposit to the N, NE, S, and SE parts that is worth exploring.
- The main pathfinder elements to the Au occurrences in the Dodoma region are Cu, Pb, Zn, and Fe.
- It is also worth noting from the study that the deposit in the area is most probably a Cu-Au porphyry type of gold deposit, although VMS type of deposit is possible with the extent of volcanic rocks within the area.
- The mineralization in the area is strongly associated with the mafic rocks, thus, the volcanics, granodiorites, and the metavolcanics with the granitic suite controlling a small amount of the mineralization in the area. Also, the trace elemental association of Cr-Ni-Co-V in the area corroborates with other mineralized greenstone belt elemental association.
- The style of mineralization in the area is similar to other Tanzania Cratons' (TC) mineralization, and hence for the purpose of further exploration, successful exploration approaches adopted in brownfields like Geita Hill gold deposit and Lupa gold field could be studied and applied in the Dodoma region.

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Author Contribution All authors contributed to the whole processes of the manuscript preparation including the approval of the final manuscript.

Compliance with ethical standards

Conflict of Interest The authors declare no competing interests.

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