Geochemical Dispersion of Elements and Their Correlation with Gold in the Regolith at the Tetteh Prospect of the Chirano Gold Mines in the Sefwi Belt of the Birimian, Southwestern Ghana

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Abstract

The processes controlling gold (Au) mineralization in Chirano, a gold prospect in south-western Ghana have been investigated using a detailed geochemical dataset of 45 variables from 197 sampling locations. The data were subjected to advanced statistical analyses and bivariate graphical interpretations in the light of the underlying lithology. Four processes of significance have been identified from the multivariate analysis in terms of the geochemistry of the soil in the area. The most important process accounts for almost half of the total variance in the dataset and also correlates strongly with Au. Although Arsenic (As) registers the highest loading under this factor, Aluminium (Al), Silver (Ag), Manganese (Mn), Copper (Cu), and Iron (Fe) record higher correlations and could serve as better pathfinders than As in the study area. This study also shows that there is a second, less prominent process contributing to the availability of Au in the area. This process ranks third amongst the processes of significance in terms of the geochemistry, and correlates negatively with As, suggesting that the latter is not suitable as a pathfinder for Au in the traditional sense. However, since this third process is weaker compared to the first, the implication of this interpretation may be limited to only some locations in the study area. In addition to the revelations from the multivariate statistics, the regolith in the study area has evolved over the years and therefore the changes in regolith should be factored into the exploration protocols. The pre-existing preserved surfaces were found to be masked predominantly by transported materials consisting of ferruginized and exotic sediments. Within the surficial regolith and especially in the Fe-oxyhydroxide rich horizons, Au concentrations increase to significant values that are higher than those of the bedrock or saprolite thereby showing the significant Au re-distribution within the regolith. This study also highlights the apparent Au depletion in the mottled clay zones and in the saprolite and the enrichment of the metal in lateritic residuum and the topsoil. The high Au expressions in the upper parts of the regolith generally are transported whereas the residual soil anomalies have low Au concentrations and do not merit further exploration follow up.

Keywords: Regolith, Gold mineralization, Pathfinder elements, Chirano mine, Sefwi belt, southwestern Ghana.

1.0 Introduction

Mineral exploration and exploitation are important economic endeavours in countries with promising mineral wealth. Depending on the stage of the exploration program, the activities can be quite expensive and significant financial losses can be incurred if the right procedures are not holistically followed. It is for this reason that exploration companies adopt rigorous scientific procedures to ensure that losses are reduced to the barest minimum at every stage of their exploration programs. This is done on the background that the majority of easy to find gold (Au) deposits have been discovered, with hidden deposits as new targets (Butt and Zeegers, 1992, Butt et al., 2000, Cohen et al., 2010). Hence to define prospective targets during geochemical exploration requires the choice of reliable pathfinders for the target mineral at the initial stages of the exploration is critically important. For gold exploration especially in Ghana, arsenic (As) has been used traditionally as a pathfinder in areas where Au mineralization is hosted in sulphide minerals (Kesse, 1985, Nude et al., 2012). However, but for the uniqueness of different Au -deposit- types it may be very imperative to assess the effectiveness of other elements as possible pathfinders in exploration programs due to the complexities of the regolith and landscape evolutional histories. In this paper the distribution of Au and other elements in the regolith at the Tetteh gold prospect of the Chirano gold mine in south western Ghana were investigated to assess the implications on the element mobility and their concentrations in the surface layers in relation to Au. Multivariate statistical analysis was also performed on the suite of elements analysed by ICP-MS techniques to determine possible pathfinders for Au.

1.1   *Location and physiographical setting of the Tetteh prospect*

The Tetteh Prospect is located at Chirano gold mine in south-western Ghana (Fig. 1), some 100 km south-west of Kumasi. Access to the area from Accra the country's capital is by a sealed highway to Kumasi and then through a south-westerly linking highway towards Bibiani and onwards southerly to Sefwi-Bekwai. The final lap to the site is via a 13 km gravel road whose junction is about 9 km westwards from Sefwi-Bekwai.

The climatic condition in the area is tropical with minor seasonal temperature variations. Daytime temperatures are high throughout the year, reaching about $30^{o}C$ on most days. The area has two seasons, with dry seasons extending from November to February. Humid season extends from March to April, with high temperatures, high humidity and occassional moderate rain, followed by a wet season extending from May to October with peaks in May to June and September to October. The annual rainfal measured in the area is 1420 mm with highest average monthly rainfall occuring in June to be 222 mm. Average relative humidity ranges from a low of 64% in January to a high of 85% in July (Dickson and Benneh, 1995).
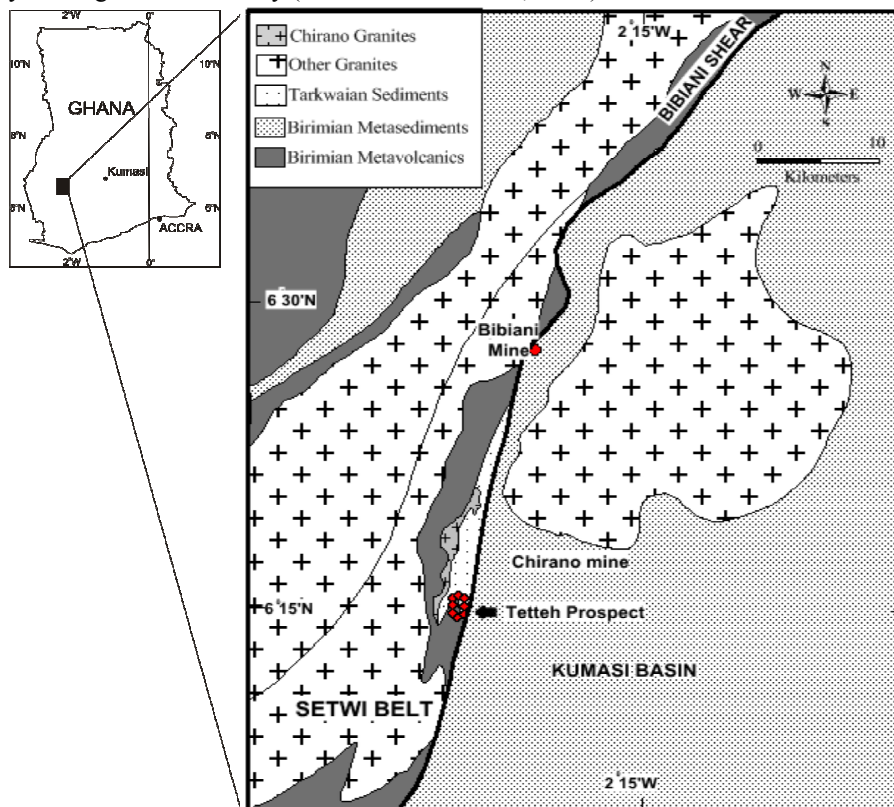

Figure 1. Geological map of parts of the Sefwi belt in Ghana showing Chirano mine and Tetteh prospect.

1.2   *Geomorphology*

Chirano mine lies within mountainous terrain with Tetteh prospect falling on a north-westerly oriented topographic high. Relief elevations generally range from 200 m to 450 m above sea level. The prospect is characterized by moderate to high elevation with dissections at places. This prospect records differential stripping of regolith and landscape lowering. Some parts of the area are covered by lateritic lags and secondary ferricrete and tend to mask the pre-existing regolith surfaces at the low-lying terrains whereas some areas are characterized by pre-existing weathering materials overlays with occasional minimum drift. Some of the laterite may have relationship to bedrock mineralisation whilst others are barren (e.g. Anand, 2001).

2.0   **Geology and Regolith**

Chirano project area lies within the Proterozoic Birimian of southwest Ghana, along a major structure separating the Sefwi belt to the west from the Kumasi basin to the east known as Bibiani shear zone (Fig. 1). The rocks consist dominantly of metavolcanic and metasedimentary rocks that have been intruded by granitoids comprising felsic and mafic intrusives. The two major types of granitoids that intruded the Birimian rocks and have been mapped in the area are characterized as follows (Kesse, 1985):

a) Basin granitoids locally referred to as Cape Coast type and occur as syn-orogenic foliated batholiths and occur chiefly in the sedimentary basins. They occur as per-aluminous and generally are granodioritic in composition;

b) Belt granitoids also known locally as Dixcove type; these are mostly late-orogenic unfoliated intrusions within the volcanic belts. They are generally metaluminous and commonly of tonalitic composition.

The sedimentary basins are typified by fine grained, deep marine sediments consisting of various lithofacies of schist, phyllite and tuffs etc. In the transition zone between the belt volcanic and basin sediments are chemical facies that consist of cherts, manganeferous and carbon-rich sediments, Fe-Ca-Mg carbonates, and sulphide mineral disseminations (Ntiamoah-Agyarkwa, 1991; Wright and Hastings, 1985). The rocks are metamorphosed but the metamorphism varies from moderate greenschist to high-grade amphibolites facies.

2.1 Concession geology

Tetteh Prospect is in Chirano mine located slightly west of the main Bibiani Shear of Sefwi Birimian belt (Fig. 1). The area is underlain by Birimian volcanic rocks and consists generally of basalts, andesite, rhyolite, tuffs, tuffaceous-phyllite and phyllite to the west and Tarkwaian formation composed of arkosic sandstones, sandstones and phyllites to the east. The Tarkwaian formation appears to be the most predominant rocks, but tuffs and phyllite are not uncommon. The igneous intrusive locally known as Chirano granites, tend to be closely associated with the Birimian volcanic units. This granitoids are hornblende and biotite bearing, mostly diorites, tonalities and granodiorites with associated quartz veins and dolerite dykes.

2.2 Regolith

Tetteh prospect is largely covered by laterite and talus deposits. These regolith materials are commonly found at the base of the ridges. In between the ridges and the valley- floors are exotic transported alluvium generally overlying extensive pre-existing surface (Fig. 2). Although the regolith at Tetteh prospect appears as *in situ* it however, contains sub-rounded and rounded clasts on close-up at places to suggest some degree of transportation. The lateritic residuum occurs as exposed and buried remnants of pisoliths that intermix with nodular duricrust at the eastern end of the prominent ridge. Talus, colluvium and alluvium on slopes of high reliefs, pediments and in valleys cover much of the weathered Birimian bedrock. The western part of the area is residual and has seen some mining operation. The classic ferruginous areas generally have a thin veneer of lateritic gravel and pisoliths or laterite cap outcropping at the surface whilst the true relict areas are uncommon. Areas mapped as relict usually have a composite profile where the talus deposits overlie the pre-existing preserved surfaces. All these regolith-landform modifications influence the gold geochemical dispersions.
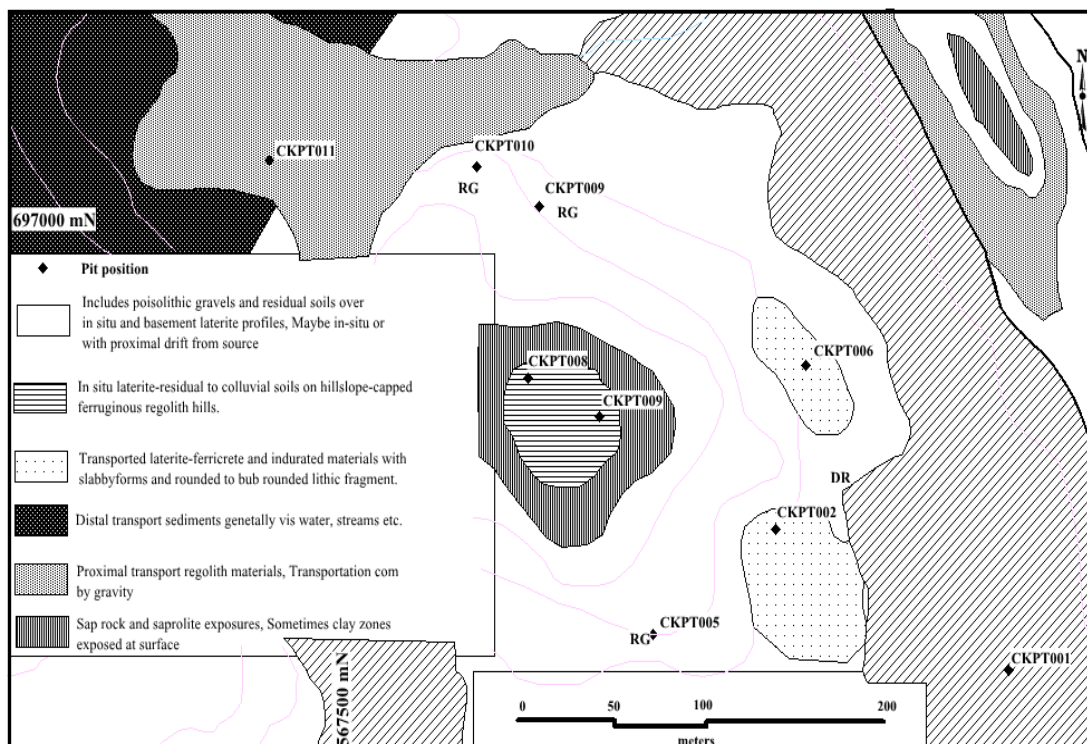

Figure 2. Regolith sketch map of Tetteh gold prospect showing pit positions.

3.0 Methodology

3.1 Regolith profile sampling

Surface and sub-surface regolith materials of amorphous soils, nodules and pisoliths, lateritic residuum and talus, exotic transported sediments and saprolite were taken as samples from 1.0 m x 1.0 m dugout pits. For health and safety purposes the pits were excavated manually up to 3.0 m depth or until bedrock was reached. Two types of

samples were taken from these pits for XRF and ICP.MS analysis for major and trace elements analysis. The XRF sample thickness were controlled by the regolith horizon thickness of which three (3) to four (4) samples were collected from a pit. Unlike the XRF samples, the ICP-MS samples were meticulously collected at approximately 10 cm interval across the regolith profile.

Regolith mapping was conducted alongside the pitting and sampling exercise. This was done by defining the different surfaces using a classification scheme acronym 'RED' (Hockings et al., 2007, Anand and Paine, 2002; Anand et al., 1993) modified to "FRED" to see the impact of the ferruginous layers to metals transport. The modified classification system categorizes land surfaces into the following categories ferruginous regolith regime (F); relict regolith regime (R); erosional regolith regime (E); and depositional regolith regime (D). The field regolith mapping is similar to traditional geological mapping, however in this, ground truth information about various regolith types and landform attributes are gathered. Method used in gathering the field information follows that of Arhin and Nude (2009). The regolith materials of same characteristics and similar weathering histories were grouped together as a single classifying unit to define the different regolith regimes. The regolith map (Fig. 2) of Tetteh prospect was generated by integrating information from the landscape and ground truth mapping coupled with the data from the dugout pits.

A total of 200 regolith samples were analysed for gold and multi-elements along with five (5) certified reference materials (CRM) of known gold concentrations and nine (9) field duplicate analyses. In this investigation a low detection limit of 0.005 ppm was used. Two low-grade CRM classes of 0.205 ppm and 0.416 ppm Au were chosen for the study and their selection were based on similarities in gold expressions in surface samples obtained by the previous explorers.

3.2   *Multivariate statistical analysis*

To identify the possible associated elements that could be used as a pathfinder instead of using the traditional chalcophile elements; multivariate statistical analysis was performed on over 50 elements analysed using ICP-MS technique. Statistical associations resulting from multivariate datasets are some of the methods used for determining key pathfinders for target economic minerals. The application of multivariate statistical techniques to multivariate geochemical datasets has proven to be effective at establishing such relationships that are useful exploration programs (Nude et al., 2012). Statistical relationships/associations do not establish cause-and-effect relationships, but provide clues from which such relationships can be deduced or ascertained. These methods have gained publicity in the Earth Sciences as effective tools for unravelling field associations (Howarth and Govett, 1983; Davis, 1987; Güler et al., 2002; Güler and Thyne, 2004; Cloutier et al., 2008, Nude et al., 2011).

In this study, factor and cluster analyses were jointly applied on the multi-element soil geochemical dataset to establish element associations with Au and possible pathfinder elements which can be used in the exploration programs at the Tetteh prospect and the Chirano mine and similar terrains in Ghana. The interpretation of the results of the multivariate statistical analyses is aided by bivariate plots of the data of the geochemical parameters.

3.3   *Quality assurance and control (QA/QC) of analysed samples*

The objective of performing QA/QC analysis on the quality control samples was to evaluate the quality of the data. In this study the quality control (QC) samples used to estimate accuracy, precision and sources of sampling and laboratory analytical errors for Au were certified reference materials (CRM), field duplicates and blank samples. The following procedures were carried out in evaluating the quality of the data: The original measured analytical results of gold (Au) were plotted:

   a. Against standard certified reference materials (CRM) of known Au concentrations (Figs. 3a & 3b) and
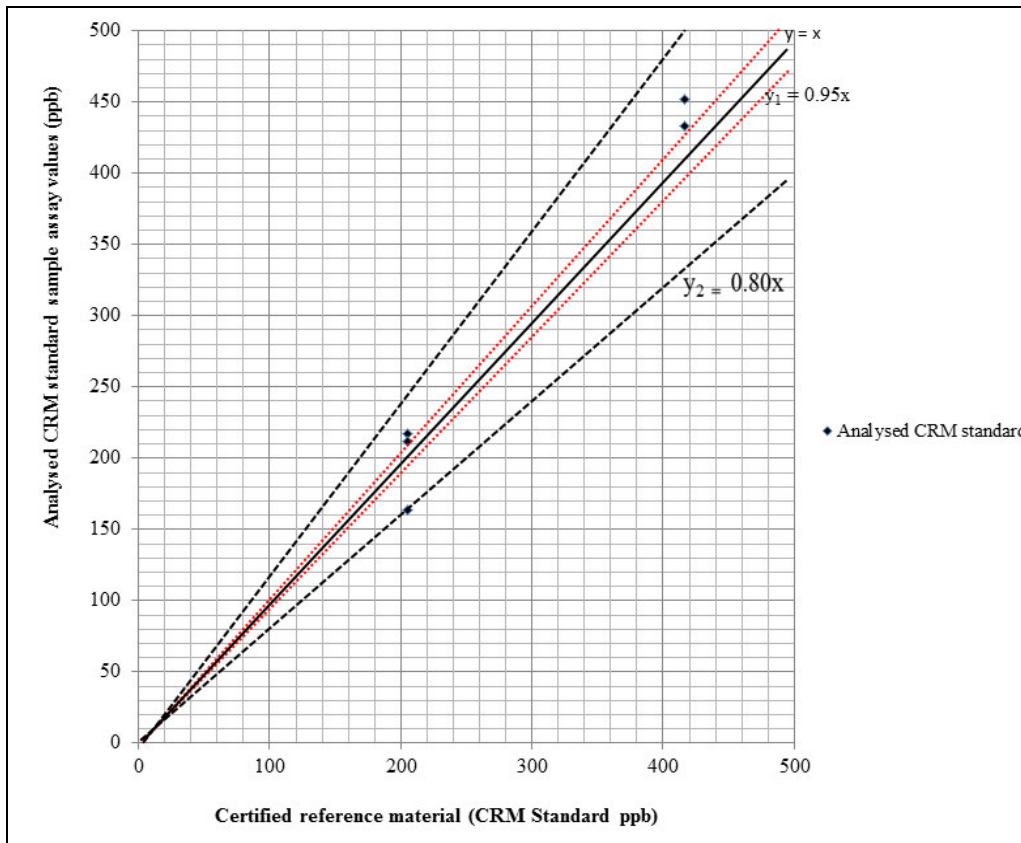   b. Against analytical Au results obtained from the field duplicate samples (Fig. 4).

Figure 3a.   Plot of CRM of known Au concentrations vs. Laboratory measured Au in CRM samples to determine accuracy of the analytical data.
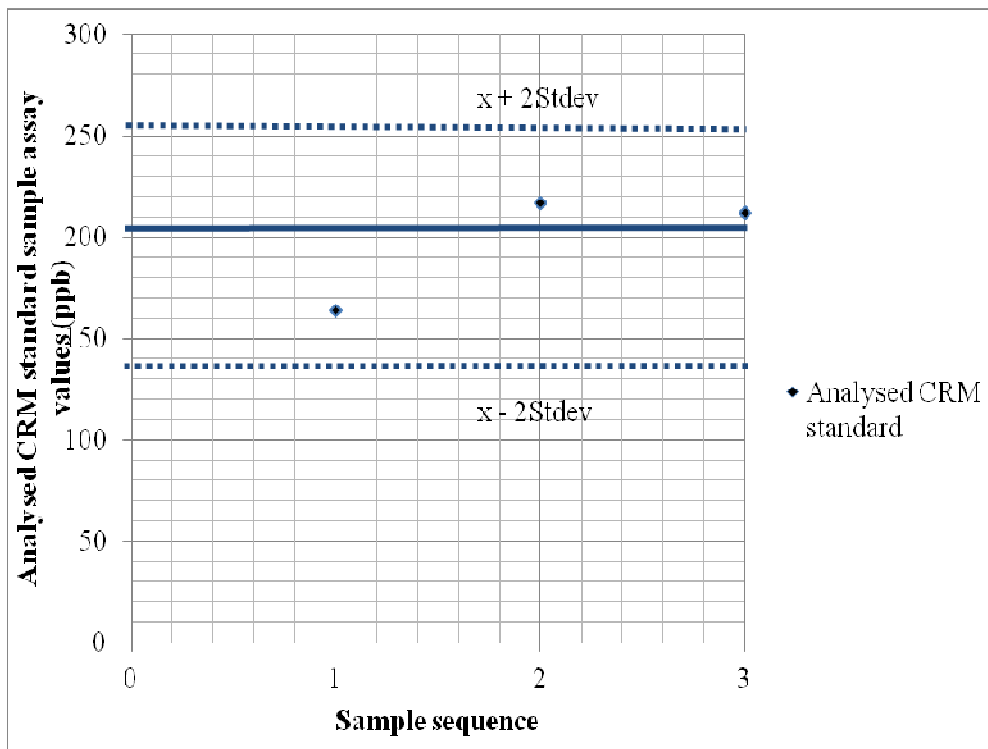

Figure 3b. Plot of standard CRM vs. Analysed Au to check Analytical Accuracy within x + 2σ acceptance limit for Greenfield exploration samples.
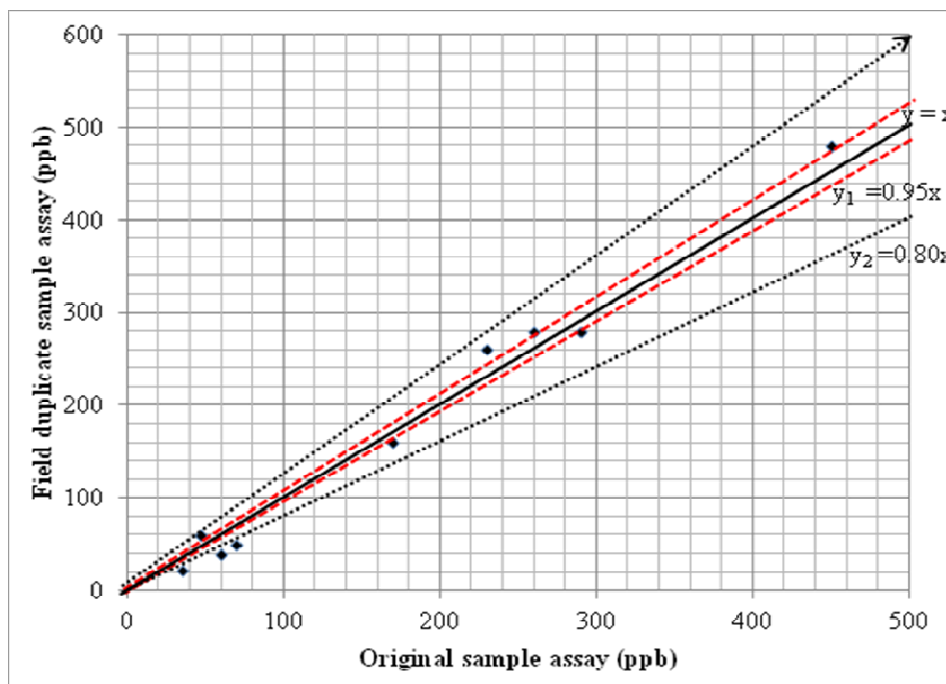
Figure 4. Plot of Au results of the original samples vs. field duplicate samples to determine the precision of the analytical data. Solid red lines mark the ideal Y=X lines. The larger the scatter of the data from it, the poorer the precisions.

The quality assurance samples showed low accuracy (Figs. 3a & 3b) and good precision (Fig. 4) in about 80% for the analytical results. However, the uncertainties in precision rather increased in duplicate samples collected from low concentration areas (Fig. 4). Similarly in Figure 3 A, one of the measured values of the 0.405 ppm Au CRM appeared to be way of the acceptance or true value of certified value. This needs to be noted because the 'true' concentration is never known; an 'accepted value' together with error limits accompanies most standards. The stage of exploration at Tetteh prospect requires samples to be reproducible and with about 80% precision as shown in Figure 4, it is suggestive that the analytical data is suitable and can be used to delineate new geochemical targets. With the acceptance of the quality of the analytical data, the multivariate statistics then followed.

R-mode hierarchical cluster analysis (HCA) and factor analysis were then applied to the dataset of 45 parameters from 197 sampling locations in the study area. In the factor analysis, 'principal components' was chosen as an extraction method and the Kaiser (1960) criterion was initially selected to reduce the number of principal components to size. Varimax rotation (Kaiser, 1960) was applied to the resulting factor matrix to maximize the differentiation of the principal components. Varimax rotation is a process of applying an orthogonal matrix to the factor matrix with the sole objective of enhancing the differentiation of the factor model. In factor analysis, it is practically possible to obtain as many factors or principal components as there are parameters in the dataset. Factor models generated in such a fashion do not necessarily address the objectives of the analysis as a dimension reduction method. This is the reason that the use of the Kaiser criterion is particularly important. The process ensures that in the final factor model, only factors or principal components with eigenvalues of at least 1 are included. The practical sense of this is that a factor representing a unique source of variation in the dataset should be able to account for the variation of at least one variable or parameter in the dataset. In this current research, the use of the Kaiser criterion resulted in too many factors, some of which did not particularly represent unique sources of variation and were thus difficult to interpret. Therefore the maximum factor criterion was used. The application of this procedure requires the determination of a priori, the maximum number of factors expected, on the basis of the underlying processes. Irrespective of the criterion used to ward off non-unique factors in the factor analysis, it is often critically important to ensure that the factors extracted account for a significant part of the total variance of the complete factor model. This ensures that the very important and key underlying processes responsible for the variation in the dataset are explained in the factor model.

Square Euclidean distances were used to measure similarities/dissimilarities in the dataset. The distance measure ensures that parameters whose variation in the factor appears to be similar are associated with the lowest Euclidean distances, whereas the very dissimilar parameters have large or high square Euclidean distances. In both cases of factor analysis and HCA, optimal results require normal distribution and stationarity of the dataset. In order to achieve both criteria, the raw data, which are largely skewed, were log-transformed to approach the

requirements of normal distribution. The log-transformed datasets were in turn standardized to their respective z-scores, which ensured that values of the parameters ranged between -3 and +3. The Ward's agglomeration scheme was used to cluster together initial clusters in the HCA procedure. In the literature, the combination of square Euclidean distances and Ward's agglomeration scheme has been noted to result in optimal outputs (Güler et al. 2002; Güler and Thyne, 2004). The dendrogram is the diagrammatic result of the HCA, and was produced in this study to link parameters and initial clusters. The determination of the number of clusters resulting from the HCA is a semi-objective procedure as there are no strict rules governing the process. Traditionally, a phenon line (Davis, 1987) is drawn across the dendrogram to sort out distinct parameter associations. The position of the phenon line is not determined by any fixed rules and can be moved up or down the dendrogram to result in less or more clusters/associations of the parameters. It is this aspect of the HCA process that makes it a semi-objective methodology. Often times, the choice of the position of the phenon line is influenced by the interpretation of the key underlying processes or factors controlling the variation in the data.

4.0   Results and Discussions
4.1   Trace elements and Au mobility and distributions in the regolith
Plots showing the distribution of Au and selected trace elements in regolith materials from Tetteh prospect arranged in order of regolith distribution and the correlation diagrams of Au with some trace elements are presented in Figures 5 – 10.
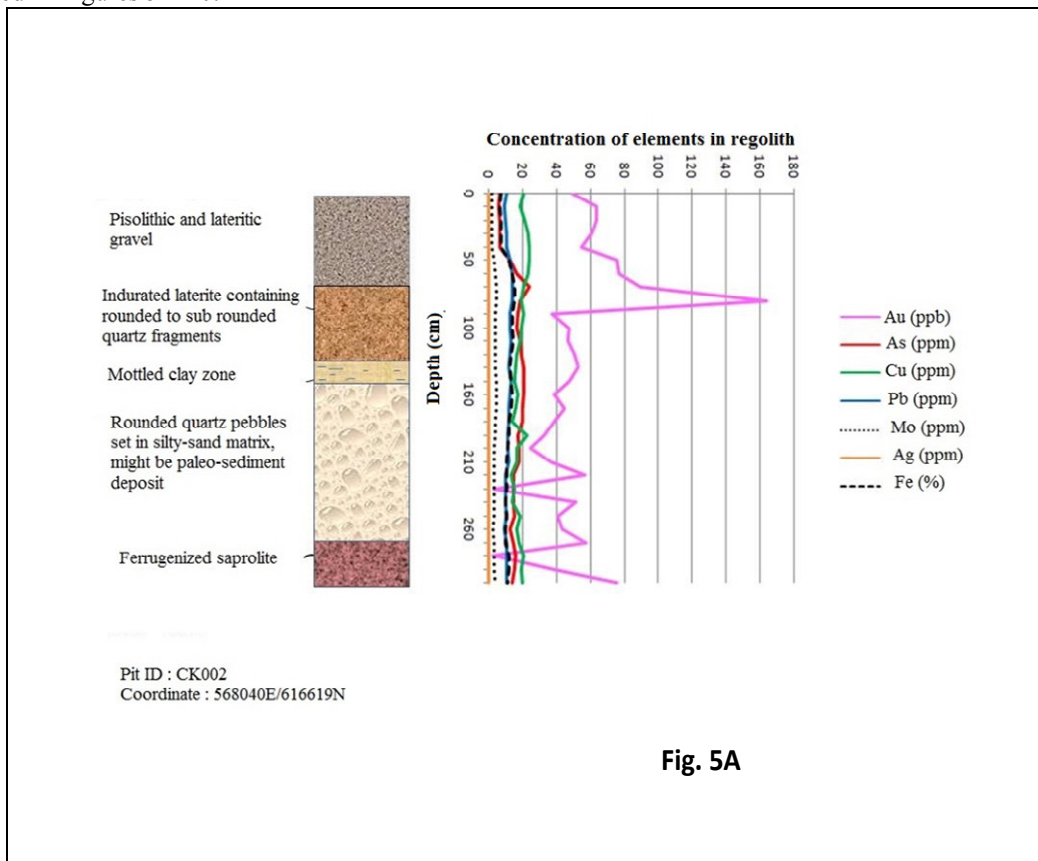

Figure 5a. Distribution of Au and selected trace elements in regolith materials in pit CK002.
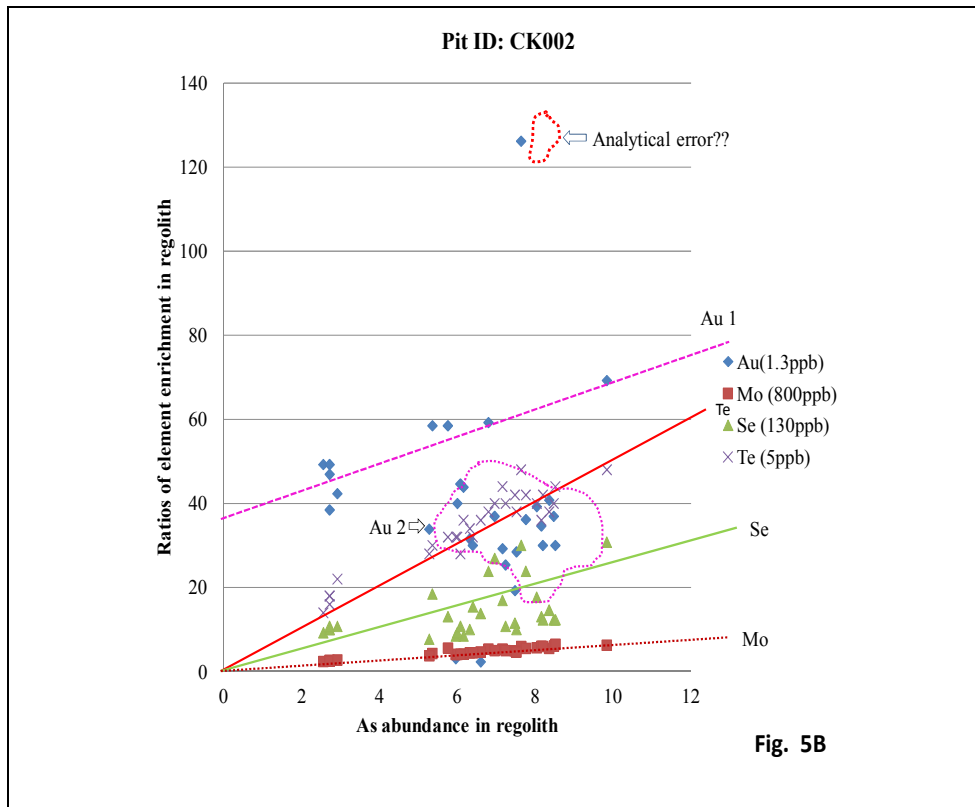
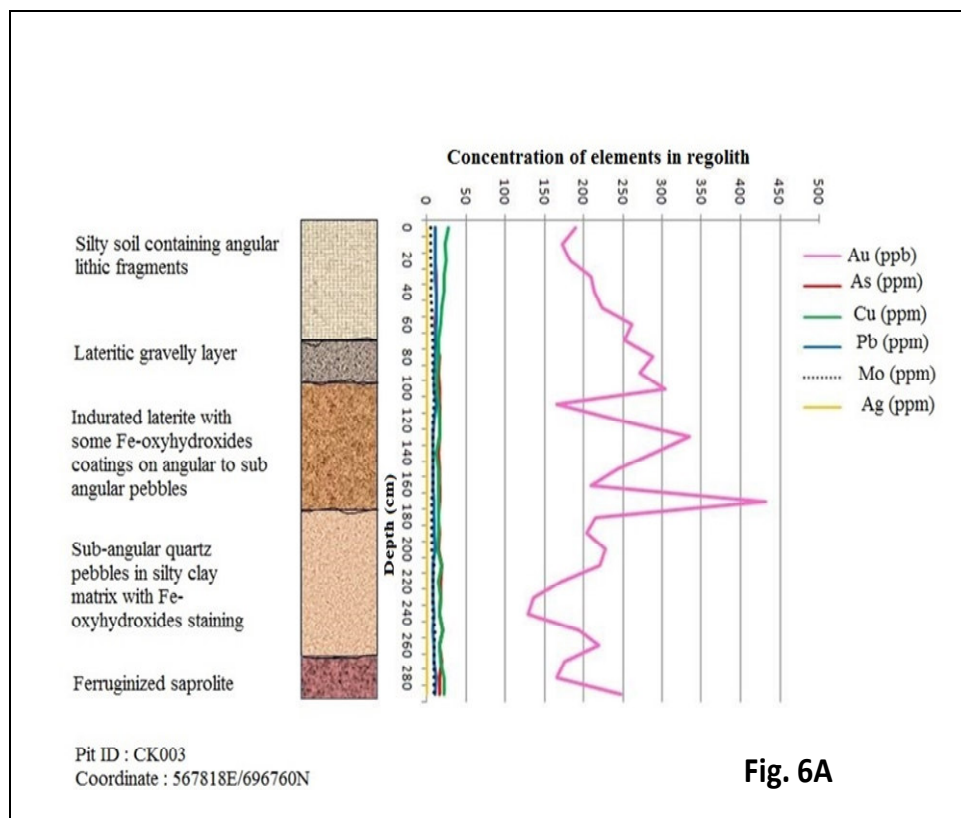Figure 5b. Correlation of Au with some trace elements in pit CK002.

Figure 6a. Distribution of Au and selected trace elements in regolith materials in pit CK003.

Figure 6b. Correlation of Au with some trace elements in pit CK003.

Figure 7a. Distribution of Au and selected trace elements in regolith materials in pit CK004.

Figure 7b. Correlation of Au with selected trace elements in pit CK004.

Figure 8a. Distribution of Au and selected trace elements in regolith materials in pit CK005.
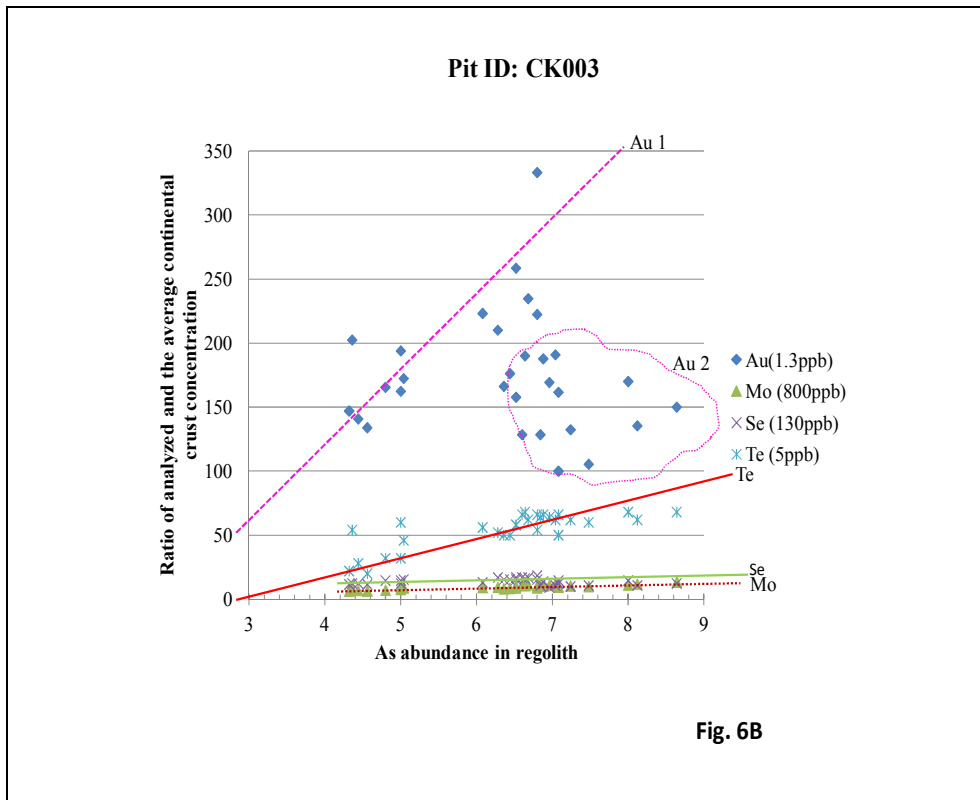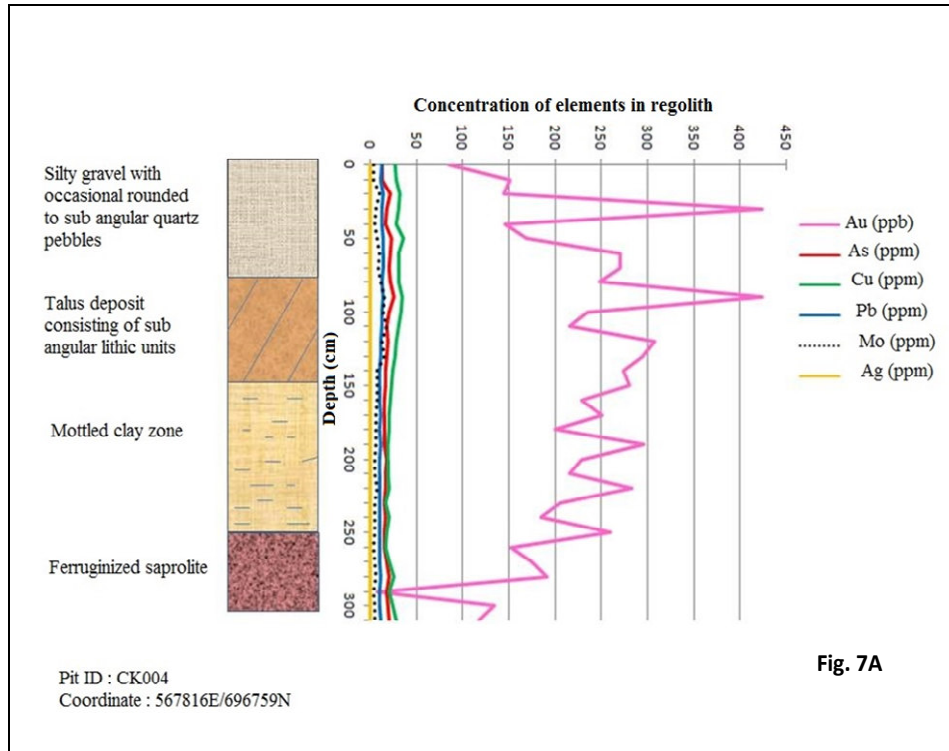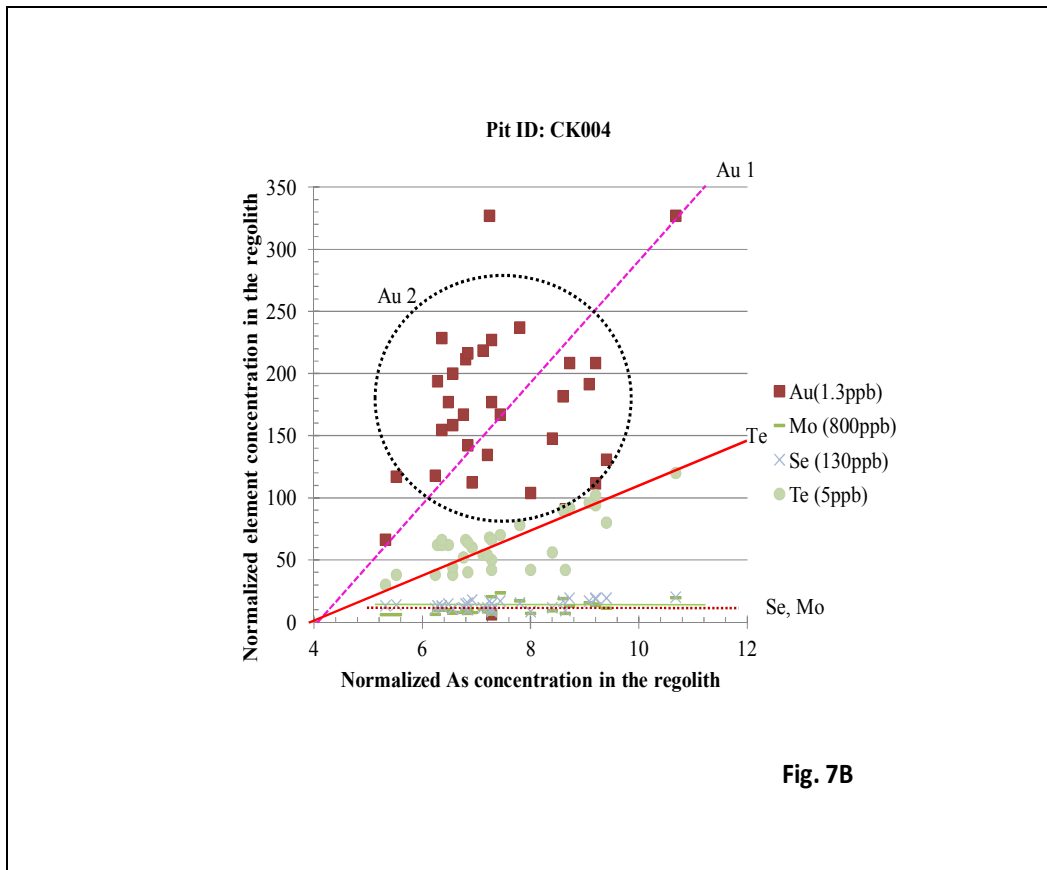
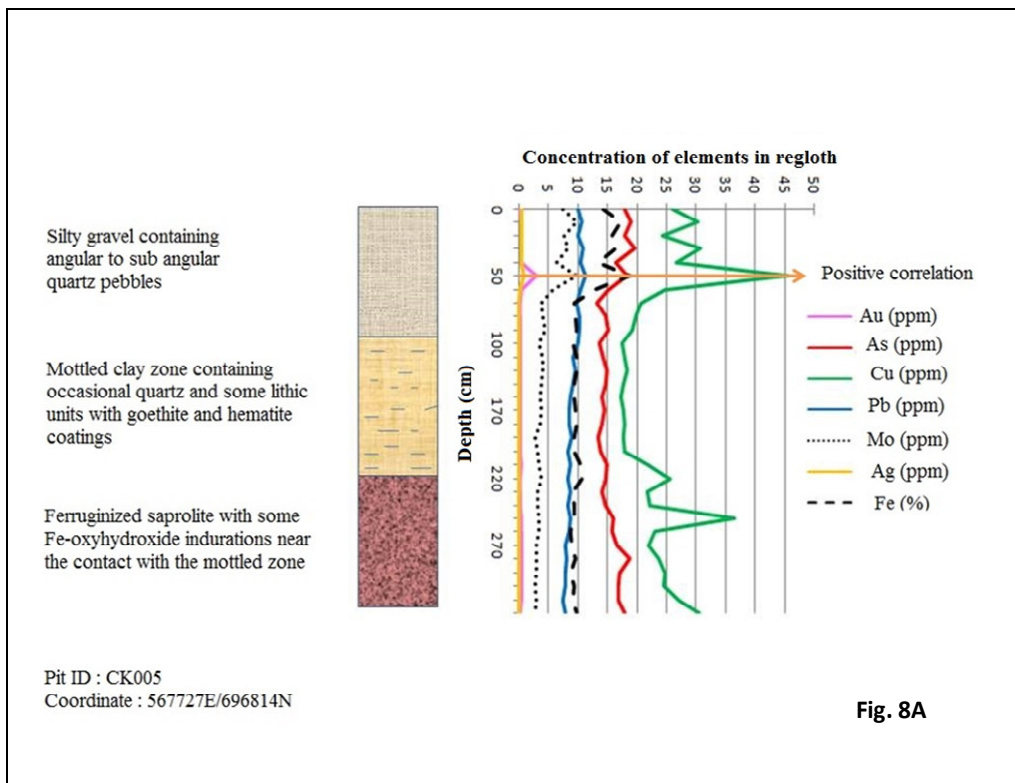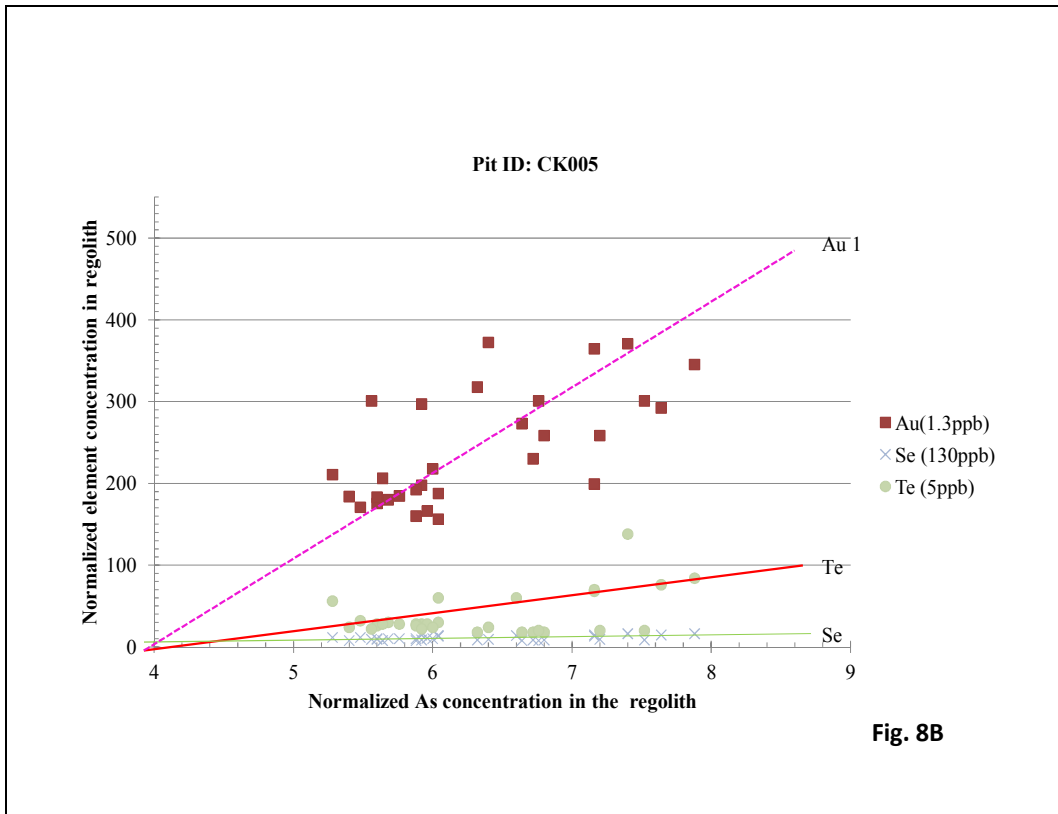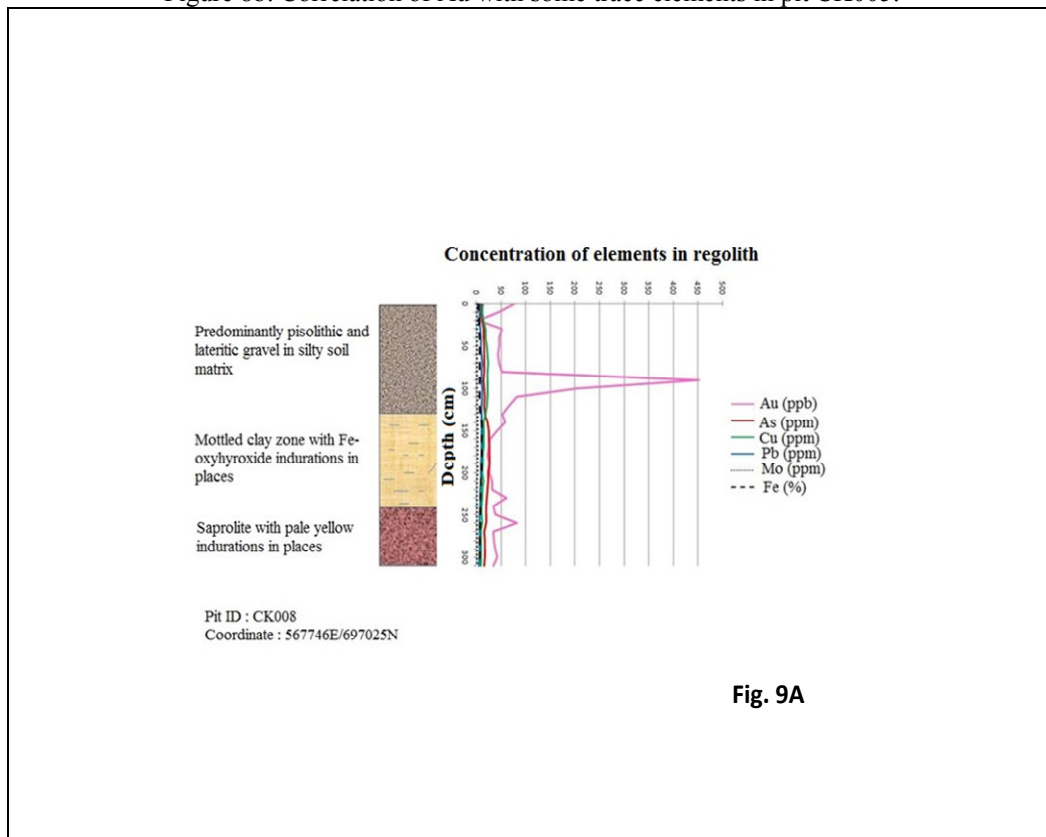Figure 8b. Correlation of Au with some trace elements in pit CK005.

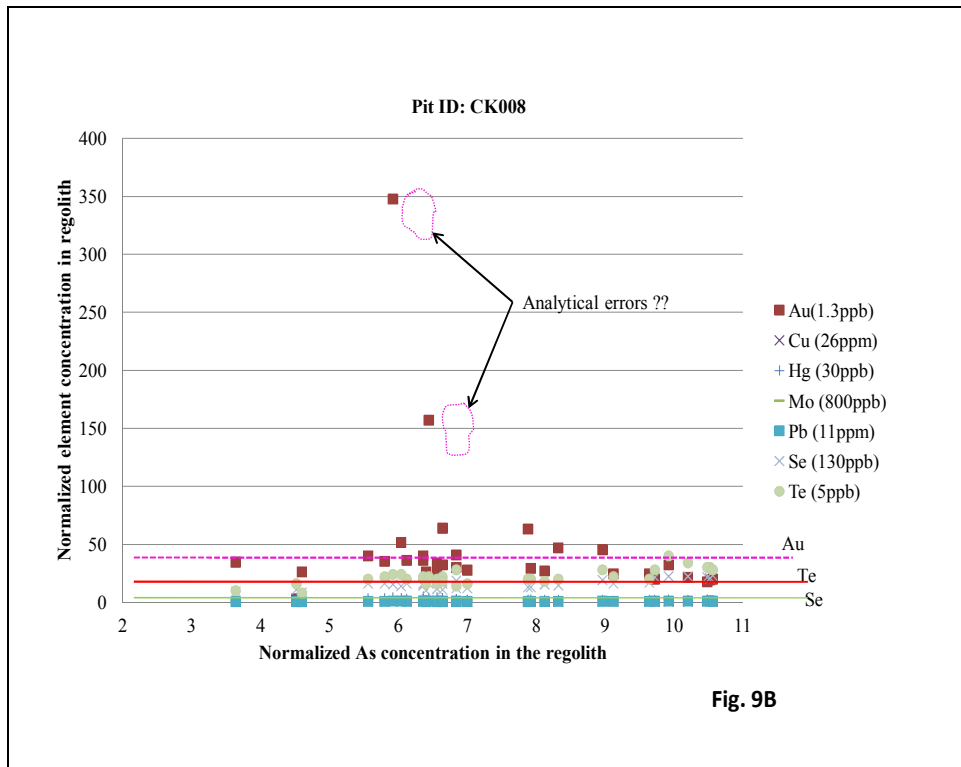Figure 9a. Distribution of Au and selected trace elements in regolith materials in pit CK008.

Figure 9b. Correlation of Au with some trace elements in pit CK008.
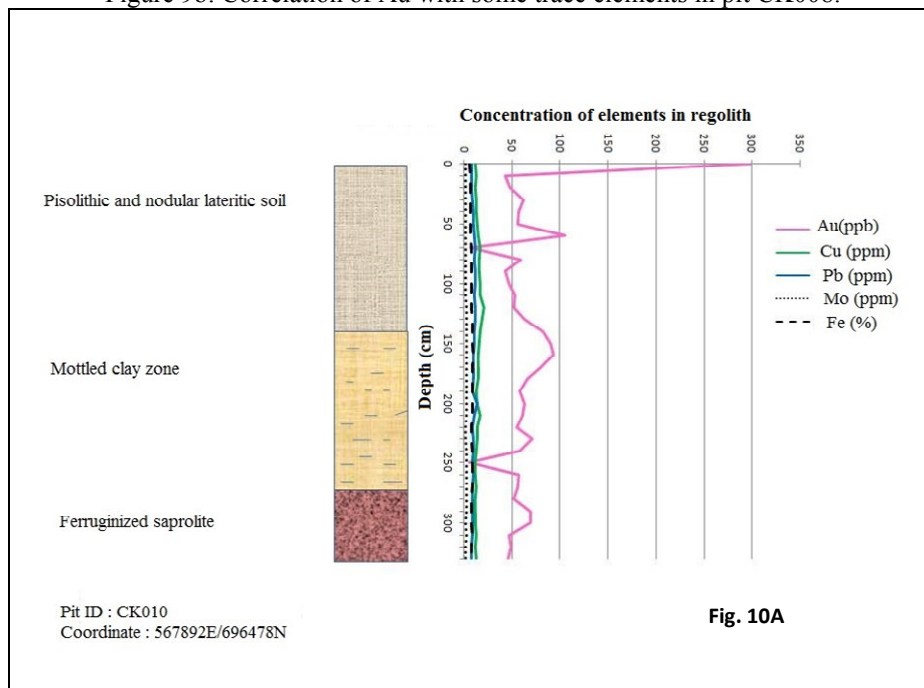

Figure 10a. Distribution of Au and selected trace elements in regolith materials in pit CK010.
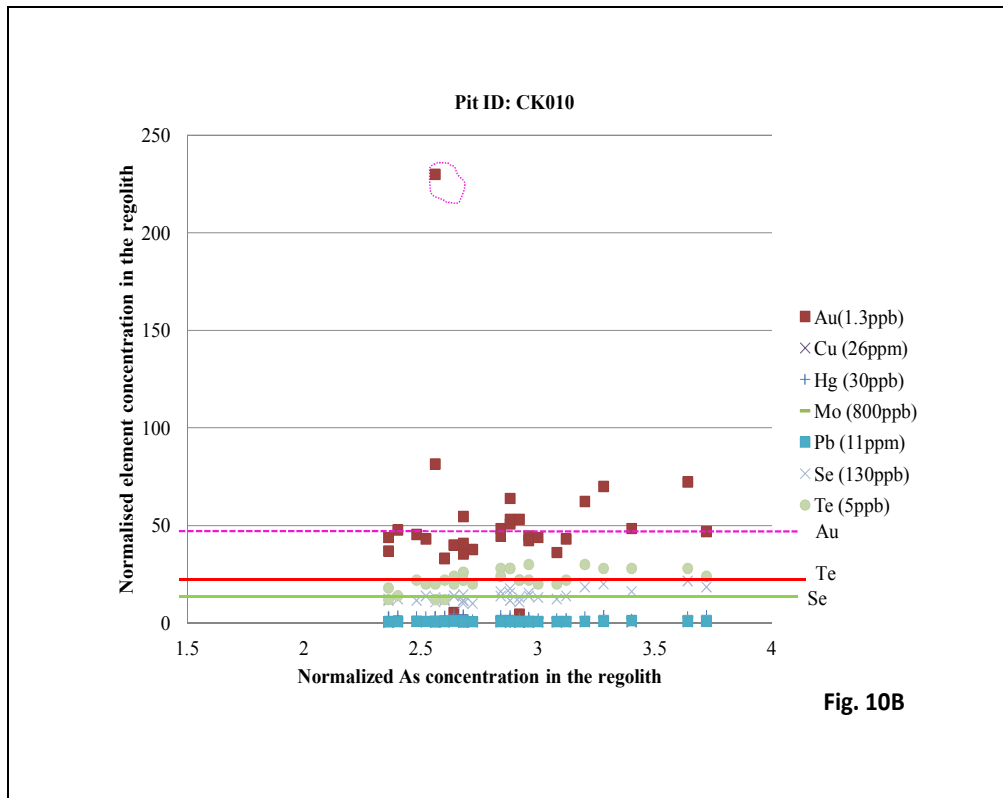
Figure 10b. Correlation diagrams of Au with some trace elements in pit CK010.

From Figure 5 (a and b) it appears the origin of the recorded gold anomalies from Pit CK002 possibly may be from two different sources: Au 1 correlates positively with Te, Se, Mo and As whereas Au 2 seems not to have any correlation with any of the selected trace elements (Fig. 5b). The correlation between Au 1 and Te, As, Se, Mo (Fig. 5b) appears not to be strong to be used as pathfinder elements but is significant. Au 1 tends to have residual Au characteristics while Au 2 may be considered to have relationship to transported overburden. Comparing the characteristics of the trace elements in this area, it is apparent that the Au distribution has been affected the regolith evolution resulting in the erratic Au signatures especially in the paleo-sediment deposit (Fig. 5a). The upper parts of the pit is enriched in Au probably from transported source demonstrated by the presence of rounded to sub rounded quartz fragments contained in the indurated laterite (Fig. 5a). It is therefore evident from the regolith material architecture mapped in CK002 that the residual Au-bearing overburden has been eroded and has been replaced by lateritized and exotic transported overburden. From Figure 5a, Au-grade increases from the topsoil to the upper part of the indurated laterite with Au assays ranging from 50-164 ppb. These assays then drop to about 40 ppb at the lower section of the indurated laterite through to the saprolite. Deductions from Figure 5 suggest possible Au enrichment by both chemical and mechanical processes. The peak point of the Au-enrichment occurs at the interface of the pisolithic soil and the indurated laterite. The Au enhancement may be due to the hydromorphic, lateral and downward mechanical accumulation as well as chemical re-precipitation of Au in the ferruginous zone. However, the relative low Au concentrations registered in the pisolith-rich samples may be attributed to the coatings of Au-grain during lateritization or increased pisoliths contents in surface layers, which dilutes and reduces the fine fraction portions.

Similarly, pit CK003 has matching characteristics to CK002 of which the significant assays seem to relate to different Au-sources or the Au signatures are modified by the regolith types. Shown in Figure 6b is an *in situ* Au 1 anomaly and transported Au 2 signatures occurring in the same pit when compared with the regolith material-types seen in Figure 6a. Integrating with the trace elements with respect to the regolith it is only Te that correlated positively with Au 1. Au 2 however has no correlation with the trace elements. CK003 is located in a ferruginous/relict regime (Fig. 3b), however, based on its topographical location it should exhibit residual Au anomaly. Figure 6a portrays significant Au enrichment but the Au enrichment in the entire regolith profile tends not to correlate with the trace elements (Fig. 6a) except Te (Fig. 6b). The QA/QC analysis performed on the standard and duplicate samples are good and do not suggest major uncertainties in the analytical data. The acceptance of the quality of the analytical data does not prohibit resampling unsure profiles. Like CK002, trace elements migrations appear to be from a combination of hydromorphic and mechanical processes or physical transport at near surface environment. Thus, leaching of trace elements from the upper part of the ferruginized zones coupled with the re-distribution and re-concentration of trace elements in the water table zone in the sub-

surface regolith can contribute to the coating of Au grains by Fe-oxyhydroxide and clay minerals which can affect the homogenization of the Au-grades. Perhaps, the disorderly distribution of the regolith materials and chemical interactions of Au and some other elements either dilutes or enhances the Au expressions. This probably resulted in the spiky Au expression patterns in a supposed relict regolith regime (Figure 6a) which is generally expected to have homogenized Au signatures relating to underlying mineralisation. Although there is Au-enrichment from the topsoil to the ferruginized saprolite; the enrichment is much pronounced near the interface of the indurated laterite and the silty clay zone where there is predominance of Fe-oxyhydroxide staining. It is probable that the Au enhancement in this section of the regolith profile is as a result of downward mechanical accumulation of Au facilitated by leaching and pedogenic processes +/- hydromorphic dispersion.

Pit CK004 has similar characteristics like CK003 in terms of regolith environment and correlation patterns of Au with trace elements (Fig. 7a and b. There is some correlation of Au with Te but it is generally weak. Mo and Se tend not to change with analysed Au. The Au-grades in this pit do not seem to be homogenized and that is evident by the wavy Au geochemical pattern (Fig. 7a). This probably may signify transported anomaly or analytical errors. However, this anomaly need not be treated as spurious because of the persistency of > 150 ppb Au concentrations from the topsoil to the upper part of the saprolite; these are indication of mineralisation nearby. It is possible that the mineralised source material may not be far as the peak anomalies were obtained near or from the talus deposit (Fig. 7a). As seen in Figure 7 (a and b) the dispersion of Au may be due to mechanical accumulation and hydromorphic dispersion mechanisms. It is likely that the Au anomaly in the topsoil is produced from soil creep (from where the smaller Au particles have been preferentially eroded).

Pit CK005 is located in a relict regime in which positive correlation of Au with the selected trace elements in the upper soils (Fig. 8b). The positive correlations of Au with the other elements do not extend into the mottled zone. Au and the other trace elements concentrations except As and Cu drop significantly to up to detection limits in the mottled clay zone. It is likely that the Au anomaly in the topsoil may be due to pedogenesis and soil creep probably from a nearby anomalous hill. It is apparent considering the migration and geochemical expression patterns of the analysed trace elements that the Au anomaly in the area is unrelated to underlying mineralization and hence may represent transported anomaly. Conversely, As and Cu have residual characteristics and probably migrated to the upper part of the regolith and got enriched through hydromorphic dispersion processes. Additionally, the trace elements dispersion in this regolith environment is via mechanical and chemical dispersions. However, the characteristics of the regolith materials shown in Figure 8b, suggest Au-anomaly source not to be far because of the angularity of quartz clasts depicting *in situ* and semi residual regime.

Pit CK008 is situated on hilltop, characterised by ferruginized regolith materials (Fig. 4). The plot of normalised Au against the analysed Au showed Au enrichment in the area (Fig. 9b). The homogenised Au grade tends to be about 50 ppb with a single point anomaly of 450 ppb. The contrast between the minimum and maximum analysed Au appeared too large and cannot be attributed to mechanical accumulation or chemical dispersion. Besides, the Au anomaly in the saprolite was generally below detection limit of 5 ppb (Fig. 9a). As a consequence the anomaly cannot be attributed to chemical re-precipitation of Au by the reduction of complexes below water table. It is most likely that the 450 ppb Au recorded in the lateritic gravel sample is from a single detrital Au or perhaps a possible analytical error.

Unlike the others, pit CK010 has high concentration Au of about 300 ppb at surface and drops to about 50 ppb Au and then increase to 100 ppb in the pisolithic soil (Fig. 10a). There is a gradual increase in Au concentration between the pisoliths and the mottled zone but peaks again up to about 90 ppb near the interface between these two regolith units. This pit is sited in a relict regime which is supposed to relate to the underlying mineralization. The distribution of Au and selected trace elements in regolith materials and the correlation chart appear not to define any correlation to aid in guiding the geochemical exploration. The high Au result of 300 ppb in topsoil likewise may be due mostly to surface soil creep re-distributing the fine particle Au from an anomalous source or could be an analytical error. Furthermore, a threshold Au value of 60 ppb may classify this area to have insignificant Au anomaly in the saprolite or the bedrock, hence no bedrock Au mineralisation in the area (Fig. 10b).

4.2   *Nature of elements associations with Au in regolith*

Table 1 is the factor model resulting from the R-mode factor analysis. Arsenic (As) recorded a low communality and is therefore obviously weakly loaded under each of the resulting four factors. Naturally, in factor analysis, parameters with low communalities are dropped so that they do not cloud the interpretation of the factor model. However, in this study, As was maintained due to its traditional role as a pathfinder element in most gold exploration programs in Ghana. The idea was to determine its relationship with the target mineral (Au) and other geochemical parameters. The first factor accounts for almost half of the total variance in the geochemical dataset. The implication is that the major processes of interest in the geochemistry are captured in factor 1, which has high positive loadings for Ag, Al, Au, Be, Bi, Co, Cr, Cu, Fe, Ge, Hg, In, Li, Mn, Mo, Ni, P, Pb, S, Sb, Sc, Sn, Te, Th, Ti, U, V, Zn, and Zr. Although As correlates weakly with all the factors, it records the highest loading under factor 1, suggesting that factor represents the major processes responsible for enriching Au and As in the

area. The results of the analysis suggest that any of the parameters listed above could have performed better as pathfinders in gold exploration in the study area than As which has traditionally been used.

The second factor has high positive loadings for Ba, Cs, K, Li, Mg, Mn, Rb, Sc, Sr, and Tl, and accounts for about 18% of the total variance in the geochemical dataset. This factor may be related to weathering of the underlying lithologies. Factors 3 and 4 are similar in terms of the percentage of total variance explained and respectively account for 8.5% and 7.2% of the total variance in the dataset. In factor 3 Au loads negatively at -0.504, and appears to contrast that of As which has its second highest loading under this factor. Factor 3 also loads positively for La and negatively for Mg, Nb, and U. These analyses suggest that two processes are probably responsible for the enrichment of Au in the soils of the study area. This observation supports Au1 and Au2 anomalies revealed in some pits when normalised-As was plotted against the other trace elements to understand their behaviour to Au concentration patterns in the regolith profiles. The first and most important process is captured by factor 1. The loadings under factor 3 imply that the second process controlling Au enrichment in the area, also leads to a reduction in As concentrations. However, this appears to be a minor process or set of processes and could be regarded as insignificant when compared with factor 1. The final factor has high negative correlations for Ce, La, and Y, and high positive correlations with S and Se.

Table 1: A factor model from the R-mode factor analysis

6	Component			
	1	2	3	4
Ag	**0.875**	0.05	-0.212	0.061
Al	**0.941**	0.122	0.032	0.026
As	0.381	-0.331	0.368	0.221
Au	**0.54**	-0.372	**-0.504**	-0.149
Ba	0.451	**0.718**	0.16	0.133
Be	**0.826**	0.1	-0.164	-0.263
Bi	**0.89**	-0.005	0.315	0.096
Ce	0.467	-0.105	-0.074	**-0.56**
Co	**0.868**	0.287	-0.189	-0.083
Cr	**0.926**	-0.214	0.125	-0.077
Cs	0.129	**0.843**	0.351	0.042
Cu	**0.707**	0.117	-0.21	-0.175
Fe	**0.879**	-0.327	0.228	0.184
Ge	**0.609**	-0.356	-0.056	0.234
Hf	0.75	-0.476	0.268	-0.065
Hg	**0.757**	0.236	-0.346	0.195
In	**0.923**	-0.293	0.053	0.019
K	0.478	**0.724**	0.245	0.194
La	-0.127	0.408	**0.664**	**-0.495**
Li	**0.688**	**0.588**	-0.084	-0.199
Mg	0.457	**0.559**	**-0.603**	-0.064
Mn	**0.644**	**0.571**	-0.164	-0.116
Mo	**0.934**	-0.248	0.021	0.087
Nb	-0.078	0.397	**-0.718**	0.031
Ni	**0.855**	0.099	-0.317	-0.304
P	**0.803**	0.407	-0.103	-0.089
Pb	**0.714**	0.356	0.228	0.112
Rb	0.164	**0.884**	0.356	0.164
S	**0.585**	0.034	0.123	**0.606**
Sb	**0.68**	-0.372	0.365	0.374
Sc	**0.654**	**-0.594**	-0.274	-0.178
Se	0.225	0.209	0.084	**0.679**
Sn	**0.82**	-0.258	-0.063	-0.388
Sr	0.31	**0.741**	-0.253	0.153
Te	**0.896**	-0.211	0.13	0.254
Th	**0.913**	-0.26	0.084	-0.201
Ti	**0.819**	-0.412	0.235	-0.075
Tl	0.303	**0.812**	0.147	-0.045
U	**0.516**	-0.06	**-0.51**	0.475
V	**0.925**	-0.299	0.108	-0.053
Y	0.291	0.263	0.442	**-0.667**
Zn	**0.814**	0.32	0.027	-0.058
Zr	**0.832**	-0.357	0.142	0.03

Figure 11 is the dendrogram from the R-mode HCA. With the phenon line drawn across the dendrogram at a

linkage distance of 15, two clearly sorted clusters are obvious in Figure 11. These clearly mimic the results of the factor analysis as presented in Table 1. Cluster (Group) 1 is similar to factor 1 in the factor analysis.
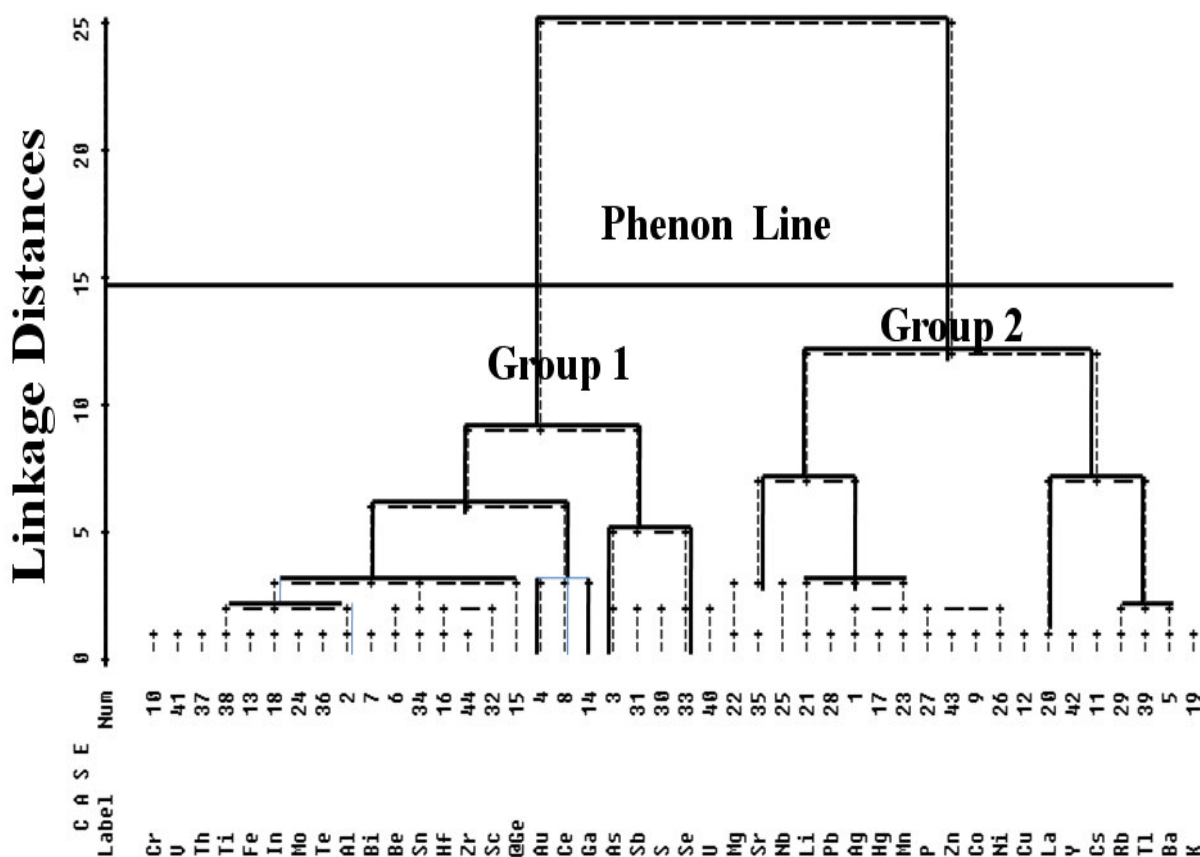

Fig. 11 A dendrogram resulting from the R-mode HCA.

5.0   SUMMARY AND CONCLUSION

Soil geochemistry results obtained from the current study and the previously obtained gold results by Chirano mine exploration team showed a number of sites with elevated gold values. When the Au-chalcophile elements geochemical results were considered in the context of the regolith-landforms, it was seen that surface dispersion processes have displaced some soil geochemical 'anomalies' relative to mineralised bedrock. The geochemical signature contrasts of trace elements including Au in the superficial regolith at or near surfaces are found to be unrelated to the underlying mineralisation. This probably explains the implications of under-appreciation of regolith evolution to geochemical gold exploration as demonstrated by the test drill of the elevated 'false- robust' soil Au geochemical anomalies at certain sites that detected no bedrock mineralisation. The regolith studies shows much of Tetteh prospect is overlain by depositional and ferruginized landforms and those terrains are expressed normally with anomalies unrelated to the underlying mineralisation. Particularly, in this area, base of hill soil geochemical anomalies were mechanically dispersed from nearby hills and were re-weathered, re-distributed and re-concentrated to show occasional discontinuous spot high geochemical values. The regolith at Tetteh prospect has evolved over the years and these changes in regolith profiles have implications for geochemical gold exploration.

The study reveals the pre-existing preserved surfaces to be masked predominantly by transported materials consisting of ferruginized and exotic sediments. Such regolith materials enhance or dilute geochemical expressions in the surficial regolith materials of which production of 'false anomalies' are likely to be followed up. Also within the surficial regolith and especially in the Fe-oxyhydroxide rich horizons, Au concentrations increase to significantly high values than the bedrock or saprolite Au grade suggesting that Au re-distribution to have occurred at the surface layers of the regolith. It thus also highlights the apparent Au depletion in the mottled clay zones and in the upper saprolite, and Au enrichment in lateritic residuum and topsoil. The high Au expressions in the upper parts of the regolith generally are transported whereas the residual Au anomalies have low Au concentrations and do not merit further exploration follow up.

Significant Au expressions and relatively higher Mo, Cu and Pb concentrations are associated with Fe-oxyhydroxide-rich regolith with uneven elemental concentrations in paleo-sediment deposits. Asernic has been noted in this study as an inappropriate pathfinder element as it showed strong negative correlation with Au. However, to a certain extent, the high anomalies of Cu and Pb in relationship with Fe suggest pyrite and chalcopyrite as pathfinder minerals in search for Au but this should be in the saprolite, more appropriately at the reduced environments. The statistical models applied to the multivariate geochemical dataset suggest that there are probably two distinct processes that control the occurrence of Au in the study area. It further suggests that the primary process controlling the occurrence of Au in the study area correlates higher with Al, Ag, Mn, Cu, and Fe than As, indicating that these elements could serve as better pathfinders for Au in addition to Te that had an association with the Au1 residual anomalies in samples collected from the dugout pits..

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