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Integrated Geochemical and Geophysical Approach to Mineral Prospecting – A Case Study on the Basement Complex of Ilesa Area, Nigeria

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1. Introduction

The crust of the earth is composed of solid rocks. When the rocks are closely examined, they are found to be composed of discrete grains of different sizes, shapes, and colours. These grains are minerals, which are the building blocks of all rocks (Mazzullo, 1996).

The formation of soils from rocks generally involves the combination of mechanical and chemical weathering resulting from surface processes. Climatic conditions under which the weathering is affected determine which of the two forms of weathering becomes more pronounced than the other. In arid climates where there is little or no water and where there are appreciable diurnal variations in temperature, chemical weathering is considerably subordinated to mechanical weathering and the rocks simply become broken into increasingly small grains and pieces in which the individual minerals that constitute the rock are easily recognized. If, on the other hand, the climate is warm and humid with appreciable rainfall, chemical weathering becomes markedly pronounced and the individual minerals that form the rock are each subjected to rather intense chemical and comparatively modest mechanical weathering with the formation of different products which are all constituents of soils (Adewunmi,1984). In most Basement Complex rocks, weathered products, reflect certain characteristics (geochemical and mineralogical) of the parent rock.

Previous studies by Ako et al. (1979), Ako (1980), Ajayi (1988) and Elueze (1977) on the Ilesa area have been suggestive ofsulphide mineralization but the scope of coverage have been limited to the Amphibolite and the area around the Iwara fault. The present work is regional in scope and seeks to uniquely use an integrated geochemical and geophysical approach around the Ilesa area which is within the Schist belt of southwestern Nigeria and consists of Schist Undifferentiated, Gneiss and Migmatite Undifferentiated, Pegmatite, Schist Epidiorite Complex, Quartzite and Quartz Schist, Granite Gneiss, Ampibolite, Schist Pegmatised and Granulite and Gneiss aimed at delineating the area for mineral exploration. The geochemical data from 61 sampling locations were subjected to multivariate analysis and interpreted to delineate geochemical anomalous zone. The geophysical investigation of the anomalous zone that follows employed the Very – Low Frequency Electromagnetic (VLF – EM), Electrical resistivityand magnetic methods.

2. Geologic setting

The Ilesa area, lies within the Southwest Nigerian Basement Complex (Schist Belt) which is of Precambrian age (De Swardt, 1953). De Swardt (1947) and Russ (1957) suggested that the Nigerian Basement Complex is Polycyclic. This was confirmed by Hurley (1966, 1970) who used radiometric method to determine the age of the rocks. The Nigerian basement is believed to have had structural complexity as a result of folding, igneous and metamorphic activities with five major rock units recognized within the Basement Complex by Rahaman (1976). These are:

The migmatite-gneiss-quartzite complex

i. Slightly migmatized to unmigmatized paraschists and meta-igneous rocks which consists of pellitic schists, quartzites, amphibolites, talcose rocks, metaconglomerate, marble and calc-silicate rocks.
ii. Charnockitic rocks
iii. Older Granites and
iv. Unmetamorphosed acid-basic intrusives and hypabyssal rocks

Geochronological data on all these rock groups were summarized by Rahaman (1988). The geological map of Ilesa area is as shown in Figure 1.

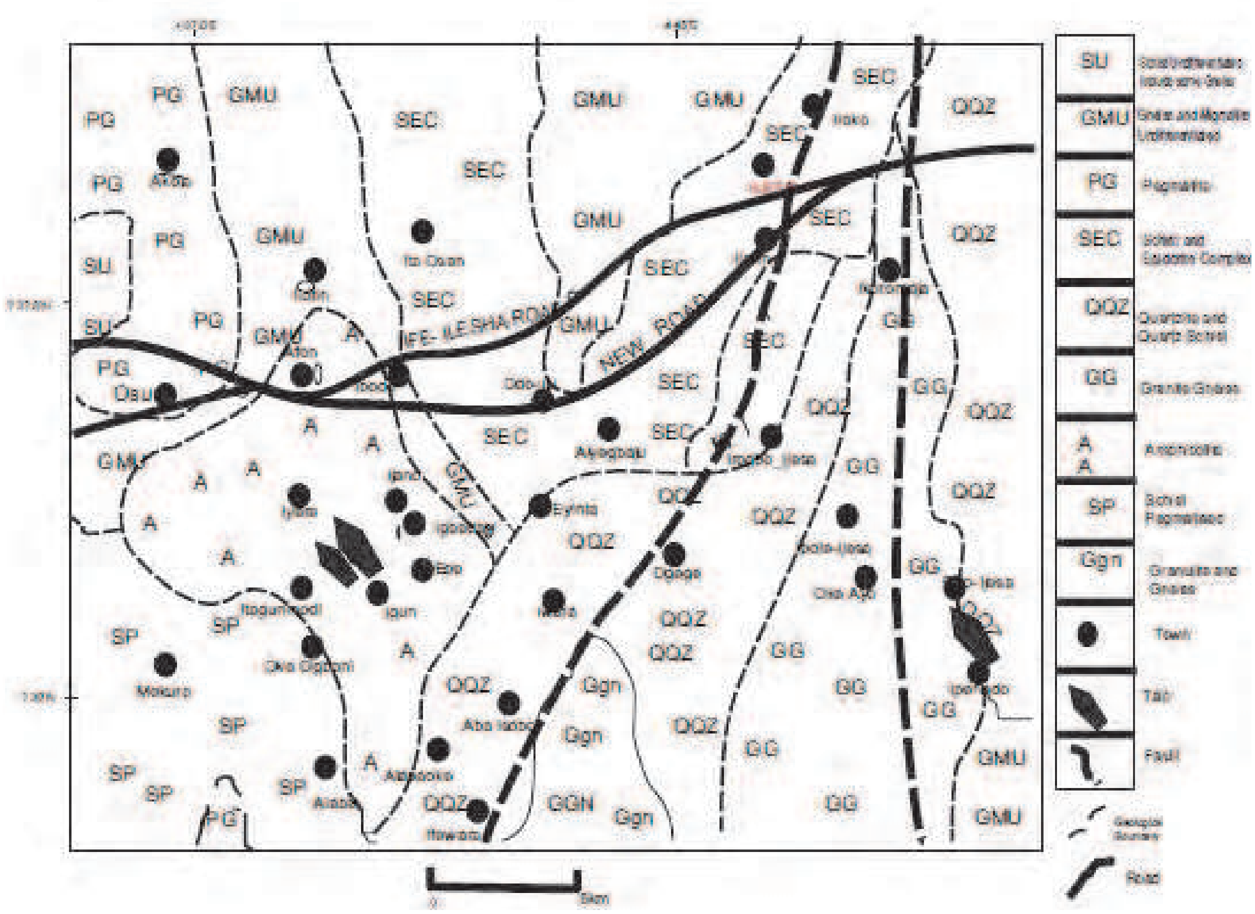

Fig. 1. Geological map of the study area (After Adebayo, 2008 and Adelusil, 2005)

The Schist Belts group of which Ilesa area is part have been variously termed“ Newer Metasediments” (Oyawoye, 1964), “Younger metasediments” (McCurry, 1976); “Schist belts” (Ajibade, 1976) and“ Slightly migmatized to non-migmatized metasedimentary and meta-igneous rocks” (Rahaman, 1988). The Nigerian Schist belts occur as prominent N-S trending features in the Nigerian Basement Complex. Lithologically, the schist belt consists of metamorphosed pelitic to semi-pelitic rocks, quartzites, calc-silicates rocks, metaconglomerates and pebbly schists; amphibolites and metavolcanic rocks. On the basis of lithology, metamorphism, structure, geochemical characteristics such as the tholeitic affinities of the amphibolites, and economic potentials, the schist belts show similarities to typical Archaean greenstone belts of the world (Wright and McCurry, 1970; Hubbard, 1975; Elueze, 1977; Klemm et al, 1979, 1984).
However, certain differences exist between these schist belts and typical greenstone belts. Though the schist belts of Nigeria have the sedimentary and ultramafic rock groups as defined by Anhaeusser et al, (1969), the so-called, “greenstone group” comprising serpentinites, crystalline limestones, rhyolites, banded ironstones of chemical origin and massive carbonated “greenstones” are either absent or less conspicuous. Also the ratio of metasediments to metavolcanics is much higher in the Schists belts of Nigeria than in the typical Archaean greenstone belts (Wright and McCurry, 1970). Mineralization is also not strongly developed in the schist's belts as in well known greenstone belts of the Canadian, Indian, Australian, and South African Precambrian shield areas.

3. Location, geomorphology and relief of study area

The area of study is located in the southern part of Ilesa and is geographically enclosed within Latitude 7^0 30\`N to $7^0$36\` N and Longitude 4^0 38\`E to $4^0$ 50\`E. It covers an area of about 1200 square kilometers. There are a good number of major and minor roads that link up the towns and villages in the study area. There are also main paths and footpaths linking the communities. These make the entire study area fairly accessible. The landscape of the area of study can be generally described as undulating, rising gently to steeply, but in some areas is punctuated by hilly ridges. The ridges are formed by quartz-schist or quartzite that rises abruptly from the enveloping basins and trend in the North to South direction. On the other hand, hills which are probably products of fragments of coarse-grained batholitic granite or resistance gneisses have a positive relief and are covered up by vegetation. Dissected topography also develops over the easily eroded basic rocks which according to De Swardt (1953) reflect the erosion cycles that separately occur in the area.

4. Research methodology

Preliminary work in the survey area took the form of a reconnaissance geological mapping followed by the statistical analysis of geochemical data to delineate areas with geochemical anomalies indicative of possible mineralization (Ariyibi et. al. 2010). This was aimed at studying the geology and selecting geophysical traverses approximately normal to the strike of the geochemical anomaly. In some cases however, the dense vegetation necessitated the cutting of traverses, although most of the traverses used were along existing roads and footpaths. The field data acquisition involved ground magnetic, electrical resistivity and VLF – EM survey methods. Essentially, the magnetic and VLF - EM measurements were carried out simultaneously on the chosen traverses located on the delineated area using topographical and geochemical anomaly maps.

The magnetometer used for this work is the GEM – 8 Proton magneto-meter which measures the Earth`s total field. The potable VLF-EM equipment used for this work was the GEONICS-EM16 (with GBR station) and on frequency of 16 kHz and it measures the real and imaginary part of the signal. The ABEM Terrameter was used for the electrical resistivity measurement.

5. Geoscientific methods used, data analysis and results

5.1 General

The geoscientific methods that can be used in mineral prospecting include, magnetic, gravity, electrical, electromagnetic, radiometric, geothermal and seismic methods. However, the choice of method (s) would depend basically upon their resolution with respect to problems encountered or conditions sought after within a given locality. More often, consideration is given to the cost, time, portability and reliability of instruments used in small scale surveys (Adewusi, 1988). The methods considered in this work include the geochemical, electrical resistivity, VLF – EM and magnetic methods.

5.1.1 The geochemical data, analysis and results

Geochemical methods of exploration should be viewed as an integral component of the variety of weapons available to the modern prospector. As the goal of every exploration method is, of course the same – to find clues that will help in locating hidden ore, the geochemical prospecting for minerals, as defined by common usage, includes any method of mineral exploration based on systematic measurement of one or more chemical properties of a naturally occurring material (Suh, 1993). The chemical property measured is most commonly the trace content of some element or group of elements; the naturally occurring material may be rock, soil, gossan, glacial debris, vegetation, stream sediment or water. The purpose of the measurements is the discovery of abnormal chemical patterns, or geochemical anomalies, related to mineralization.

Sampling and analysis of residual soil is by far the most widely used of all the geochemical methods. The popularity of residual-soil surveying as an exploration method is a simple reflection of the reliability of soil anomalies as ore guides (Gill, 1997). Practical experiences in many climates and in many types of geological environments has shown that where the parent rock is mineralized, some kind of chemical pattern can be found in the residual soil that results from the weathering of that rock. Where residual soil anomalies are not found over known ore in the bedrock, further examination usuallyshows either that the material sampled was not truly residual or that an unsuitable horizon or size fractionof the soil was sampled, or possibly that an inadequate extraction method was used. In other words, when properly used, the method is exceptionally reliable in comparison with most other exploration methods.

By definition, an anomaly is a deviation from the norm. A geochemical anomaly, more specifically, is a departure from the geochemical patterns that are normal for a given area or geochemical landscape. Strictly speaking, an ore deposit being a relatively rare or abnormal phenomenon is itself a geochemical anomaly. Similarly, the geochemical patterns that are related either to the genesis or to the erosion of an ore deposit are anomalies (Hawkes and Webb,1962). Anomalies that are related to ore and that can be used as guides in exploration are termed significant anomalies. Anomalies that are superficially similar to significant anomalies but are unrelated to ore are known as non-significant anomalies.

As with all geochemical surveys, the first step in approaching an operational problem is to conduct an orientation survey. Such a survey normally consists of a series of preliminary experiments aimed at determining the existence and characteristics of anomalies associated with mineralization. This information may then be used in selecting adequate prospecting techniques and in determining the factors and criteria that have a bearing on interpretation of the geochemical data.

Although the orientation study will provide the necessary technical information upon which to base operational procedures, the final choice of methods to be used must also take into account other factors, such as cost of operation, availability of personnel, and the market value of the expected ore discoveries. The nature of the overburden, whether it is residual or is of glacial, alluvial, or wind-borne origin, is the first question that must be answered by the orientation survey. Sometimes it is surprisingly difficult to discriminate between residual and transported soil. The safest method therefore, is to make critical and careful examination of complete sections of the overburden at the start of every new field survey. If road-cut exposures are not available, the soil should be examined by pitting or auguring. Previous orientation studies carried out by Olorunfemi (1977) and Adewunmi (1984) in parts of southern Ilesa established that the C horizon is the preferredhorizon for sampling. Details of laboratory procedures and analysis of the samples were reported by Ariyibi et al. (2010)

5.1.1.1 Statistical results

The multivariate technique, has proven to be viable and credible when applied on geochemical data as reported by Grunfeld (2003). The Principal Component Analysis (PCA) which isa multivariate technique, describep observable random variables x_1, x_2, ….,x_p in terms of the joint variation of a fewer number, k (<p) variables. The purpose of PCA is to determine factors (i. e. principal components) in order to explain as much of the total variation in the data as possible with as few of these factors as possible. This will uncover their qualitative and quantitative distinctions.

Table1 shows the descriptive statistics of the data. The data are not widely dispersed from the average when values of standard deviation are compared with the raw data. The measured values of Fe in the samples are quite large and so account for the large value of standard deviation (5. 0903) as seen in the table. The covariance matrix is shown in Table 2 and the corresponding correlation coefficients are shown in Table 3 and this was used to obtain the coefficients of the principal component using MATLAB as shown in Table 4 from standardized variable.

Observation elements are on the rows of Table 4. For example, Pb is denoted by X_1 and Fe by X_2 and so on. U_1, ………,U_8 are the principal components. The loadings or coefficients of the principal components are on the vertical columns. The magnitude of loadings greater than or equal to 0. 5 is to be considered for interpretation (Dillon and Goldstein,1984) as this will give the element with higher association ratio. On the last two rows of Table 4 is the eigenvalues of covariance matrix of the data and the Hotelling's T^2 statistic which gives a measure of the multivariate distance of each observation from the centre of the data set. A plot of the variability (in %) and the Principal component is as shown in Figure 2.

The three principal components with elements having loadings of 0. 5 and above (for which also the variability is greater than 10%) are: U_1, $U_2$and U_3 and these combined, account for 85. 34 % variability in the data. In U_1 are the elements : Fe and Mn in association (i. e. Fe-Mn)

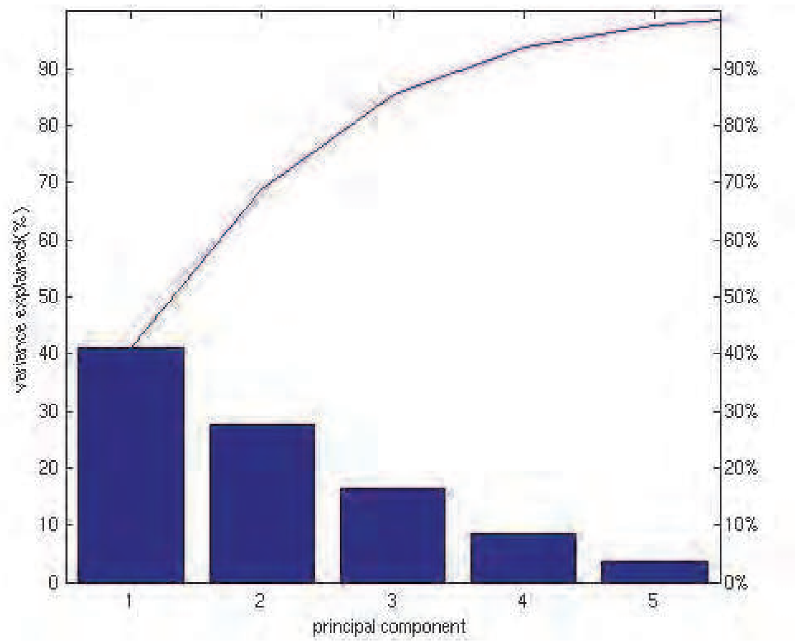

Fig. 2. A plot of the variability of the Principal Component, with five components accounting for 97. 44%.

accounting for 41. 11%. In U_2 the elements,Pb and Cr (i. e. Pb – Cr) accounting for 27. 65%and U_3 the elementsCd and Zn in association (i. e. Cd-Zn) with 16. 58 %.

Element	Threshold (ppm)	Range (ppm)	Geometric Mean (ppm)	Std. dev.
Pb	4. 50	3. 00 – 8. 00	1. 10	0. 0512
Fe	400. 00	50. 00 – 1750. 00	346. 00	5. 0903
Ni	5. 00	1. 50 – 7. 00	4. 00	0. 2121
Cd	0. 80	0. 03 – 1. 70	0. 50	0. 3043
Cr	0. 40	0. 01 – 1. 00	0. 30	0. 3512
Cu	0. 04	0. 01 – 0. 90	0. 03	0. 0090
Zn	0. 20	0. 01 – 0. 40	0. 14	0. 0113
Mn	10. 00	0. 20 – 26. 0	7. 30	1. 2015

Table 1. Descriptive statistics of the elements

Element	Pb	Fe	Ni	Cd	Cr	Cu	Zn	Mn
Pb	6. 41	438. 90	-0. 02	0. 08	-0. 05	0. 01	0. 08	4. 73
Fe	438. 90	281721. 80	339. 80	50. 00	3. 26	0. 14	2. 32	3602. 40
Ni	-0. 02	339. 8	1. 81	0. 21	0. 06	0. 01	0. 02	4. 26
Cd	0. 08	50. 00	0. 21	0. 18	0. 02	-0. 01	0. 02	0. 81
Cr	-0. 05	3. 26	0. 06	0. 02	0. 05	0. 01	0. 01	0. 15
Cu	0. 01	0. 14	0. 01	-0. 01	0. 01	0. 01	0. 01	0. 02
Zn	0. 08	2. 32	0. 02	0. 02	0. 01	0. 01	0. 01	0. 03
Mn	4. 73	3602. 4	4. 26	0. 81	0. 02	0. 02	0. 03	52. 41

Table 2. Covariance Matrix of the elements

Element	Pb	Fe	Ni	Cd	Cr	Cu	Zn	Mn
Pb	1. 00							
Fe	0. 35	1. 00						
Ni	0. 01	0. 48	1. 00					
Cd	0. 12	0. 22	0. 37	1. 00				
Cr	-0. 05	0. 03	0. 22	0. 17	1. 00			
Cu	0. 15	0. 01	0. 01	-0. 03	0. 08	1. 00		
Zn	0. 33	0. 04	0. 14	0. 37	0. 11	0. 40	1. 00	
Mn	0. 29	0. 94	0. 44	0. 27	0. 09	0. 09	0. 03	1. 00

Table 3. Correlation coefficients of the elements

	%	U_1 (41. 11)	U_2 (27. . 65)	U_3 (16. 58)	U_4 (8. 31)	U_5 (3. 79)	U_6 (2. 51)	U_7 (0. 04%)	U_8 (0%)
Pb	X_1	-0. 0022	0. 5905	-0. 1851	-0. 4640	0. 3429	-0. 1434	-0. 2725	0. 4351
Fe	X_2	-0. 5046	0. 2445	0. 0376	0. 0729	-0. 1184	0. 3095	0. 6589	0. 3674
Ni	X_3	-0. 3897	-0. 3036	-0. 1220	0. 5128	0. 5782	-0. 0440	-0. 2619	0. 2707
Cd	X_4	-0. 1052	-0. 3599	-0. 6629	-0. 1409	-0. 4200	-0. 3702	0. 0425	0. 2912
Cr	X_5	0. 0880	-0. 5187	0. 4400	-0. 3967	-0. 0550	0. 2898	-0. 1527	0. 5118
Cu	X_6	0. 4073	0. 2412	0. 2444	0. 5520	-0. 3130	-0. 2636	-0. 0585	0. 4905
Zn	X_7	0. 4034	0. 0405	-0. 5018	0. 1695	0. 0080	0. 7336	-0. 0911	0. 0929
Mn	X_8	-0. 5001	0. 2024	0. 0696	0. 0757	-0. 565	0. 2304	-0. 6214	-0. 0809
Eig. of Cov. Matrix		3. 2890	2. 2120	1. 3262	0. 6653	0. 3033	0. 2008	0. 0034	0. 0000
T^2		6. 1250	6. 1250	6. 1250	6. 1250	6. 1250	6. 1250	6. 1250	6. 1250

Table 4. Coefficients of the Principal component transformation (Numbers in Bracket are the proportion of total variance in %) of the elements

The principal components U_4, U_5, U_6, U_7 and U_8 have smaller variability and have respective eigenvalues of 0. 6653, 0. 3033, 0. 2008, 0. 0034 and 0. 0000. These when compared to the first three components are very small which is an indication of their relative decrease in significance in the data. So any association suggested by them cannot be realistic.

Results of a previous regional geochemical survey carried out by Ajayi and Suh (1993) using the factor analysis statistical techniquerevealed the existence of : Zn – Co – Cd, Ni – Cr, Fe – Mn and Cu – Pb as relevant associations mainly in the Amphibolites rocks. The results from the present study compare favourably well to these earlier results obtained from factor analysis but the association region extends to the quartz-schist rocks as can be seen in Figures 3, 4 and 5. Figure 3 shows the association ratio of Fe – Mn. The range of values is shown by the coloured circles. Values are classified as low (in purple circles) with concentration less than 20ppm, moderate (in yellow circles) with concentration range of 21 – 40ppmand high (in blue circles) with concentration greater than 41ppm. It can be seen that higher values are clustered at the central part of the figure which is on the Amphibolite, Schist and Epidiorite Complex and also on the Quartzite/Quartz Schist. At other parts, the values are distributed between moderate and lower values, though, with some isolated higher values probably due to rock intrusions. For examples, the higher values near Iperindo are surrounded by lower and moderate values.

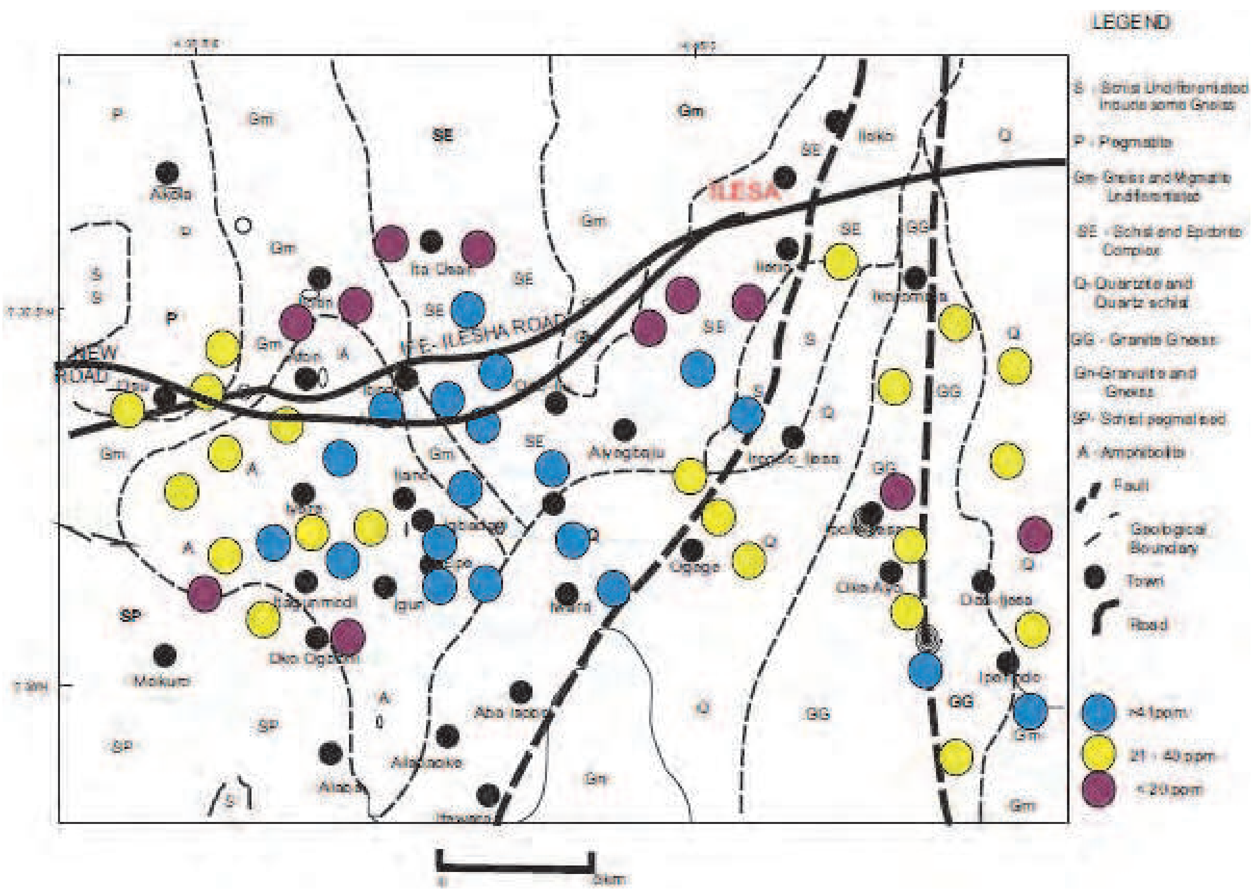

Fig. 3. Map showing the association ratio of Fe – Mn in the study area.

The association ratio of Pb – Cr are as shown in Figure 4. The higher values with concentration greater than 21ppm are more widely distributed than the Fe – Mn association ratio. However, most of the higher values are still concentrated on the Amphibolite, Quartzite/Quartz Schist and Schist Epidiorite Complex, though, with some moderate and lower values in between them. The association ratio of Cd – Zn is shown in Figure 5. The values are seen to be more widely distributed for most part of the figure. This shows the spread of the association over the basement rocks. Cd is known universally to associate with Zn. It actually reflects the strong lithologic influence related to the mafic minerals with which Zn is associated. It can thus be seen, that for the plotted concentration ratios, higher values of the metallic association are distributed largely towards the centre of the study area. This partly corresponds to the suggested mineralized areas by previous geological and geophysical studies of Ako (1980) and Ajayi (1988). Similar studies (such as the present one) were carried out on the Elura Deposit in the Cobar Mining district of Central New South Wales, Australia. The study identified high grade Zn – Pb - Agsulphide mineralization and this was later followed by extensive geophysical surveys to map the siliceous, pyriticand the pyrrhotitic ores (Palacky, 1988). A combined map of Figures 3, 4 and 5 is as shown in Figure 6. This gives the combined map for the geochemical anomaly over the study area. The Fe – Mn ratio is represented in red circles, the Pb – Cr ratio is represented in green circles while the Cd – Zn ratio is represented in blue circles. The anomaly is seen to be widely distributed over the delineated area. Also shown on the map are the geophysical locations and traverses to investigate the anomaly.

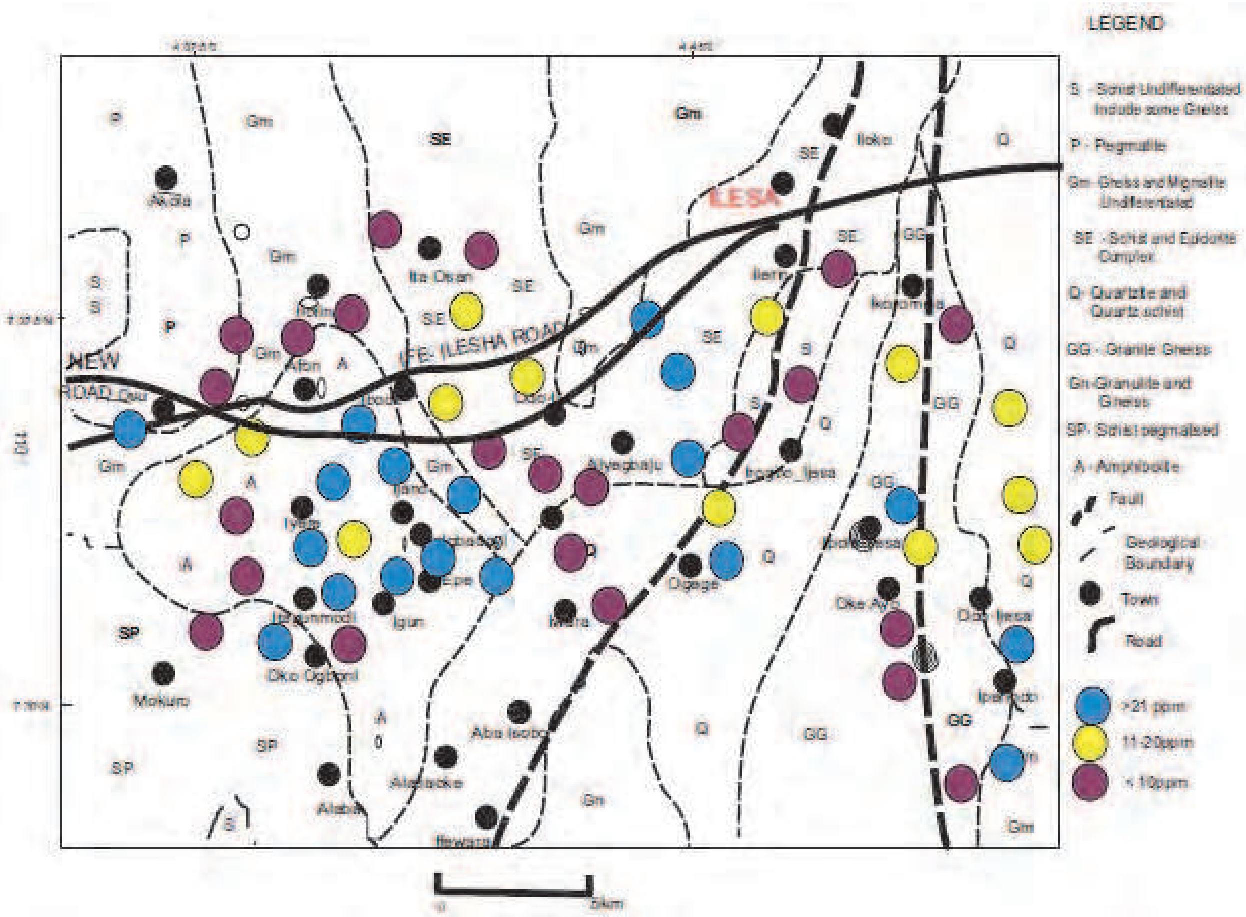

Fig. 4. Map showing the association ratio of Pb – Cr in the study area.

5.2 The electrical resistivity data, analysis and results

Electrical methods are generally referred to as “resistivity surveys”. Metallic minerals are relatively good conductors of electricity. In contrast, common rock forming minerals are generally poor conductors. This fact is the basis for geophysical exploration methods which measure conductivity to evaluate the metal content of rocks. The methods also provide some limited information about the geometry of the subsurface metallic mineralization. Surface electrical methods are limited to shallow depths (<200m), but the electrical properties of rocks can be measured at much greater depths by using electrical borehole instruments sent down deep drill holes. The location of the seven (7) VES data points are as shown in Figure 6. They are located so as to provide subsurface geological information including, layer resistivity, thickness and depth to the bedrock which will be useful in the geophysical modeling that will follow in the subsequent section. The Wenner configuration was used with electrode separation (a) varying from 1 - 96m. VES curves were interpreted using the partial curve matching technique followed with computer iteration procedure on the WinGLink computer software version 1. 62. 08. On this software, computed curves are compared with observed field curves. Where a good fit (i. e. 95 % correlation and above) was obtained between the two curves, the interpretation results was considered satisfactory; otherwise the geoelectric parameters were modified as appropriate and the procedure repeated until a satisfactory fit was obtained. The result from the computer iteration is as summarized with their geoelectric parameters in Table 5.

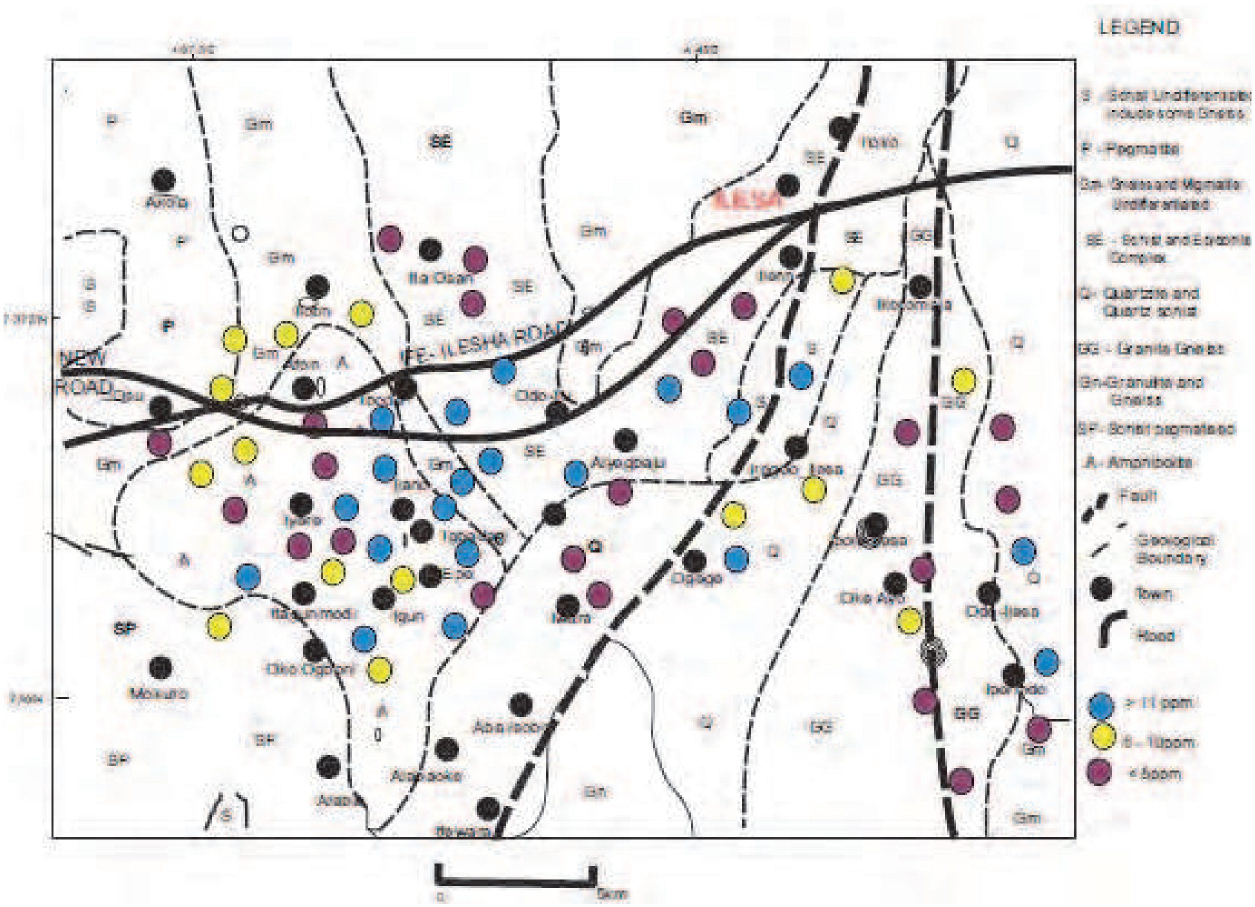

Fig. 5. Map showing the association ratio of Cd – Zn in the study area.

5.3 VLF– EM data, analysis and results

The Very Low Frequency (VLF) electromagnetic method uses powerful remote radio transmitters set up in different parts of the world for military communications (Klein and Lajoie, 1980). In radio communications terminology, VLF means very low frequency, of about 15 to 25 kHz. Relative to frequencies generally used in geophysical exploration, these are actually very high frequencies. The radiated field from a remote VLF transmitter, propagating over a uniform or horizontally layered earth and measured on the earth's surface, consists of a vertical electric field component and a horizontal magnetic field component each perpendicular to the direction of propagation.

These radio transmitters are very powerful and induce electric currents in conductive bodies thousands of kilometers away. Under normal conditions, the fields produced are relatively uniform in the far field at a large distance (hundreds of kilometers) from the transmitters. The induced currents produce secondary magnetic fields that can be detected at the surface through deviation of the normal radiated field. The VLF method uses relatively simple instruments and can be a useful reconnaissance tool. Potential targets include tabular conductors in a resistive host rock such as faults in limestone or igneous terrain. The depth of exploration is limited to about 60% to 70% of the skin depth of the surrounding rock or soil. Therefore, the high frequency of the VLF transmitters means that in more conductive environments, the exploration depth is quite shallow; for example, the depth of exploration might be 10 to 12 m in 25-Ωm material (Milsom, 1989). Additionally, the presence of

conductive overburden seriously suppresses response from basement conductors, andrelatively small variations in overburden conductivity or thickness can themselves generate significant VLF anomalies. For this reason, VLF is more effective in areas where the host rock is resistive and the overburden is thin.
In the VLF method, two orthogonal components of the magnetic field were measured, and normally the tilt angle, α, and ellipticity, *e*, of the vertical magnetic polarization ellipse are derived. Real (in-phase) and imaginary (quadrature) are used in the Karous – Hjelt Fraser filter (KHFFILT) programme. These components are based on the tilt angle, (α) and ellipticity *(e)* as:

$$Re = \tan(\alpha)\ 100\% \quad \text{and} \quad Im = e\ 100\%. \tag{1}$$

VES No	Layer Resistivity (Ω –m)	Layer thickness (m)	Curve type	Remark
1	231 368 892 233	3. 77 6. 01 13. 50 -	AK	AMP*
2	127 439 104 324	0. 59 2. 23 13. 28 -	KH	AMP
3	795 202 455 3065	1. 03 11. 45 7. 68 -	HA	AMP
4	407 257 49 320	0. 60 2. 11 4. 87 -	QH	GMU
5	350 177 445 238	1. 13 1. 80 36. 43 -	HK	GMU
6	550 1195 1804 186	0. 50 6. 28 25. 03 -	AK	SEC
7	330 455 2212 319	1. 26 6. 16 22. 82	AK	QQS

*AMP = AmphiboliteGMU = Gneiss and Migmatite Undifferentiated
QQS = Quartzite/Quartz Schist SEC= Schist and Epidiorite Complex

Table 5. Geoelectric layer parameters of the study area

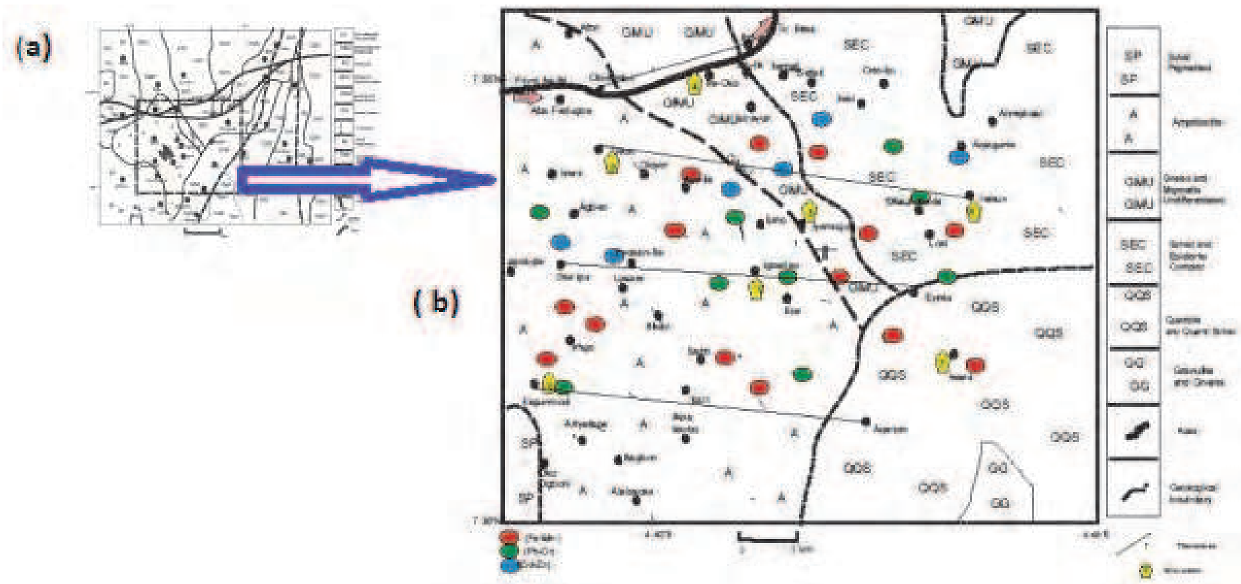

Fig. 6. The geochemical anomalous zone is enclosed by the rectangle with dashed lines on the geological map (a) and the geophysical traverses and locations on the zone (b).

The real and imaginary data values were first plotted using the Microsoft Excel. Next was the plot using the KHFFILT programme (Pirttijarvi, 2004) to obtain the Fraser - filtered plot and the Karous – Hjelt filtered pseudo-section.

The Fraser and Karous – Hjelt filtering are the two methods widely used in processing VLF –EM data (Fraser, 1969: Karous and Hjelt, 1983). The Fraser filter transforms the zero-crossing points into positive peaks which indicate conductive structures. The Karous – Hjelt filter is also used to obtain relative current density pseudo-sections, in which lower values of relative current density correspond to higher values of resistivity (Benson et al., 1997). The areas of high current density (represented in red colour) flow correspond to positive values and low current density (in blue colour) flow to negative values on the accompanying colour scale (for example see Figure 8).

5.3.1 The four west – east VLF (EM) profiles

The filtered response for the four West – East profiles are presented as in Figure 7 based on their respective locations in Figure 6 to correlate and describe the fractures across the area with the geochemical anomaly. The magnitude of the filtered response is varied along the four profiles due to the nature of the conductivity of the underlying materials. It is clear that the response along Olorombo to Ibode (7a) differs from those along Gada to Iwikun, Okeipa to Eyinta and that of Itagunmodi to Aiyetoro which are similar (Figures (7 b– d)).

The positive peaks labeled F1 is seen to occur across the three profiles in Figures 7 b,7c and 7d. It occurs at about station 1000m along each profile on the Amphibolite. This shows that the linear feature, interpreted as mineralized fracture is consistent in occurrence in the Amphibolite. The positive peaks labeled F2 and F3 are observed to cut across the three profiles also on the Amphibolite as shown in Figures 7 c and 7 d. The linear feature labeled F4 is observed to be consistent in occurrence in Figures 7c and 7d and actually lie near the boundaries of the amphibolites and gneiss/migmatite Undifferentiated rocks (Figure 7c) and amphibolites and quartzite/quartz schist rocks (Figure 7d). The linear feature labeled F4 is not visible in Figure 7b due largely to the nature of the material hosted by the gneiss/migmatite Undifferentiated and the schist/epidiorite complex rocks along this profile.

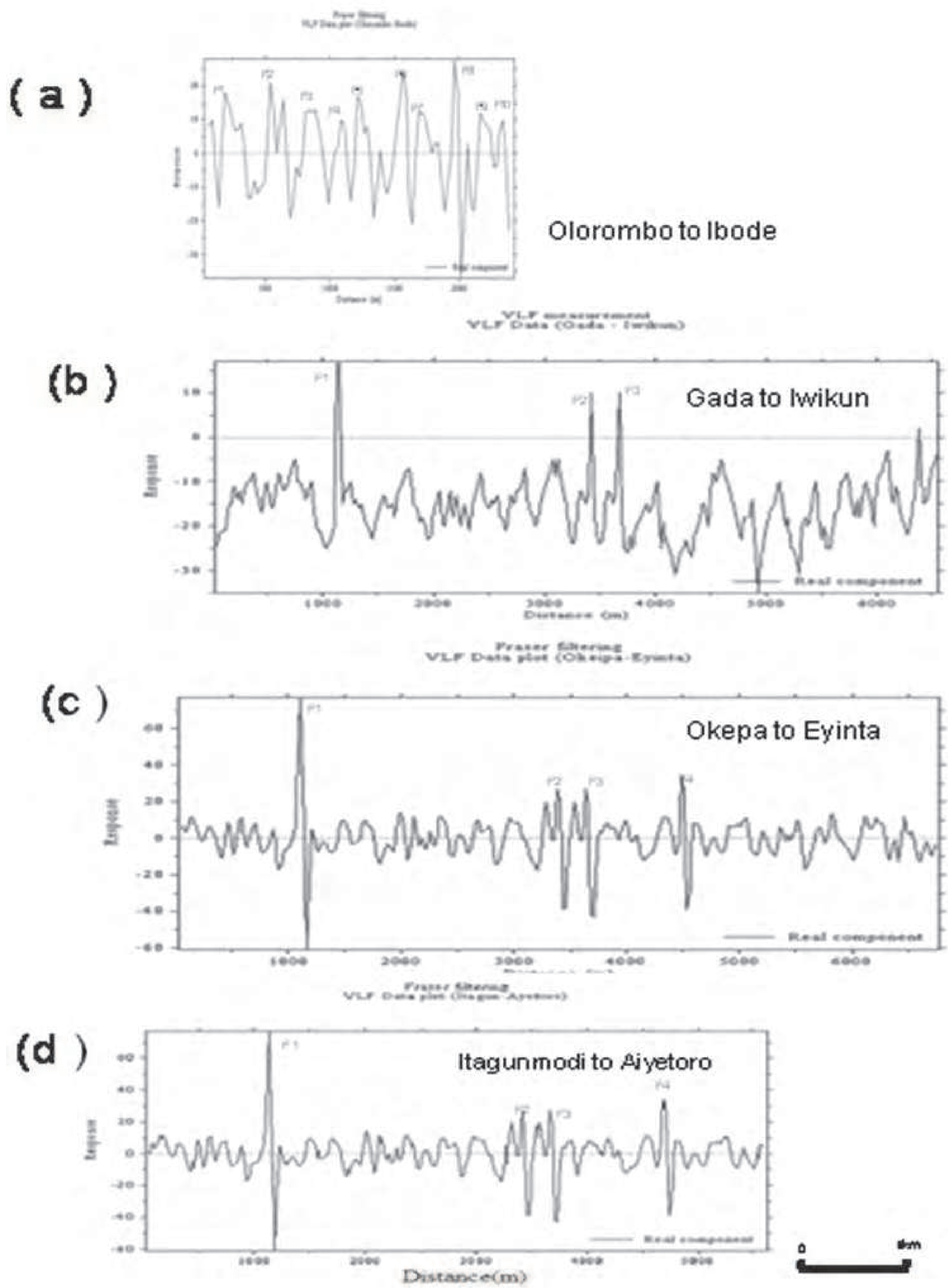

Fig. 7. The VLF – EM filtered real profiles for the four West – East traverses

Figure 8 is the pseudosections for the four West – East profiles. The figure shows the character of the labeled linear features earlier discussed. The linear feature labeled F1 is observed to be dipping conductors (as are observed on the Amphiboliteat about station 1000m) in all the three traverses of Gada to Iwikun, Okeipa to Eyinta and Itagunmodi to Aiyetoro. These are seen to have values thatrange between 15% and 70%. The occurrence of these dipping fractures from near the surface to depth of 100m and approximately along the N – S direction suggest that it is one and the same linear feature which cuts across the study area. The other fractures (F2 and F3) also on the amphibolites which are almost vertical and at between stations 3000m and 4000m occur at a depth range of 20 -70m are also one and the same linear features which cut across along N – S direction in the Amphibolite. Vertical conductive structures are also observed in the schist/epidiorite Complex and inthe quartzite/quartz schist rocks. The occurrence of these linear features in the study area has implications for mineralization, geotechnical and groundwater studies (Palacky,1988). Minerals that are structurally controlled such as lateritic nickel, gold, talc and clay deposits can be prospected along the identified linear features.

5.4 The magnetic data, analysis and results

Magnetism has been studied for a very long time in human history. Early Greek philosophers knew about the attraction of iron to a magnet. The first magnets consisted of a naturally occurring rock called lodestone, a variety of massive magnetite (almost pure iron oxide). Magnetite is the only naturally occurring mineral with distinctly obvious magnetic properties. Only a few other minerals have any detectable magnetism. However, extremely sensitive magnetometers can detect trace magnetism in many different minerals. Iron, because of its atomic structure, has the greatest tendency to become magnetized. Other elements, such as cobalt and nickel, have fewer tendencies to become magnetic. Any mineral or rock which contains any of these elements is likely be more magnetic.

The Earth possesses a magnetic field caused primarily by sources in the core. The form of the field is roughly the same as would be caused by a dipole or bar magnet located near the Earth's center and aligned sub-parallel to the geographic axis. The intensity of the Earth's field is customarily expressed in S. I. units as nanotesla (nT) or in an older unit, gamma (γ):1 γ = 1 nT = 10^{-3} µT. Except for local perturbations, the intensity of the Earth's field can vary between about 25 and 80 µT. Many rocks and minerals are weakly magnetic or are magnetized by induction in the Earth's field, and cause spatial perturbations or "anomalies" in the Earth's main field. Man-made objects containing iron or steel are often highly magnetized and locally can cause large anomalies up to several thousands of nT. Magnetic methods are generally used to map the location and size of objects that have magnetic properties.

In order to produce a magnetic anomaly map of a region, the data have to be corrected to take into account the effect of latitude and, to a lesser extent, longitude (Reynolds, 1997). As the Earth's magnetic field strength varies from 25000nT at the magnetic equator to 69000nT at the poles, the increase in magnitude with latitude needs to be taken into account. Survey data at any given location can be corrected by subtracting the theoretical field value F_{th}, obtained from the International Geomagnetic Reference Field, from the measured value, F_{obs}. Regional latitudinal (φ) and longitudinal (θ) gradients can be determined for areas concerned and tied to a base value, F_o. Gradients northwards ($\delta F/\delta\varphi$) and westwards

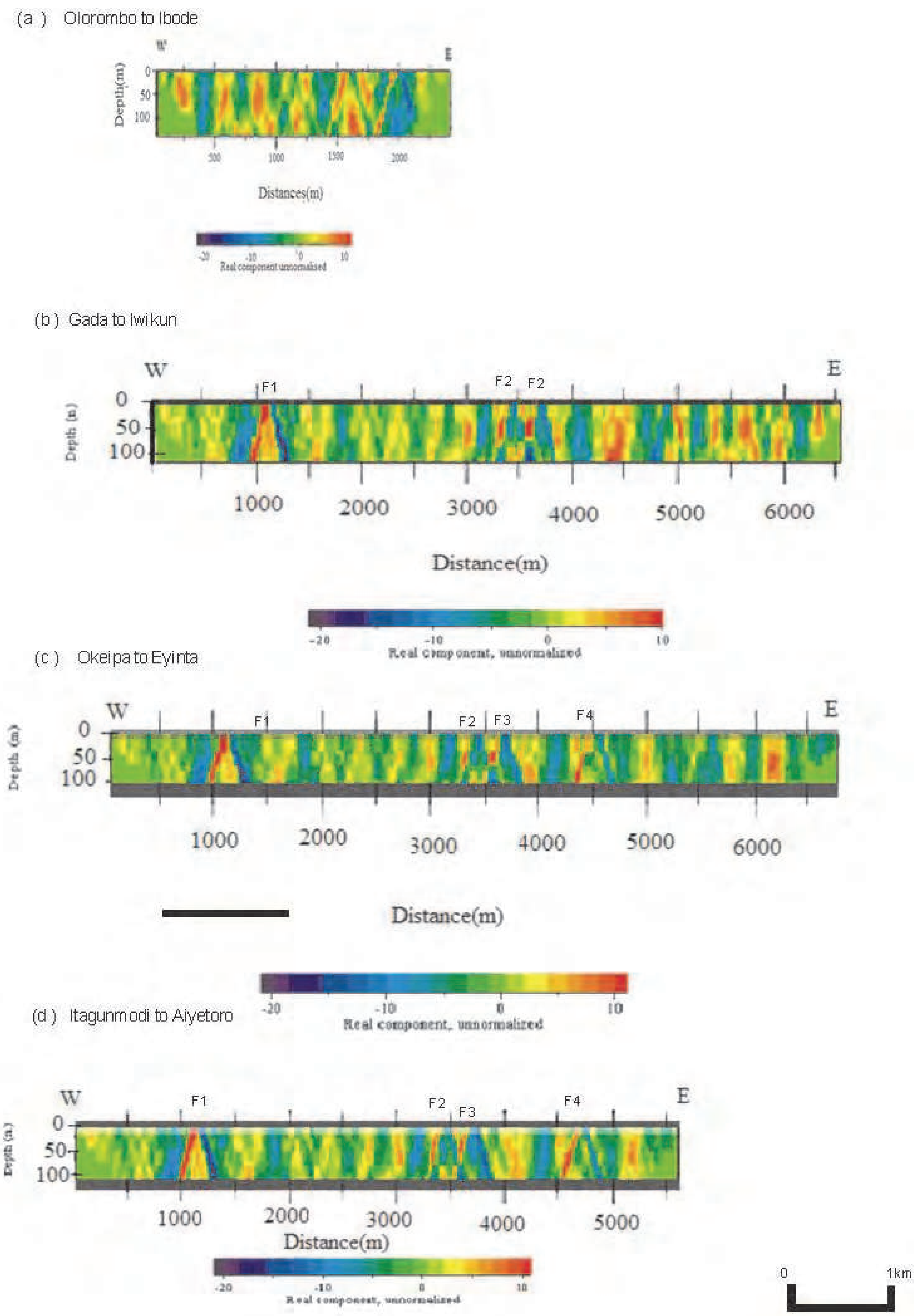

Fig. 8. The VLF – EM pseudosection for the four West – East traverses

(δF/$\delta\theta$) are expressed in nT/km. Consequently the anomalous value of the total field (δF) can be calculated from

$$\delta \mathrm{F} = \mathrm{F}_{\mathrm{obs}} - (\mathrm{F}_{\mathrm{o}} - \delta\mathrm{F}/\delta\phi + \delta\mathrm{F}/\delta\theta) \quad (\mathrm{nT}) \tag{2}$$

Geophysical (Magnetic) traverses over the delineated area are as shown in Figure 6b. In this survey, the total magnetic field was measured. The data reduction involved removing the regional field, reduction to the pole and vertical continuation before the plot of profile along the traverse. Removing the regional field helps to emphasize the magnetic anomaly of interest and this was done by subtracting the known regional field from the measured value. The reduction to the pole helps to change the actual inclination to the vertical. It was performed by convolving the magnetic field with a filter whose wave number response is the product of a polarization-orientation factor and the field –orientation factor (Baranov, 1957; Gunn, 1975; Spector and Grant, 1985). Also the field upward continuation attenuates anomalies caused by local, near – surface sources relative to anomalies caused by deeper more profound sources.

5.4.1 The magnetic models

Information available from the magnetic profiles along the four West – East traverses, VLF – EM, VES data and the geochemical anomaly are used in the modeling of magnetic data to confirm the existence of the linear features, basement depth (and topography) and the basement tectonic framework which are revealed in the area. The magnetic profiles were modeled using the 2. 5D modeling algorithm of the WingLink software programme (version 1. 62. 08). The profiles which are along the West – East include: Olorombo to Ibode, Gada to Iwikun, Okeipa to Eyinta and Itagunmodi to Aiyetoro. The modelling of these profiles shows very reasonable fit between the observed and the calculated magnetic profiles.

Figure 9A shows the observed and the calculated anomaly for the magnetic profile along Olorombo to Ibode and the corresponding geologic section in Figure 9B. Three model bodies are involved in the computation and these include the Amphibolite (s = 280 SI unit), Gneiss/Migmatite Undifferentiated (s = 300 SI unit) and Schist Epidiorite Complex (s = 100 SI unit) together with the overburden (s= 5 SI unit). The contact between the rock types may represent structural or lithological contacts especially in the area of basement outcrops (El-Shayeb, Personal communication). The model lithological contacts when correlated with the known geology shows that the contact between the Amphibolite and the Gneiss/Migmatite Undifferentiated partly correlated but the contact between the Gneiss/Migmatite Undifferentiated and the Schist Epidiorite does not correlate with the known geology. An overburden thickness of 2m is observed on theGneiss/Migmatite Undifferentiated rock at station 750m while the thickness is 1. 5m in the Schist Epidiorite Complex rock. The overburden is deepest (14m) in the Gneiss/Migmatite Undifferentiated rock at station 1350m.

Figure 10A shows the observed and the calculated anomaly for the magneticprofile along Gada to Iwikun and the corresponding geologic section in Figure 10B which is on the central part of the delineated area. Three model bodies are involved in the computation and these include the Amphibolite (s = 250 SI unit), Gneiss/Migmatite Undifferentiated (s = 130 SI unit) and Schist Epidiorite Complex (s = 150 SI unit) together with the overburden (s= 10 SI unit) and a Quartz vein (s=35 SI unit). The model has three bodies representing the three

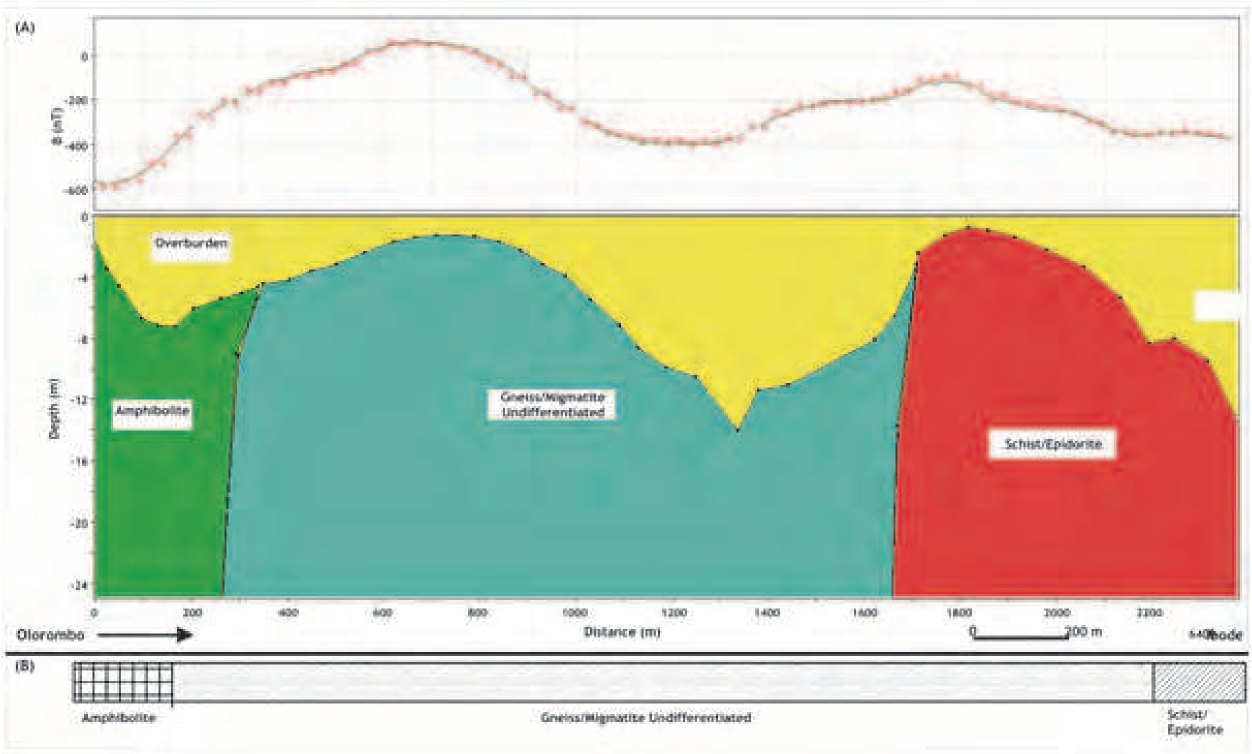

Fig. 9. The observed and calculated magnetic profile along Olorombo to Ibode

basement blocks. The contact between bodies represents structural or lithological contacts. The model lithological contacts when correlated with the known geology show afair correlation. The model result suggests a westward shift in the geological boundary. The model also revealed the existence of a Quartz vein (s = 35 SI Unit) sandwiched between the Amphibolite and the Gneiss/Migmatite Undifferentiated rocks at stations between 2400 – 2600m along the profile. The model reveals the outcropping of the Schist Epidiorite Complex at stations 4100m and 5500m. The overburden is deepest (48m) in the Amphibolite rock at station 400m.

Figure 11A shows the observed and the calculated anomaly for the magneticprofile along Okepa to Eyinta and the corresponding geologic section in Figure 11B which is on the central part of the delineated area. Three model bodies are involved in the computation and these include the Amphibolite (s = 200 SI unit), Gneiss/Migmatite Undifferentiated (s = 100 SI unit) and Schist Epidiorite Complex (s = 300 SI unit) together with the overburden (s= 5 SI unit) and a dyke body (s=40 SI unit). The contact between bodies represents structural or lithological contacts. The model lithological contacts do not correlate with the known geology probably due to the "masking" effect of the overburden. The model reveals the existence of a dyke body (s = 400 SI unit) in the Quartzite/Quartz Schist rock just before station 6400m. Observed also are the five fractures in the Amphibolite at stations 200, 1400, 1600, 2300 and 3000m along the profile. The modeled basement blocks magnetic susceptibility contrast ranges between 100 – 300 SI units and reflects the variation in the composition of the basement rocks across the profile.

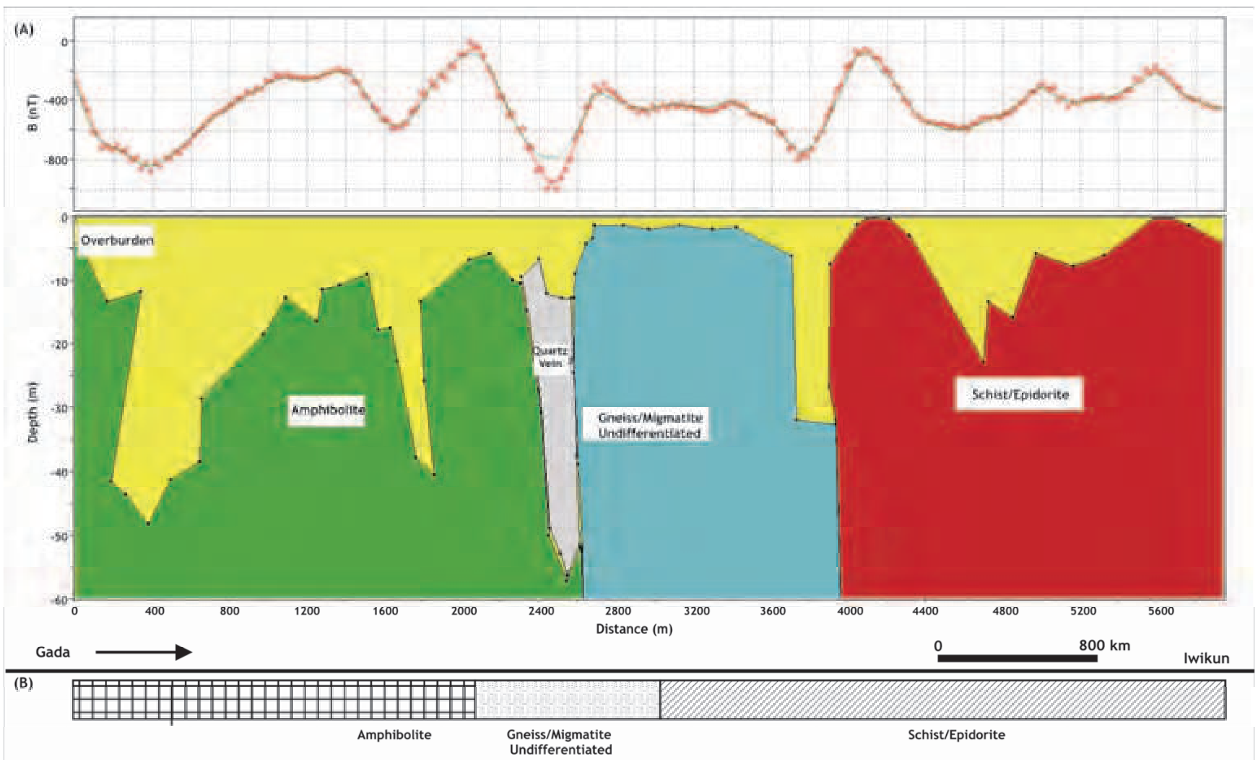

Fig. 10. The observed and calculated magnetic profile along Gada to Iwukun

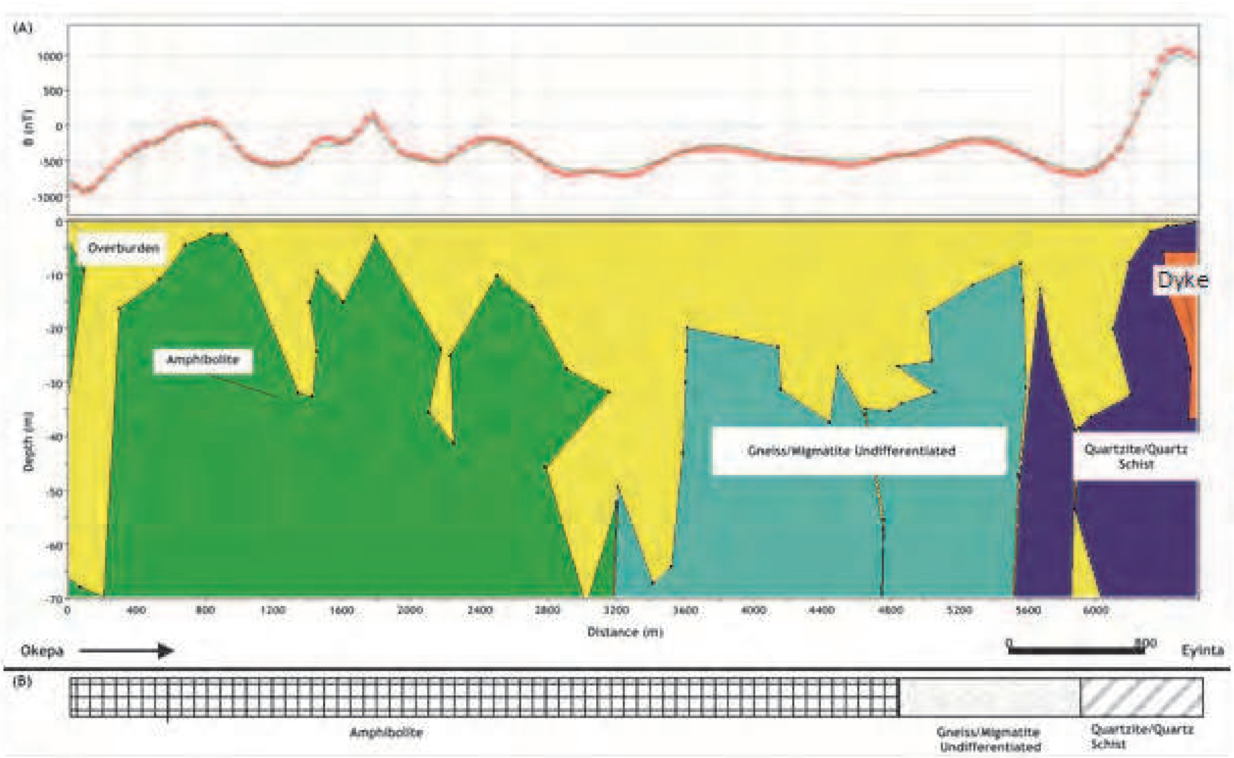

Fig. 11. The observed and calculated magnetic profile along Okepa to Eyinta

Figure 12A shows the observed and the calculated anomaly for the magneticprofile along Itagunmodi to Aiyetoro and the corresponding geologic section in Figure 12B which is on the southern part of the delineated area. Two model bodies are involved in the computation and these include the Amphibolite (s = 280 SI unit), Quartzite/Quartz Schist (s = 400 SI unit) together with the overburden (s= 10 SI unit). The contact between bodies represents structural or lithological contacts. The model lithological contact when correlated with the known geology shows a good correlation. Observed also are many fractures/faults in the Amphibolite along the profile. The modeled basement blocks magnetic susceptibility contrast ranges between 280 – 400 SI units.

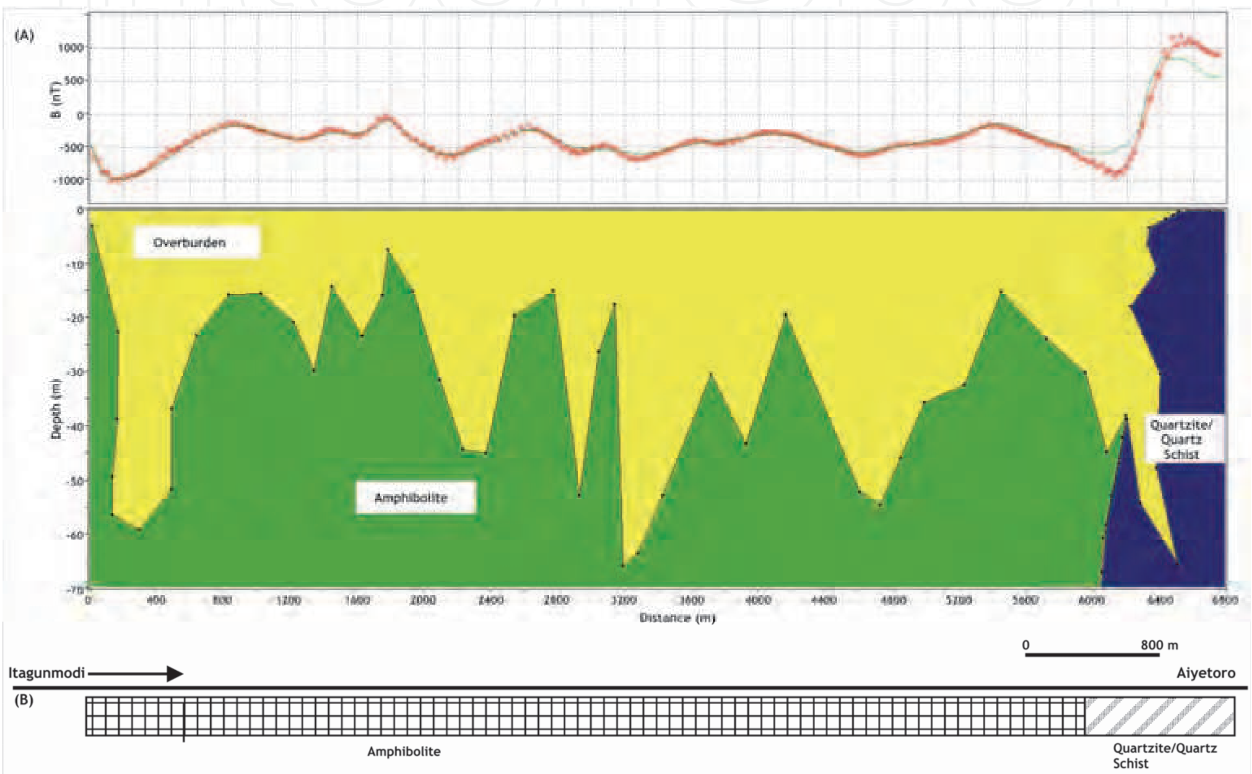

Fig. 12. The observed and calculated magnetic profile along Itagunmodi to Aiyetoro

6. Discussion and conclusions

The geochemical data shows an anomaly with elemental association of Fe – Mn, Pb – Cr, and Cd – Zn and trends approximately along the North – South direction. The VLF-EM data revealed the existence of linear features which are interpreted as mineralized fractures, faults and veins. These linear features are consistent across the study area and run approximately in the N – S direction. These structures exist from near the surface to a depth of up to 100m. The magnetic data also mapped the linear features, magnetized bodies (interpreted as dykes) and the geological contacts. The coincidence of electromagnetic (VLF) and magnetic anomalies and their correlation with the geochemical anomaly, especially on the amphibolites, is an indication of the occurrence of sulphide deposits rich in Zn-Pb-Cralong the identified linear features . The geophysical methods engaged have helped to map the structural complexity such as evidence of faulting, mineralized fractures, joints and dykes in the study area. In addition, it is now evident that mineralization is not limited to

within the amphibolites, but also exist in the other rock types. There is an improved delineation of the rock contacts which has hitherto been difficult to map as a result ofdearth of outcrops and the presence of overburden.
Based on the combined geological, geochemical and geophysical data which are available (and the modeled results) and interpreted over the delineated area, a new geological map is proposed for the area. Figure 13 shows the disposition of the prominent linear features, dykes and the inferred mineralized zone found in the area. The fractures are seen to trend approximately in the N – S direction. The frequency of fracturing is a function of rock elastic properties, structure and tectonic history. The rock with high fracture frequency is known to be highly brittle and prone to fracturing. From this study the occurrence of fractures on the Amphibolite is high and so also that on the Quartzite/Quartz Schist and Gneiss/Migmatite Undifferentiated rocks are moderately high. The Quartzites/Quartz Schist isalso strongly magneticprobably due to the occurrence of iron oxides as described by Ajayi (1988).

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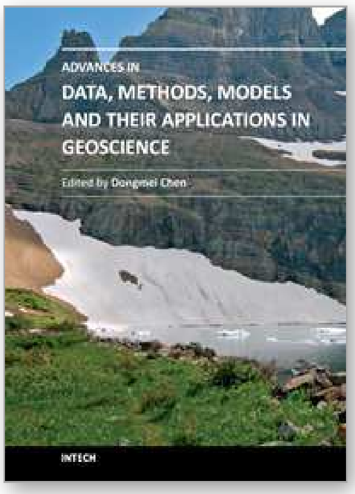

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With growing attention on global environmental and climate change, geoscience has experienced rapid change and development in the last three decades. Many new data, methods and modeling techniques have been developed and applied in various aspects of geoscience. The chapters collected in this book present an excellent profile of the current state of various data, analysis methods and modeling techniques, and demonstrate their applications from hydrology, geology and paleogeomorphology, to geophysics, environmental and climate change. The wide range methods and techniques covered in the book include information systems and technology, global position system (GPS), digital sediment core image analysis, fuzzy set theory for hydrology, spatial interpolation, spectral analysis of geophysical data, GIS-based hydrological models, high resolution geological models, 3D sedimentology, change detection from remote sensing, etc. Besides two comprehensive review articles, most chapters focus on in-depth studies of a particular method or technique.