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Using Spatial Distribution of Termite Mounds To Support Subsurface Geological Imaging In A Complex Regolith Terrain of Sefwi-Bibiani Gold Belt, SW Ghana

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Abstract

Termites burrow along discontinuities in search for food and water in the earth system. Some discontinuities intersect with major and minor faults others coincide with stratigraphic contacts whilst others extend to the base of the regolith. Using the spatial distribution of termite mounds can support subsurface imaging of the hidden structures that may be hosting minerals of interest. In this research, a total of 1171 termite mounds were mapped, processed to determine the termite mounds correlations, densities, directional trends and relationships with geological structures as well as geophysical anomalies. The results showed most of the termite mounds spatially were located along a major NE-SW trend, a recognized major structure in the Birimian of southwest Ghana and NNW-SSE. In conclusion, the study realized the highest density per kilometre occurred along the stratigraphic contacts and fault zones. Significantly the application of spatial distribution of termite mounds can define structures hidden under the regolith and will be cheaper compared with other techniques of structure identification for mineral exploration.

Keywords: *Termite, mound, spatial, autocorrelation, spatial distribution, Subsurface*.

I. INTRODUCTION

. Surface geochemistry for gold exploration is fraught with challenges in defining anomalies, particularly in complex regolith terrains. This problem of identifying defects is thus heightened, considering the exhaustion of easily discoverable near-surface deposits (Henckens et al. 2016). The mining industry sustainability depends on the ability of defining and locating new deposits. This is important because civilization and society's prosperity depend on the continuous flow of minerals for development (Gandhi & Sarkar, 2016). In addition, most countries' Gross Domestic Products (GDP) depends on access to minerals. Conversely, the discovery rate of world-class mineral deposits continues to decline, which has increased the attention on geochemical exploration methods designed for regolith-dominated terrains (Butt, Lintern, & Anand, 2000). The regolith in most part of the world has been forming continuously for over 100 my. The upper regolith materials often sampled for gold geochemistry to aid in determining the surface anomalies have occurred and continued to evolve under climates ranging from humid rainforest, savannah to semi-arid, and hence are an expression of the cumulative effects of this long weathering history. The resultant landforms in the different climatic environments are broadly similar and may be grouped into ferruginous, relict, erosional and depositional regimes (Emmanuel Arhin, Jenkin, Cunningham, & Nude, 2015) or can be classified into relict, erosional and depositional domains (Anand, r.R., Smith, R.E., Phang, C., Wildman, J.E., Robertson. I.D.M and Munday, 1993). Characterizing all these areas is deep weathering, modified to varying degrees by leaching, erosion and any subsequent depositional processes. This regolith and landform modifications have led to full and complicated regolith profiles, which presents particular challenges in exploration. Typically, in complex regolith environments, the weathered mantle may be regionally continuous, so that almost no parent rock crops out for thousands of square kilometres. Mapping the geology and the associated structures that may host the mineralization are not possible. However, most of these areas masked by the regolith are the focus of mineral exploration. Though, attempts to find gold anomalies concealed by complex regolith have been carried out by several authors. Examples are biogeochemical plant surveys in mineral exploration for gold by Brooks (1973); McInnes et al. (1996); Reed and Hill (2010) and termiteria sampling by Affam and Arhin (2005); Arhin & Nude, (2010) and (Emmanuel Arhin, Boadi, & Esoah, 2015a). These methods, as a complement to traditional methods such as soil sampling and pattern drilling, have not always proved successful in anomaly detection (Arhin E., 2009). The nearest that most geologists have come to in mapping the geology and the geological structures in such terrains is the use of geophysical methods such as aeromagnetic, Induced Polarisation (IP) and Resistivity surveys among others. This approach, however, is costly during the initial stages of exploration.

Hence the need to use another low-cost technique to target the anomaly and to identify the deep-seated geological structures without employing geophysics may be recommendable. In this regard, this paper seeks to investigate the spatial distribution of termite mounds as an alternate and supporting tool to support subsurface imaging of the geological structures concealed by the regolith-landform units.

II. LOCATION, GEOMORPHOLOGY AND CLIMATIC SETTINGS

The study location is Pelangio Gold Concession at Pokukrom-Subriso in Manfo Traditional Area of Ahafoano Region in Ghana (Fig. 1). It is 75 km from Kumasi, the second capital of Ghana to the site and approximately 270 km northwest of Accra, the national capital. The access road from Kumasi or Accra is via a first-class highway with the last 14.5 km from Tepa to be a secondary, but all weather pave way.

Fig. 1. Location of the study area

The landscape consists of undulating terrains with low and isolated hills separated by relatively broad and narrow valleys. The small and high hill's height ranges between 190 m and 280 m above sea level (Dickson and Benneh, 1995). The area is in the wet semi-equatorial zone with double maxima rainfall in June and October. It has a mean annual rainfall of 1,750mm, with reasonably high temperatures of between 26° C in August and 30° C in March. Dry seasons are from late November to February. The average monthly rainfall is 116 mm per month, and the annual precipitation ranges from 700 to 2,100 mm. Vegetation is rainforest-type with several canopies of trees and undergrowth. However, the indiscriminate logging of the upper and middle layers of trees and farming had led to the primary forest to turn into secondary forest and shrubs.

Regolith

The area is characterized by deep weathering with simple and complex weathering histories at places. These forms of weathering histories tend to render the distributions of the regolith-landform units uneven. The characteristic features in the area that make gold geochemical expressions in the surface environment challenging are the jumble of the regolith materials unevenly distributed in this area. Relict regolith accounts for the most part of the city, but patches of ferruginous, erosional and depositional regolith domains are also not uncommon. The relict regolith characterized by cumulative regolith profiles from bottom up consists of sap rock, saprolite, clay zone, and top soils often with thin veneer of organic-rich soils on top. This regolith type tends to occupy most of the elevated areas, including the hilly areas. The hill slopes are marked by thin soils over clays and in some places over saprolite. Areas characterized by these features were mapped as part of erosional regime in addition to the outcropping and sub-cropping exposures of rocks. The erosional regolith regime generally occupies the Hillcrest, the hill-slopes while some crops out in streams and at the low-lying areas. The erosional landform has a composite profile at some places and shows overprinting and mixing between weathering profiles from the parent rock and proximally transported lithic units. Thin layers of soils occasionally are found on top of eroded surfaces. In addition to these two regolith types is the depositional regolith. Compound profiles characterize depositional regolith regime. Weathering and sedimentation processes form the profiles. These processes control the modifications of the upper regolith and are episodic. Sediments in this regime are able to mask the erosional surface and the pre-existing preserved surfaces at the relict regolith regime. This invariably affects the gold geochemistry in such environments. Characterising these landform areas are fluvial sediments from rivers/streams, and gravel colluvium moved downslopes from elevated landscapes/hills to occupy base of hills; some of which were transported recently. The fourth regolith is patchily distributed and is formed by the re-cementation of partially transported sediments. The matrix materials are polymictic, hosting sub-angular to sub-rounded lithic and quartz fragments. The surface processes that moved the regolith mapping units around and subsequently cemented the units during lateritization processes do influence the associated gold geochemistry. Avoidance of defining 'False' anomaly as 'True' anomaly may be realized on the assurance of collecting surface samples beneath the complex regolith or on the guarantee that surface samples collected are residual in character.

Geology

The study area is situated at the eastern edge of the Paleoproterozoic Sefwi-Bibiani Birimian Belt. Underlying the area is primarily the metavolcanic, metasedimentary, volcanoclastic, and belt and basin granitoids, (Hirdes, Davis, Lüdtke, & Konan, 1996). The metavolcanic rocks contain basalt and dolerite, with lesser gabbro, tonalite, and diorite (Kesse, 1985). Intruding the volcanic rocks is belt granitoids. They are small discordant to semi-discordant, late or post-tectonic soda-rich hornblende-biotite granites or granodiorites that grade into quartz diorite and hornblende diorite (Hirdes et al., 1996). They are generally massive, but in shear zones, they are strongly foliated. The basin granitoids intrude the metasedimentary rocks that are made up of phyllite, schist and some wackes. The intrusive bodies consist of large concordant and syntectonic batholitic granitoids commonly banded and foliated. They are two-mica potassic granitoids, containing both biotite and muscovite, with the biotite dominating (Leube, Hirdes, Mauer, & Kesse, 1990). The rocks in this area were deformed around 2.1 Ga during the Eburnean orogeny (Abouchami et al., 1990; Milési et al., 1991; Taylor et al., 1992). This orogeny had been reported to have association with shear-zone mineralisation (Kesse, 1985 and Griffis et al., 2002). These deformational events, therefore, place the study area into the orogenic gold province of global significance.

Mineralization

The gold anomalies defined by soil geochemistry and drill intersections are localised along a significant northeast-striking fault zone, referred to as the Sefwi Bibiani fault zone. This fault system controls the gold mineralisation and placed it in a structurally controlled orogenic type deposit. Other mineralisation controls seem to have association with broad zones of pervasive to fracture-controlled quartz-sericite-carbonate-pyrite alteration. In addition to the orogenic type mineralization situated in the fault zone is an intrusive related mineralization This overprints hematite alteration hosted predominantly in sheared and locally brecciated, altered granitoids rocks, and to a lesser extent brecciated hematite-altered mafic metavolcanic rock (Consulting, 2013)

Termite mounds and factors influencing termite mound spatial distributions

Termites are eusocial insects that live in the subterranean part of the Earth, on trees and dry woods. They are considered as destructive insects; destroying farm produce and eating dry woods of building (Obi, Ogunkunle, & Meludu, 2008) but also has economic importance in mineral exploration (Arhin et al., 2018). Termites that destroy farm produce and contribute to the identification of hidden mineral anomalies in complex regolith terrains (Emmanuel Arhin, Boadi, & Esoah, 2015b) are the subterranean termites. Subterranean termites build large earthen structures on the surface of the Earth, as their habitat. They collect subsurface materials to build the mounds. They are therefore referred to as soil engineers; vertically transporting and altering organic and inorganic materials during foraging (Chakravarthy & Sridhara, 2016), in the form of lithic fragments during the mound building. The foraging behaviour of termites results in the transportation and deposition of ore or mineral elements into the surface soil or termite nest structures which have long been used as geochemical and mineralogical sample media for the discovery of ore deposits buried beneath weathered cover and shallow sediments (Anand et al. 2016; Gleeson & Poulin, 1989; Kebede, 2004; Prasad and Vijayasaradhi, 1984; Prasad et al. 1987). The mobility of these elements and minerals mainly by termite workers are most dominant from the Phreatic (above the water table) zone and within the arid to the semi-arid regions of the world (Allibone et al. 2004).

It is therefore imperative that the deep weathering landscapes consisting of ferruginous duricrust and lateritic residuum towards the surface, which in places are buried by transported overburden and are characterised by complex weathering and geomorphic histories adversely could impact on mineral anomaly identification. The success of termites burrowing deep beyond the complex regolith will take advantage of the weak zones, which invariably may coincide with the geological structures hosting the mineralization. Like the option of pattern drilling through transported cover was recognized as an effective method in detecting hidden anomalies in areas undercover; this approach does come with high cost which very few mineral explorers can afford the cost over large areas. Similarly, the option of using geophysics to image geological structures through complex regolith may be effective; however, it could be expensive for many companies to afford. Conversely, the habit of termites building nests relative to the local climate suggests burrowed materials might come from different depths in the weathered materials in their search for food and water. This mechanism of termite burrowing materials could be along old fault zones or fault lines that is infill with weathered materials. Confirming the burrowed materials to have links with the fault zones is Mège & Rango (2010) revelation of the lining of termite mounds along fracture dense dykes that serve as conduits for groundwater. Similar observation was made by West (1970) who noticed that termites burrow down to groundwater table depths to access groundwater for body metabolism. These accounts and many other accounts including Arhin et al. (2015) and Stewart et al. (2012) suggest mineral exploration in complex regolith terrains can rely on termites as miniature prospectors for geological structures and mineral anomalies identifications.

Although termites burrow several meters below the earth surface, they cannot tunnel within and extract material from hard rock (Mège & Rango, 2010). They, therefore, build tunnels in already existing geological structures such as weathered dykes and fractured/sheared fault zones (Mège & Rango, 2010). These geologic structures can sometimes contain clay or moisture, which is an essential resource for the construction and maintenance of the mound (Harris, 1956). The presence of these clay or moisture can sometimes influence the spatial distribution of the mounds. The termites, therefore, assume a preferential path along these structures for easy accessibility to the resources (clay and moisture), making them align their mounds either along or across such geologic features. An example is an alignment of termite mounds along a dolerite dyke, reported by Mège & Rango, (2010) in Ethiopia.

Clay and moisture can sometimes accumulate in dykes and paleochannels. According to Babiker & Gudmundsson (2004), dykes are preferred pathways for groundwater recharge. Dykes could also serve as storage for groundwater in the dry season (Mège & Rango, 2010). Subterranean termites build their mounds on the soil surface, often in areas of increased moisture (Davies et al. 2015). This helps them to maintain the humidity of their mounds (Harris, 1956). Termites typically search for moisture and clay and in the process transport earth materials to the surface, possibly from such weathered dykes. Old buried river channels (paleochannels) can sometimes be associated with areas of increased moisture and can hence also be a potential target for termite activity. Paleochannels are old river channels, buried within the current landscape (Singh et al. 2011). These channels sometimes contain graded sedimentary deposits of very fine silt or clay materials, and permeable deposits, which make them a potential source for groundwater recharge (Samadder et al. 2011). Termites in search of clay and moisture construct mounds that can sometimes reveal these old buried channels. It is believed that the spatial distribution of termite mounds is influenced by some geological features, hence analysing the spatial pattern of these mounds could be used to detect geological structures concealed by the regolith.

III. MATERIALS AND METHODS

Methods

The materials looked at to image the subsurface geological structures using termite mounds include fieldwork, and geophysical data processing and interpretations.

Fieldwork

Termites appear to burrow down depth in the earth system to look for food water and sometimes clay. Weak zones such as dykes, faults, geological contacts, and other weak structures tend to be the most prospective targets if termite mounds are to be located. Confirmation of termites taking advantage of weak zones in the landscape was identified by Mège and Rango (2010) who observed the lining of termite mounds along fracture dense dykes that serve as conduits for groundwater. Consenting to Mège and Rango (2010) notion, ground truth of previously supplied gridded geophysical image anomalies, detailed photography of the surface geology, vegetation cover and landforms were followed to locate termite mounds occurrences. The spatial distribution of termite mounds was mapped, using GPS device with map datum WGS 84. The coordinates of termite mounds were recorded in a gridded pattern with an eTrex 30x GPS. GPS reading of each mound was kept at an average accuracy of 3 meters. These recorded coordinates represented point measurements of the termite mounds that were later used to distinguish the different spatial orientations of the mounds. Additional information gathered from the mounds includes the colour, whether the mound was active or inactive, presence or absence of lithic fragments, among others. Also, the locality name of each termite mound was indicated. About 1171 termite mounds with their GPS coordinates were recorded.

Data and Image Processing

The data obtained for the termite mounds locations were transformed to show the spatial distribution patterns using spatial statistical analysis in Arc Map 10.5.1 in a GIS environment. The spatial statistical analysis employed spatial autocorrelation (or Moran I global autocorrelation), kernel density and standard deviational trend analysis to determine the areal density of the mounds as well as the structural trends within the distribution of the mounds.

The spatial autocorrection employs Moran’s I global autocorrelation, which is an inferential statistical approach that analyses the overall spatial similarity of a data set based on the spatial location of the data, and its attributes (Moran, 1950). It thus evaluates whether a distribution is clustered, dispersed, or random and finally calculates the Moran's Index value, a Z-score and a P-value. The Moran's Index of values such as -1, 0 and 1 indicates perfect dispersion, perfect randomness, and perfect clustering respectively (Zhou & Lin, 2008). The lower P values and positive Z scores indicate that the Morans Index (I) is significant, whiles higher P values and negative Z scores indicate non-significance in the Moran's Index (Bhunia et al. 2013). Similar to the termite mound navigation using the GPS device, a map datum of WGS 84 was used for the spatial autocorrelation. The mounds spatial distributions were used as input feature whilst the mounds locality names generated on the field, (e.g. Pokukrom-East and Pokukrom-West) were coded into numerical values, e.g. 0 and 1, and used as a distance decaying factor to the input field. The spatial autocorrelation between the objects was then conceptualised using the inverse distance relation; where objects close to each other is much more related than objects farther away (Tobler, 1970). The Euclidean distance method was then used as a measure of distance between the termite mounds.

The kernel density distribution tool applied by (Silverman, 1986) was then used to calculate the magnitude of features per unit area. The tool uses a kernel function to fit a smooth surface to each feature. In this instance, the plotted termite mounds were used in Arc Map 10.5.1 to establish the density distribution of the termite mounds. These data analyses use the termite mound plot as the input feature. The attribute field representing similarities among the mounds (coded locality name) was used as the population field and the distance measurements between any two termite mounds in a straight line was obtained using the planar method of distance measurement.

Finally, the spatial distribution of the termite mounds was used as an input feature to obtain the directional trends of the termite mounds. The size of the output ellipse was set to 1-standard deviation, to encompass 68 percent of the distribution similar to (Bland & Altman, 1996) method. The distribution was then weighted by the location in the X and Y direction, to restrain the trends within the locations of the termite mounds. Structural corridors were manually created to help in the superimposition of other structural features derived from the available geophysical imageries. The integration of all the processed data used same map datum- WGS 84, same projection-30 degrees northern hemisphere and same UTM coordinate systems.

IV. RESULTS AND DISCUSSIONS

Results

The 1171 termite mounds mapped during the ground truth survey is presented in Fig. 2. The distances between two adjacent mounds have unequal separation suggesting variable factors control the burrowing process by the working termites. The spatial correlations of the termite mounds distributions in space is randomly dispersed and clustered at places (Fig. 3). The significance of the spatial distributions of

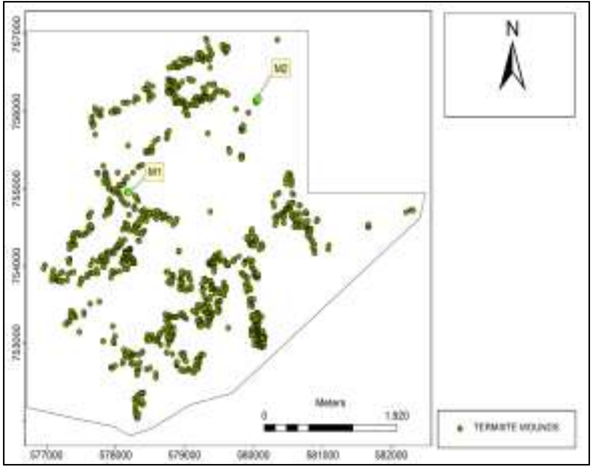

Fig. 2. Spatial distribution of termite mounds

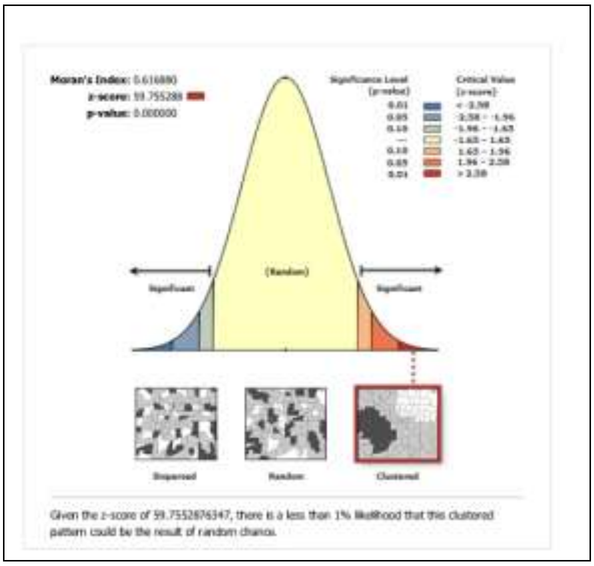

Fig.3. Spatial autocorrelation analysing the overall spatial similarities of termite mounds

The termite mounds are shown by the kernel density of the mounds (Fig. 4). The most populated areas of the termite mound distribution occur at the south-eastern portion of the study area. The directional trends of the termite mounds were presented in Fig. 5. The relationships between the directional trends of the termite mounds and the inferred major faults, the geophysical anomalies and the integrated plots of the termite mounds and the inferred major faults, the geophysical anomalies were presented in Figs. 6 – 7 respectively.

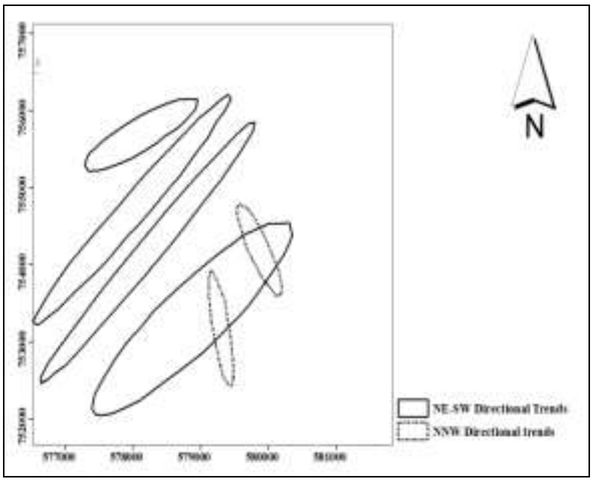

Fig. 4. Directional trends derived from spatial distributions of termite mounds

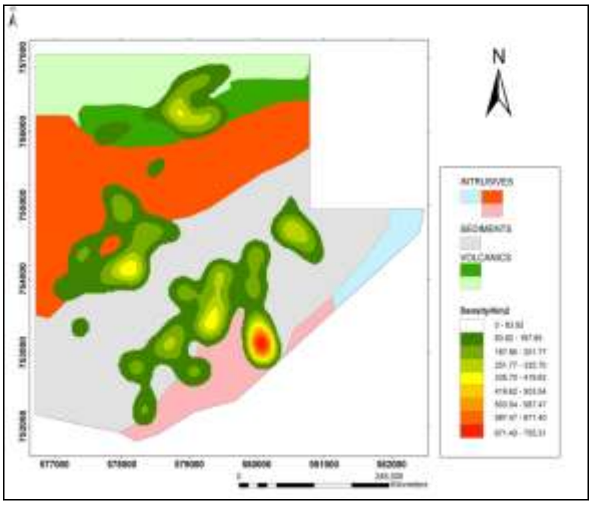

Fig. 5. Termite mound densities using Kernel density per km^2 method

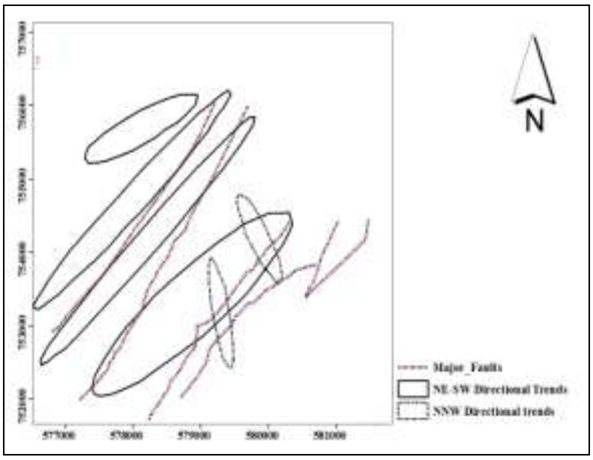

Fig. 6. Relationship between directional trends of termite mounds and inferred geological structures

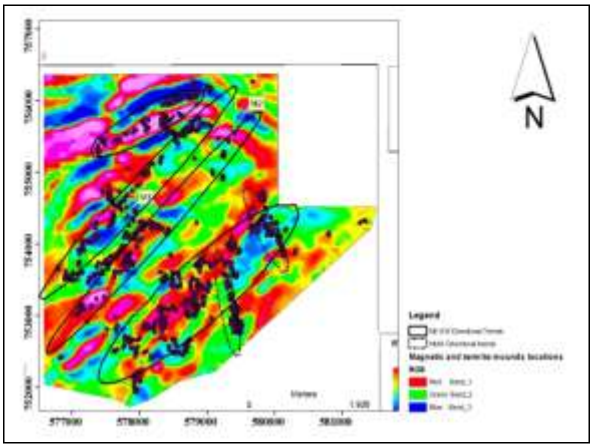

Fig. 7. Relationship between the directional trends of termite mounds and some geophysical anomalies

Discussions

The study location, as shown in Fig. 1 is similar to most prospective areas in south-western Ghana, where gold mineralization have been linked to geological structures. Examples of such discoveries are the gold mineralization at AngloGold Ashanti at Obuasi and Newmont Kenyasi and Abirem mines. The mineralized bodies in these areas are associated with shear zones, faults, and thrust contacts (Griffis and Agezo, 2002; Kesse, 1985). The regolith that masks the rock outcrops tend to be less complex in the known mining areas, unlike the study area where the regolith characteristics seem to be very complex. Mapping the geological structures in the complex regolith terrain appear impractical with little success rate in gold anomaly definitions. Consequently, the application of geophysics may appear too expensive, particularly at the Greenfield exploration stage. But on the contrary, if termites can burrow deep into the earth system, then that can be done via a weak one which may be a fault, lithological contact or maybe a shear zone. On the assumption that this is true, then the spatial correlation and directional trends defined by the termite mounds may reflect the buried geological structures and paleoplacers. As seen in Fig. 2, the 1171 termite mounds identified in the study area have some spatial similarities. The spatial distributions gave clues as to the orientation of the underlying structures the termites are burrowing through. From Fig. 3 the spatial distribution of the termite mounds may be dispersed, randomly distributed, and maybe clustered in the landscape. The termite mounds may follow linear or circular structures as may be derived from geophysics. The linear spatial patterns of the termite mounds may represent fault zones whilst the circular structure may represent intrusive contacts. From Fig. 4, it could be seen that the termite mounds trend linearly in the northeast-southwest direction similar to the regional trend of the Birimian volcanic rock units. This suggests that some of the directional trends of the termite mounds are defining the regional trends which hitherto would have been detected through geophysical data interpretation. In addition to the NE-SW trends, there are NNW-SSE trends.

The outcome of the Moran's I global autocorrelation recognized some of the termite mound distribution as clustered, dispersed, and/or random (Fig. 4). But as seen in Fig. 4, the termite mound spatial distribution appears controlled by geology and the available structural discontinuities. The area with the highest termite density occurs at the contact between an intrusive body and the metasediments at the southeastern end with termite density of about 760 termite mounds km^{-2}. All the other clustered areas of termite mounds D1, D2, and E are along a contact or close to a lithological contact. This thus confirms Mège and Rango (2010) assertion of termite burrowing the mound materials from the structural discontinuous zones infill with weathered materials and clay. Again the kernel density plot further confirms the NE-SW trend and depicts the advantage of the termites to burrow the mound-building materials at the stratigraphic contacts (Fig. 4). The density plot of the mounds as seen in Fig. 4 had also revealed the influence of spatial factors such as geology and discontinuities as well as explaining the characteristics of the termite mound autocorrelation. It thus seen the termite's mound distributions in the study area not to be random rather linear and dispersed.

These spatial patterns of the termite mounds defined two main trends which some coincides with some defined inferred faults (Fig. 5). The NE-SW trend seems to mimic the regional trends and some major structures in the rocks of the Birimian Greenstone Belts (Fig. 6) of Southwest Ghana. Many gold discoveries have been found in association with this trend. Examples are the AngloGold Ashanti deposit at Obuasi, Newmont Kenyasi and Kinross deposit at Chirano (Griffis and Agezo, 2002, Kesse, 1985). It is clear that the termites generally follow north-east, south-west trend, which is a significant trend within the Birimian orogenic terrain of Ghana (Leube et al., 1990). The other trends may have relations with some minor structures that could have association with gold mineralization. The minor structures if related to gold mineralisation may explain the structurally controlled mineralization and orogenic gold deposits in the Birimian System. The intersections between the major and minor structures could be sites for potential mineralisation also (Fig. 7).

V. CONCLUSION

The study area has complex regolith geology that masks the structural discontinuities hosting prospective mineralization. The 1171 termite mounds mapped identified four directional trends of mounds of which one of the trends conformed with the NE-SW regional trend of rocks in the area. The other trend NNW-SSE was considered minor compared to the NE-SW. In addition to these, the termite mound densities showed clusters along the stratigraphic contacts between the intrusive and metasedimentary contacts and also contacts of the metavolcanics and metasedimentary units at some places. It indicated lack of randomization of termite mounds but rather showed dispersed and clustered spatial distributions of mounds. Based on the information deduced from the kernel mound densities the authors concluded that the termites burrow weathered infill materials from the discontinuities fault zones and stratigraphic contacts of major rock type in the mound-building. They, however, postulate the use of spatial distribution of termite mounds to support subsurface geological imaging in a complex regolith terrain as the method has been effective in defining the major known structures as well as the minor structures without the application of expensive geophysical tools.

REFERENCES

[1] Affam, M. and Arhin, E. (2005). Termite Mound-A Supplementary Geochemical Gold Sampling Medium in Complex Regolith Terrain. Ghana Mining Journal, (8), 10–15.

[2] Allibone, A., Hayden, P., Cameron, G., & Duku, F. (2004). Paleoproterozoic Gold Deposits Hosted by Albite- and Carbonate-Altered Tonalite in the Chirano District, Ghana, West Africa. Economic Geology, 99(3), 479–497. https://doi.org/10.2113/gsecongeo.99.3.479

[3] Anand, r.R., Smith, R.E., Phang, C., Wildman, J.E., Robertson. I.D.M and Munday, T. J. (1993). Geochemical exploration in complex lateritic environments of the Yilgarn Craton, Western Australia. In Report 442R, CSIRO Division of Exploration and Mining, Perth.

[4] Anand, R. R., Aspandiar, M. F., & Noble, R. R. P. (2016). A review of metal transfer mechanisms through transported cover with emphasis on the vadose zone within the Australian regolith. Ore Geology Reviews, 73, 394–416. https://doi.org/10.1016/j.oregeorev.2015.06.018

[5]Arhin E., and N. P. M. (2009). Significance of regolith mapping and its implication for gold exploration in northern Ghana: a case study at Tinga and Kunche. Geochemistry: Exploration, Environment, Analysis, 9, 63–69.

[6] Arhin, E., & Nude, P. M. (2010). Use of termitaria in surficial geochemical surveys: evidence for >125- m size fractions as the appropriate media for gold exploration in northern Ghana. Geochemistry: Exploration, Environment, Analysis, 10(4), 401–406. https://doi.org/10.1144/1467-7873/09-004

[7] Arhin, Emmanuel, Boadi, S., & Esoah, M. C. (2015a). Identifying pathfinder elements from termite mound samples for gold exploration in regolith complex terrain of the Lawra belt, NW Ghana. Journal of African Earth Sciences, 109, 143–153. https://doi.org/10.1016/j.jafrearsci.2015.05.022

[8] Arhin, Emmanuel, Boadi, S., & Esoah, M. C. (2015b). Identifying pathfinder elements from termite mound samples for gold exploration in regolith complex terrain of the Lawra belt, NW Ghana. Journal of African Earth Sciences, 109, 143–153. https://doi.org/10.1016/j.jafrearsci.2015.05.022

[9] Arhin, Emmanuel, Jenkin, G. R. T., Cunningham, D., & Nude, P. (2015). Regolith mapping of deeply weathered terrain in savannah regions of the Birimian Lawra Greenstone Belt, Ghana. Journal of Geochemical

Exploration, 159, 194–207. https://doi.org/10.1016/j.gexplo.2015.09.008

[10] Babiker, M., & Gudmundsson, A. (2004). The effects of dykes and faults on groundwater flow in an arid land: the Red Sea Hills, Sudan. Journal of Hydrology, 297(1–4), 256–273. https://doi.org/10.1016/j.jhydrol.2004.04.018

[11] Bhunia, G. S., Kesari, S., Chatterjee, N., Kumar, V., & Das, P. (2013). Spatial and temporal variation and hotspot detection of kala-azar disease in Vaishali district (Bihar), India. BMC Infectious Diseases, 13(1), 64. https://doi.org/10.1186/1471-2334-13-64

[12]Bland, J. M., & Altman, D. G. (1996). Statistics notes: Measurement error. BMJ, 312(7047), 1654–1654. https://doi.org/10.1136/bmj.312.7047.1654

[13] Butt, C. R. M., Lintern, M. J., & Anand, R. R. (2000). Evolution of regoliths and landscapes in deeply weathered terrain — implications for geochemical exploration.

[14] Chakravarthy, A. K., & Sridhara, S. (2016). Economic and ecological significance of arthropods in diversified ecosystems: Sustaining regulatory mechanisms. In Economic and Ecological Significance of Arthropods in Diversified Ecosystems: Sustaining Regulatory Mechanisms. https://doi.org/10.1007/978-981-10-1524-3

[15] Davies, A. B., Eggleton, P., van Rensburg, B. J., & Parr, C. L. (2015). Seasonal activity patterns of African savanna termites vary across a rainfall gradient. Insectes Sociaux, 62(2), 157–165. https://doi.org/10.1007/s00040-014-0386-y

[16] Gandhi, S. M., & Sarkar, B. C. (2016). Essentials of mineral exploration and evaluation. Gleeson, C.F. & Poulin, R. (1989). Gold exploration in niger using soils and termitaria. Journal of Geochemical Exploration, 31, 253–283.

[17] Hirdes, W., Davis, D. W., Lüdtke, G., & Konan, G. (1996). Two generations of Birimian (Paleoproterozoic) volcanic belts in northeastern Côte d'Ivoire (West Africa): consequences for the 'Birimian controversy.' Precambrian Research, 80(3–4), 173–191. https://doi.org/10.1016/S0301-9268(96)00011-3

[18] Kebede, F. (2004). Use of termite mounds in geochemical exploration in North Ethiopia. Journal of African Earth Sciences, 40(1–2), 101–103. https://doi.org/10.1016/j.jafrearsci.2004.06.002

[19] Leube, A., Hirdes, W., Mauer, R., & Kesse, G. O. (1990). The early Proterozoic Birrimian Supergroup of Ghana and some aspects of its. Precambrian Ore Deposits Related to Tectonics., 46(1–2), 139–165.

[20] Mège, D., & Rango, T. (2010). Permanent groundwater storage in basaltic dyke fractures and termite mound viability. Journal of African Earth Sciences, 57(1–2), 127–142. https://doi.org/10.1016/j.jafrearsci.2009.07.014

[21] Moran, P. A. P. (1950). Notes on Continuous Stochastic Phenomena. Biometrika, 37(1/2), 17. https://doi.org/10.2307/2332142

[22] Obi, J. C., Ogunkunle, a O., & Meludu, N. T. (2008). Effect of termite infestation on the farming system characteristics of an endemic area in the Guinea savanna region of Nigeria. American-Eurasian Journal of Scientific Research, 3(1), 1–6.

[23] Prasad, E.A.V. and Vijayasaradhi, D. (1984). Termite mound in geochemical prospecting. Curr. Sci, 53, 649–651.

[24] Prasad, E.A.V. ayarama Gupta, M. and Dunn, C. E. (1987). (1987). Significance of termite mounds in gold exploration. Curr. Sci, 56, 1219–1222.

[25] Samadder, R. K., Kumar, S., & Gupta, R. P. (2011). Paleochannels and their potential for artificial groundwater recharge in the western Ganga plains. Journal of Hydrology, 400(1–2), 154–164. https://doi.org/10.1016/j.jhydrol.2011.01.039

[26] Silverman, B. (1986). Density estimation for statistics and data analysis. Chapman and Hall, 37(1), 1–22. https://doi.org/10.2307/2347507

[27] Singh, V. P., Singh, P., & Haritashya, U. K. (2011). Encyclopedia of Snow, Ice and Glaciers. In V. P. Singh, P. Singh, & U. K. Haritashya (Eds.), Springer. https://doi.org/10.1007/978-90-481-2642-2

[28] Stewart, A. D., Anand, R. R., & Balkau, J. (2012). Source of anomalous gold concentrations in termite nests, Moolart Well, Western Australia: implications for exploration. Geochemistry: Exploration, Environment, Analysis, 12(4), 327–337. https://doi.org/10.1144/geochem2012-126

[29] Tobler, W. R. (1970). A Computer Movie Simulating Urban Growth in the Detroit Region. Economic Geography, 46, 234. https://doi.org/10.2307/143141

[30] Zhou, X., & Lin, H. (2008). Moran's I. In S. Shekhar & H. Xiong (Eds.), Encyclopedia of GIS (p. 725). https://doi.org/10.1007/978-0-387-35973-1_817