Mapping of sub-surface fracture systems using integrated electrical resistivity profiling and VLF-EM methods: a case study of suspected gold mineralization

Kartiranje podpovršinskih sistemov razpok z integriracijo električnega upornostnega profiliranja ter VLF-EM-metode: primer domnevnega orudenja z zlatom

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Abstract: This study highlights the application of horizontal electrical resistivity profiling (HRP) and Very Low Frequency Electromagnetic (VLF-EM) methods as mapping tools for detection of subsurface structural features in respect of gold mineralization prospects located at the outskirt of New-Bussa, Niger State. Nigeria. The overall intent is to map and delineate the possible structural controls on gold mineralization in the study area. In total seven (7) EM-profile lines and three (3) HRP-profile lines were established, while data processing of the VLF-EM results involved Fraser and Karous-Hjelt filtering followed by 2D inversion.

Interpretation HRP data and quantitative evaluation of VLF-EM data revealed a number of subsurface zones with high real component current density which define the potential subsurface structural features (as fracture zones) with possible gold mineralization. In addition, correlation and extrapolation of the anomalous low resistivity zones with high current density zones revealed fracture systems trending roughly N–S at a strike range of 350° to 005°. These zones are interpreted as the potential or inferred structurally controlled fracture zones with possible gold mineralization worthy of follow-up geochemical exploration studies.

Original scientific paper

Izvleček: Raziskali smo možnost uporabe horizontalnega električnega upornostnega profiliranja (HRP) in zelo nizkofrekvenčne elektromagntne metode (VLF-EM) kot orodja za kartiranje podpovršinskih struktur za odkrivanje mineralizacije z zlatom na obrobju New-Bussa, Niger, Nigerija. Namen naloge je na raziskovanem območju kartirati in izdvojiti možne strukture, orudene z zlatom. Meritve smo opravili v sedmih (7) EM in treh (3) HRP-profilih ter VLF-EM podatke obdelali z Fraserjevim ter Karous-Hjeltovim filtriranjem, ki mu je sledila 2D-inverzija.

Interpretacija HRP podatkov in kvantitativno vrednotenje VLF-EM podatkov sta pokazala številne podpovršinske cone z visoko realno komponento gostote toka, s katerimi definiramo potencialne podpovršinske strukturne oblike (npr. razpoklinske cone) z možno mineralizacijo z zlatom. Korelacija in ekstrapolacija anomalnih nizkoupornostnih con s conami z visoko gostoto toka kaže na sistem razpok, usmerjenih približno S–J, z razponom smeri od 350° do 005°. Ta območja smo interpretirali kot strukturno kontrolirane cone razpok z možnim orudenjem z zlatom, ki bi jih bilo smiselno raziskati tudi geokemično.

Key words: VLF-EM-method, electrical resistivity profiling method, 2-D VLF inversion, apparent resistivity, current density, fracture mapping

Ključne besede: metoda VLF-EM, metoda električnega upornostnega profiliranja; 2D VLF-inverzija; navidezna upornost, gostota toka, kartiranje razpok

INTRODUCTION

In the recent past, integrated geophysical investigations have found useful and increasing applications in many geological studies ranging from shallow engineering studies, groundwater and mineral deposits explorations as well as in a variety of geo-environmental studies like investigations of contaminated sites or waste disposal areas (OLORUNFEMI & MESIDA, 1987; SHARMA, 1997; FROHLICH & PARKE,1989; STEEPLES, 2001). High urbanization rate and urgent need for natural resources on one hand and non-invasive character of the geophysical methods such as geoelectrics, electromagnetic methods, very low frequency (VLF), and induced polarization (IP), which can provide information over larger areas, are said to expedite this trend (FROHLICH et al., 1994; Dahlin, 1996; Aristodemu & Thomas-Betts, 2000; Draskovits & Vero, 2005; Gokturkler, et al., 2008). Especially geoelectric and electromagnetic methods are widely and jointly employed in many geological investigations to solve various problems (Bernstone et al. 2000; Karlik & Kaya 2001; Oskooi & Pedersen, 2005).

The electrical resistivity, a commonly used method, is based on the apparent resistivity measurements along the earth surface (Frohlich & Parke, 1989; Sporry, 2004). The measured apparent resistivity represents some kind of averaging of the true resistivities existing between the ground surface and the depth reach of the electrodes configuration (Telford et. al., 1990). For this study, resistivity profiling (Wenner array) was employed which entails apparent resistivity measurements using a fixed electrode array at different locations (stations) along a survey line. The interval between stations is preferably kept constant while the variation of earth resistivity along the profile line is measured with a more or less constant investigation depth. The concept is based on the fact that the variation of resistivity for an inhomogeneous earth is caused by the distortion of current flow lines and with that, of the electric potential field around the potential electrodes. Hence, for a stratified earth, the distortion is systematic, with the consequence that through processing and interpretation the stratification of the earth can be derived from a systematic collection of resistivity data at one location (Milsom, 1989; Sporry, 2004).

The VLF-EM is a well known method for quick mapping of near surface geologic structures most especially in respect of mineral exploration and related geological structures (Saydam, 1981; Ligas & Palmoba, 2006; Babu et al., 2007). In addition, it has been used to high level of success to map weathered basement layer and detection of water – filled fractures or shallow faults. The VLF-EM method is considered as one of the most used among electromagnetic methods and is adequately described by several authors (e.g. Wright, 1988; McNeill & Labson, 1991). The VLF-EM uses radio signals from worldwide network transmitter stations and operates in frequency ranges between 5 kHz and 30 kHz.

The principle of VLF-EM survey is based on the fact that the ratio of the secondary vertical magnetic component to the horizontal primary magnetic field is a measure of conductivity/resistivity contrast since this tipper component is of internal origin of the anomalous body (Chouteau et al., 1996; Gharibi & Pedersen, 1999). To this end an integrated geophysical investigation (Very Low Frequency electromagnetic and electrical resistivity survey) techniques have been employed in this study as mapping tools with the overall objective of geophysical mapping for possible detection of buried subsurface structural features (such as fractures, quartz or pegmatitic veins) in respect of gold mineralization prospects located at the outskirt of New-Bussa, Niger State. Nigeria. The present evidence of gold mineralization is a quatz-pegmetitic vein which is exposed within a farmland grown with groundnuts at a coordinate of about 9° 50’ 32” N & Longitude ≈ 4° 32’ 10” E. Hence, further specific objectives are:

a) to isolate zones within the study area with gold mineralization / enrichment
b) to highlight possible structural features and control (fractures and mineralized veins).

The study is also partly intended to possible structural features (fractures and mineralized veins). The combined geophysical techniques are expected to provide information on the subsurface structural features in respect of gold mineralization potential in the study area and possible further localized geochemical investigation.

STUDY AREA

Location and Accessibility

The study area is located at the outskirt of New Bussa near Kainji with main access via the major road from Mokwa to Wawa, off the Ilorin-Jebba-Mokwa Federal Highway. The study site at the outskirt of New Bussa is linked by an unpaved rural road/foot path about 4 km south of New Bussa Township. Figure 1 is a generalized geological map of Nigeria showing the location of the study area. The study area has a tropical savannah climate with temperature averaging ≈32 °C and up to 40 °C during the peak of the dry season. The climate is characterized by two distinct seasons; hot dry season (mid-October to April) and rainy season (May to mid-October) with average precipitation of about 600–800 mm. The local physiography comprises of relatively flat but undulating topography with valley as low-lying areas. This generally flat relief is characteristic of savannah forest dominated by grasses and shrubs as undergrowths with scattered tress such as shear-butter and locus beans tress.

Geological Setting

Regionally, the study area lies within the Precambrian Basement Complex and located at the northern edge of the

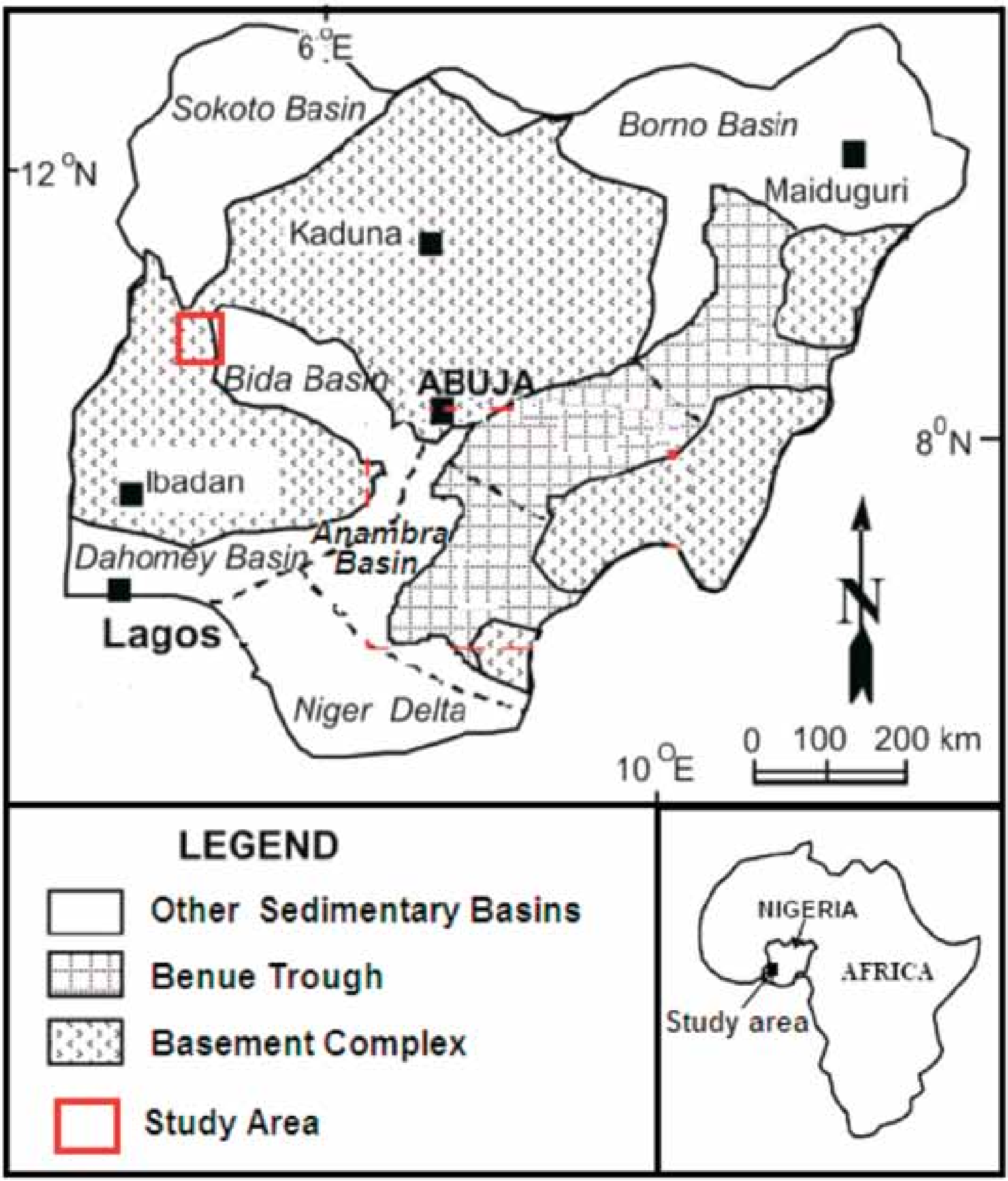

Figure 1. Generalized geological map of Nigeria showing the location of the study area

Basement Complex of South-Western Nigeria. The study area and environs are underlain by crystalline igneous and metamorphic basement rocks, mostly undifferentiated migmatized granite-gneiss, quartzite and quartz-schist complex as well as localized pegmatite and quartz veins intrusions. Various studies have described the geology and characterized the rock units of the Basement Complex setting in South-Western Nigeria (JONES & HOCKEY, 1964; OYAWOYE, 1970; RAHAMAN, 1976; ODEYEMI, 1976 and ODEYEMI, 1981).

Locally, the study area is characterized by Precambrian Basement Complex rocks, mostly the migmatite-gneiss, schist-quartzite complex. Figure 2 highlights the local geological of the study area and environs. In the immediate vicinity of the study area, there are limited outcrops mainly of granite gneisses, schist and amphibolite complex with evidence of shearing and brecciated (cataclastic) zones in places.

Within the study site, gold mineralization veins are exposed in farmland areas at an approximate coordinate of 9° 50' 32" N & ≈ 4° 32' 10" E located about 500–800 m from the main Mokwa-New Bussa-Wawa highway. The geology around the veins consists of mainly gneiss and schist with amphibolite unit as well as pegmatitic intrusion as found within the central part of the study area. The intrusion apparently created an alteration aureole in the pre-existing metamorphosed mafic rock units. The observed main alteration is the growth of porphyroblastic texture in gneisses especially in the western section of the study area.

The general strike of rock foliation and main structural trends is between 350° and 005° azimuth, while the veins trends between 305–315°. This implies that the veins are injected into joints systems that are not conformable to the joints system of the host rock. Veins exposures show a dextral displacement of less than 1 m, while further detailed study may help to expose larger fault/ fracture systems in the study area. Furthermore, field observations revealed a couple of shear zones to the south-west portion of the study site and a number of the observed veins composed of highly ferruginized quartz, while the gold occurrence seems to correlate with the degree of ferruginization. The implication of this in terms of exploration is that secondary enrichment may be found in weathered regolith.

Field methods and data collection

Geophysical measurements were carried out during a field camping exercise at Kanji – New Bussa area by late 2008. The field investigation involved application of both Very Low Frequency electromagnetic (VLF-EM) measurements and horizontal resistivity profiling (HRP) for mapping of subsurface conductive zones.

VLF-EM Measurements

Very Low Frequency electromagnetic (VLF-EM) geophysical prospecting method is a passive geophysical method which uses radiation from military navigation radio transmitters operating in the VLF band (15–30 kHz) as the primary EM field to generate signals for various applications (Babu et al., 2007). In this study, VLF-EM method was employed to map the study area with the object of isolating fractured zones which are likely to be enriched with gold mineralization. ABEM Wadi VLF electromagnetic equipment with in-built digital display unit and powered by battery was used. For the VLF-EM measurements, radio signal from stations GBR and GBZ in Rugby UK (52N22, 001W11) were the main signal stations tuned / selected. These correspond to frequency values of 22.6 kHz and 19.6 kHz and are employed to generate the primary electromagnetic field around the buried conductors in order to induce the detected secondary field and measured as a fraction of the primary field by the VLF-meter.

In total 7 E–W trending profiles were occupied with measurement station intervals of 20 m. Each profile is about 1 km long and runs perpendicular to the general N–S geologic strike in the study area. The position of profiles is shown in Figure 3. Central profile-1 runs across the existing/identified gold mineralized fracture zone at the central part of the study area. Other profiles (2–7) run parallel and symmetrical to the central profile-1 with spacing of about 50–100 m. Generally, due to the rural nature of the study area there are no sources of noise such as power lines that might have affected the data quality.

Electrical Resistivity Profiling Measurements

For the electrical resistivity profiling investigation, resistivity of rocks is usually determined in the field using an array of four electrodes where electrodes A and B are used to run the electrical current, I into the ground (current electrodes), while electrode M and N measure the difference ΔV between the potentials at the positions of these elec-

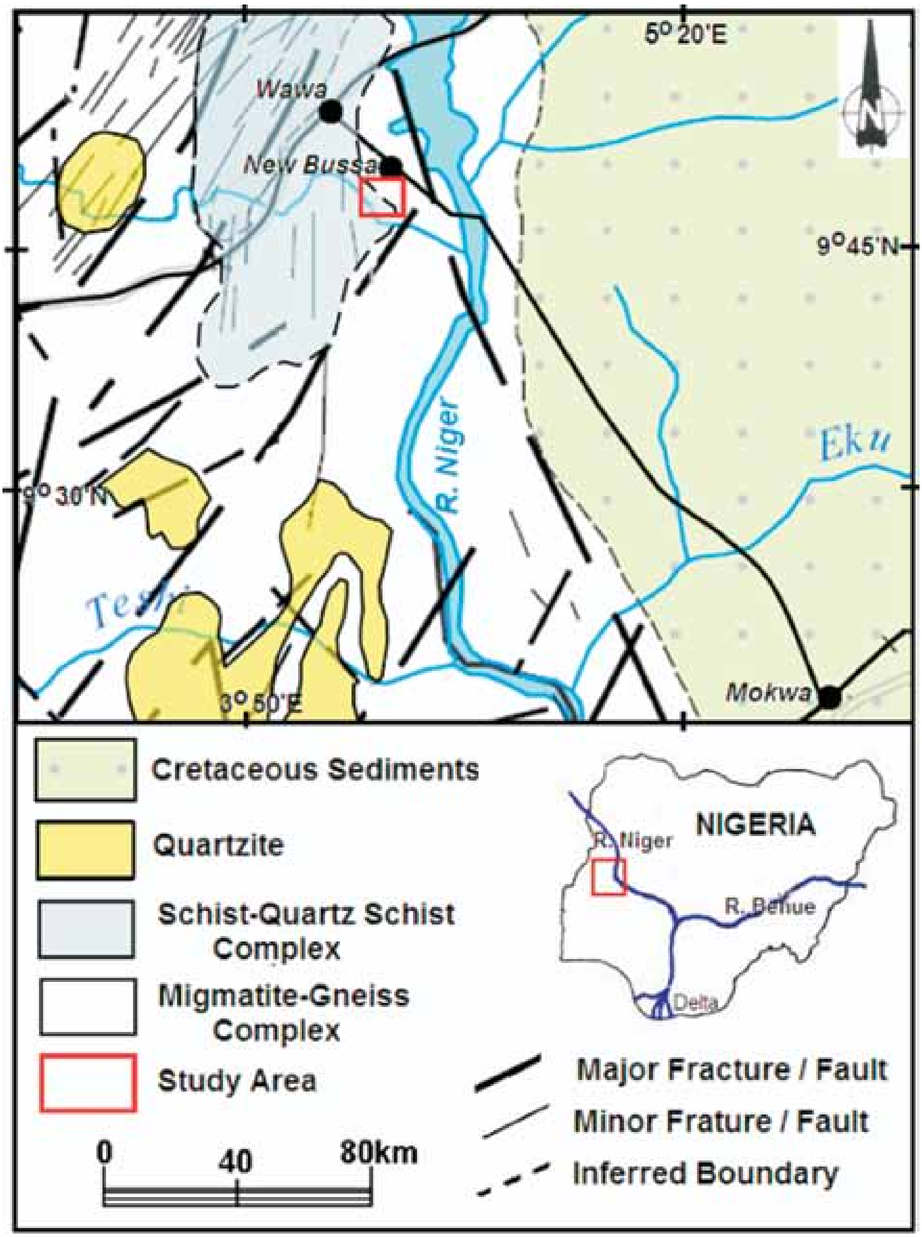

Figure 2. Geological map of the study surrounding neighborhoods of the study Area (Compiled from NGSA Lineament and Geological Map of Nigeria, 2006)

trodes (potential electrodes) (Milsom, 1989). In this study Wenner array was applied using AGI Terrameter model Sting R1 with in-built digital display unit connected to a 12 V battery for adequate energization of subsurface. A constant separation of 15 m was employed with station interval of 15 m, while the profile/traverse lines are about 600–850 m long. In total three (3) HRP-profile lines were established as also indicated in Figure 3, while measurements were taken in approximately E–W profile direction which is more or less perpendicular to the general N–S geologic trend in the study area. Profile 1 coincides with VLF–EM profile 1, i.e. at the center of the field while profiles 2 and 3 are 100 m to the north and south of profile 1 respectively.

Data Processing / Evaluation

Subsequent to field survey measurements, VLF-EM data as well as those of the HRP measurements were subjected to data processing and evaluation as the basis for interpretation.

For the VLF-EM, the acquired field data were processed to simplify the obtained complex information into a profile in which the displayed function is directly related to a physical property of the underlying rock. Thus measured raw real and imaginary components were subjected to Fraser (Fraser, 1969) and Karous-Hjelt (Karous & Hjelt, 1983) filtering operations to suppress noise and enhance signal. The Fraser filter (Fraser, 1969) converts crossover points into peak responses by 90° phase shifting. This process removes direct current bias that reduces the random noise between consecutive stations resulting from very low frequency component of sharp irregular responses (Al-Tarazi et al., 2008).

The filtered profile data were then subjected to 2D inversion operation. The 2D inversion involved joint inversion of the real and imaginary components of the tipper based on a forward solution using the finite-element method. Pilot resistivity survey and geologic field investigation of the area of study supplied the priori information for the subsurface model with RMS misfit of 0.7 obtained after 16 iterations. Subsequently, the obtained current density information was used to isolate regions having contrasting conductivity value when compared to the host rock that could be interpreted in terms of fractures within the basement rocks. The Karous-Hjelt filter (Karous & Hjelt, 1983) uses the linear fit theory to solve the integral equation for the current density. This forms the basis of the overall interpretation and delineation of potential fracture zone and or mineralized zones.

For the HRP, the resistivity is calculated from the relationship below where K is termed the Geometrical Factor, dependent on the type of electrode array:

$$\rho_a = K \cdot \Delta V/I \qquad (1)$$

Because the earth is not homogeneous and isotropic, the measured resistivity is generally addressed as apparent resistivity ρ_a (ROY & APPARAO, 1971; KELLER & FRISCHKNECHT, 1966). Hence, direct interpretation of the apparent resistivity values with respect to the inter-electrode spacing (a) was employed for quantitative interpretation of the HRP results.

RESULTS AND INTERPRETATION

VLF-EM Surveys

As highlighted earlier, the acquired field data were processed to simplify the obtained complex information. The representative results of the Fraser model filtered data plots as well as Karous-Hjelt filter 2-D inversion current density plots for Profiles 1, 5 and 6 are presented in Figures 4 to 6. The 2-D inversion shows the variation of apparent current density, and change in conductivity with depth. With such apparent current density cross-section plots, it is possible to qualitatively discriminate between conductive and resistive structures where a high positive value corresponds to conductive subsurface structure and low negative values are related to resistive one (BENSON et al., 1997; SHARMA & BARANWAL, 2005).

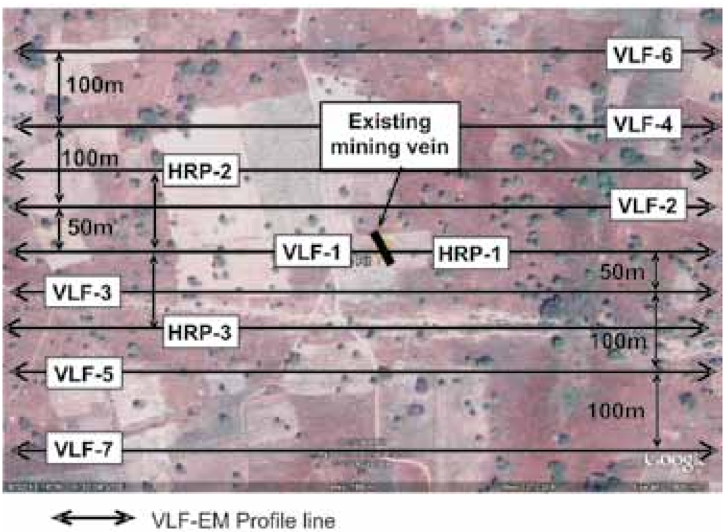

Figure 3. Lay-out of the field measurements for VLF-EM and HRP operation

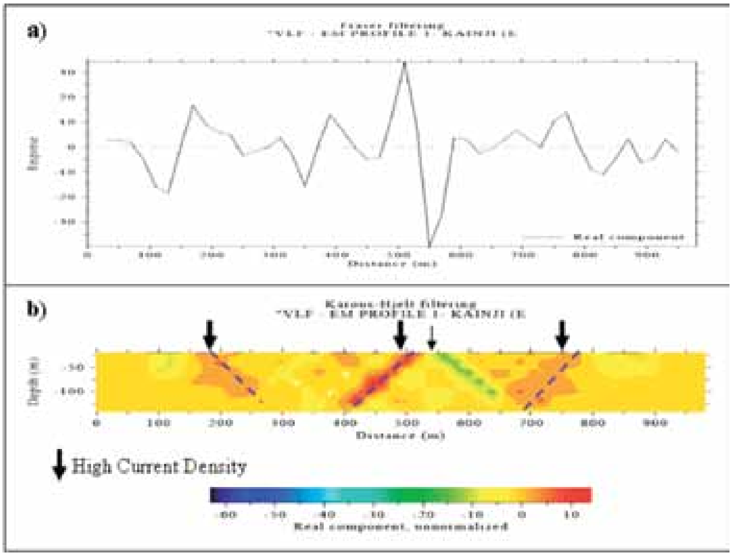

Figure 4. Fraser model filtered data plots and the Karous-Hjelt current density plots showing inferred fracture and / potential mineralized zones for VLF-EM Profile – 1

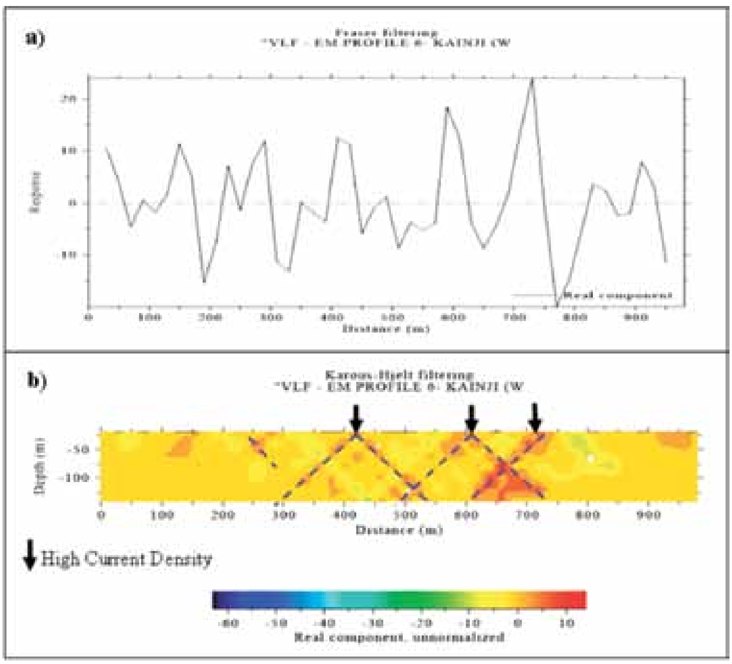

Figure 5. Fraser model filtered data plots and the Karous-Hjelt current density plots showing inferred fracture and / potential mineralized zones for VLF-EM Profile – 6

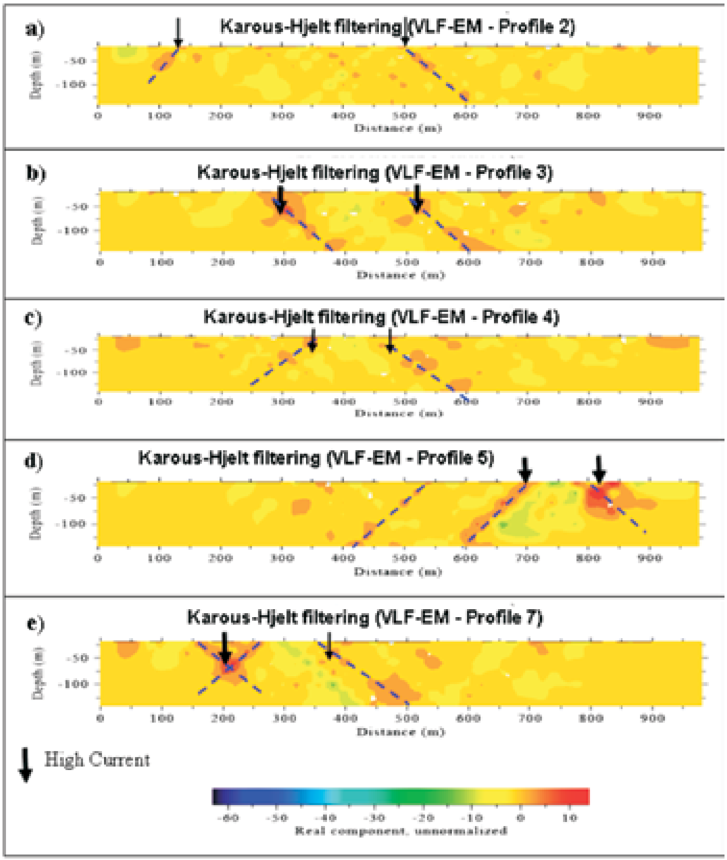

Figure 6. Fraser model filtered data plots and the Karous-Hjelt current density plots showing inferred fracture and / potential mineralized zones for VLF-EM profiles 2, 3, 4, 5 and 7.

The apparent current density cross-section of profile 1 (Figure 4) reveals the presence of a major anomaly at the central section of the profile (at about 500 m). Qualitatively it is hard sometimes to discriminate between deep and shallow sources, partly due to possible influence of water saturation (NOBES, 1996; SHARMA & BARANWAL, 2005). However, this anomaly coincided with the existing mineralized vein in the study area. Furthermore, two high current density zones at about 200 m and 750 m along the profile (Figure 4) can also be inferred as indications of the potential subsurface fracture systems and/or mineralized zones. In addition, the Fraser filtered data plots and the Karous-Hjelt current density plot for profile 6 as presented in Figure 5 revealed a number of anomalies which reflect conductive subsurface structural trends of inferred fractures and/or mineralized zones. These together with other high current density zones as outline in Figure 6 represent apparently fractured and jointed quartz fillings associated with gold mineralization. However, an incline vein, dipping to the right at 540 m of VLF profile 1, having negative real component value of about –10 to –20 (zone marked X) represents fracture/vein apparently filled with unsaturated materials such as massive non-fractured quartz veins. This type of zone as also evident along profiles 2, 5 and 6 are, unlike the mineralized zones, usually associated with massive barren quartz veins with no gold mineralization. Similarly, 2D current density cross-section plots of VLF-EM profiles 2, 3, 4, 5 and 7 showing inferred fracture and / potential mineralized zones are presented in Figures 6 a, b, c, d and e respectively.

These apparent current density cross-sections disclose a number of anomalies with structural disposition at depths that can be attributed to subsurface structural features which may be mineralized. Although the exploration depth in the study area is expected to be about 50 m, the representative apparent current cross-sections of profiles 3, 4, 5 and 7 (Figure 6) exhibited conductive anomalies at much greater depths. This can be attributed to a combination effect of fracture systems with or without mineralization but saturated with groundwater systems at depths. In other words, the development of conductive zones of high apparent current with positive values reflects inferred subsurface structural fractures and/or mineralized zones.

Horizontal Resistivity Profiling (HRP) Surveys

As pointed out earlier, Wenner electrode configuration with constant electrode separation of a = 15 m and inter-station distance of 15 m was adopted for effective lateral coverage of the subsurface in the study area. HRP profile 1 coincides with VLF–EM profile 1, i.e. at the center of the survey area while HRP profiles 2 and 3 are 100 m to the north and south of profile 1 respectively. The field data for the HRP surveys were presented in form of profile plots as presented in Figures 7, 8 and 9 below, indicating the apparent ground resistivity trends against distance along W–E direction.

As shown in HRP profile 1 (Figure 7), the two closely spaced existing mineralized veins exhibited apparent resistivity low of about 110 Ω m. The additional two low resistivity zones around 200 m and 700 m are consistent with the high current density zones at about 200 m and 750 m along the VLF-EM profile 1 (see Figure 4). These can also be inferred as indications of the potential subsurface fracture systems and/or mineralized zones.

Therefore, baring minor discrepancies in the data which could be due to irregularity in surface topography as well as non-linearity of the profile lines, resistivity values of less than 110 Ω m may be inferred as threshold value indicative of areas with similar electrical resistivity properties as the known mineralized vein. Hence such identified low resistivity zones as also highlighted in Figures 8 and 9 for HRP 2 and 3 respectively could be taken as potential zones for further ground-truthing in form of reconnaissance pitting and geochemical survey / sampling.

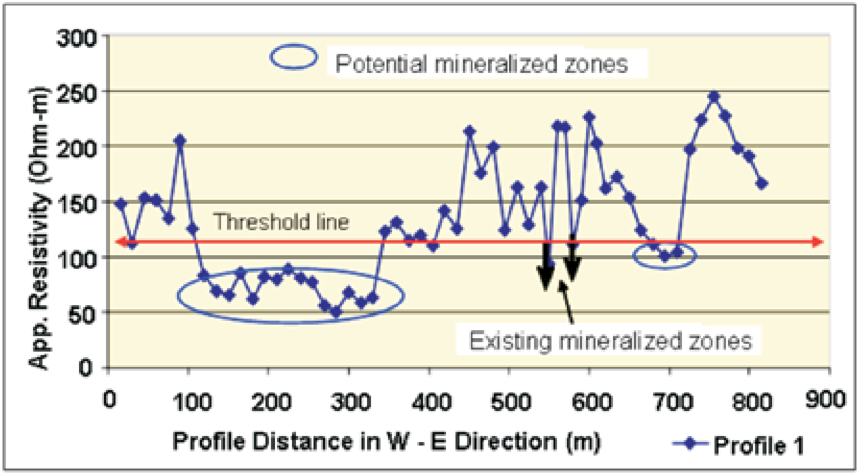

Figure 7. Plot of HRP data indicating the trends of apparent ground resistivity against distance for HRP – 1

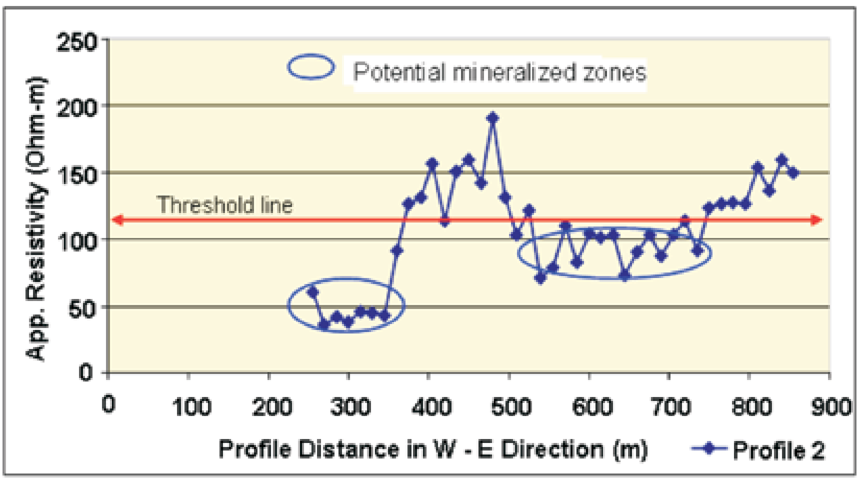

Figure 8. Plot of HRP data indicating the trends of apparent ground resistivity against distance for HRP – 2

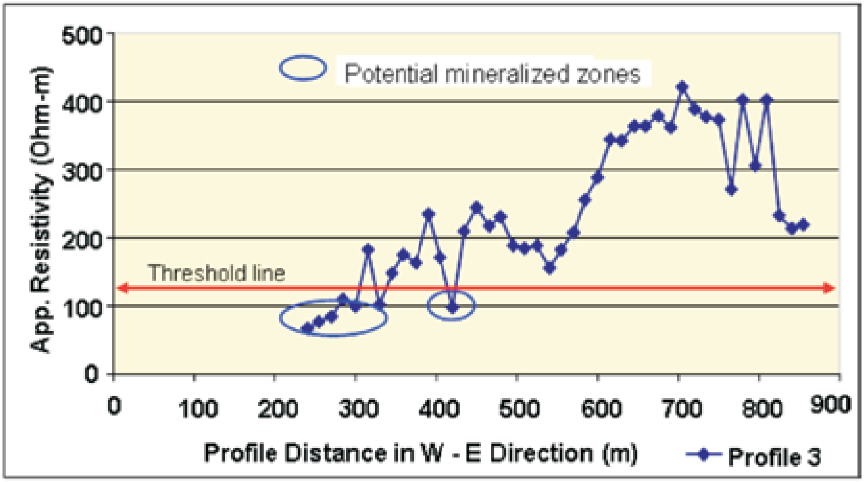

Figure 9. Plot of HRP data indicating the trends of apparent ground resistivity against distance for HRP – 3

Synthesis and conclusion

This study presents the results of the combined application of VLF-EM and electrical resistivity profiling HRP methods in highlighting the distribution of subsurface structural lineaments. Based on the VLF-EM data plots, Profile 1 filtered result as shown in Figure 4 shows major fracture patterns at the center of the profile about 500 m midway along the profile. As indicated the two identified fractured zones coincide with the known mineralized zones where there are active illegal mining activities as at the time of this study. The fracture on the left (about 500 m) was determined from the plot to be about 18 m in diameter, about 120 m in length and dipping at about 35°. Therefore, the results of EM profile-1 are in good agreement with field observation.

Similarly, EM-VLF profile 6 as presented in Figure 5 as well as profiles 2, 3, 4, 5 and 7 presented in Figure 6 display areas with isolated and high current density values; similar to region with gold mineralization enrichment in profile-1. For example, EM-profile 6 in particular displays structural controlled zones of high conductivity at about 400 m, 600 m and 700 m along the profile. Likewise, profiles 3, 5 and 7 (see Figure 6) display similar zones with high conductivity. The values of current density in all these cases are in excess of 8 which could have been due to the high conductivity of infill material within the fracture zones, suspected to be similar to that established in EM-profile 1.

Qualitative interpretation of VLF-EM profiles using different linear filtering such as Fraser and Karous–Hjelt filters (Figures 4 to 6) show a number of subsurface low resistivity zones in the study area, most of which are reflected as subsurface image of narrow linear features on the apparent current density cross-sections. The disposition of these linear features revealed two sets of fractures systems with dips of about 30–40°; one dipping to the west and other dipping to the east with general strike direction of N–S at about 350° and 005°. This result demonstrates the consistency between qualitative and quantitative interpretation; in terms of relative disposition of the discrete conductors, frequency and influence of different anomalies size and depth as also observed by Al-Tarazi, et al., (2008).

As part of further evaluation and synthesis, the results of the HRP-1 indicate some regions with isolated low resistivity that are indicative of fractured zones which are likely filled with conductive deposit. HRP profile 1 (Figure 7) shows anomalous resistivity sink around 500 m; center of profile 1. This is in agreement with the VLF-EM profile-1 results as well as field observation. In addition a synthesis of the EM-VLF and HRP results for profile 1 as presented in Figure 10 revealed coincidental zones of high current density and low resistivity as potentials fracture/mineralized zones. This is also a clear indication of the usefulness and complementary nature of the integrated EM and resistivity studies employed in this study.

Similarly, a synthesis of the HRP results as presented in Figure 11 shows the combined plots of the three HRP profiles with identified inferred fracture zones. A rough extrapolation and correlation of the anomalous resistivity drops revealed potential fracture systems trending roughly in N–S direction at a strike of about 320° to 350° which is consistent with the general structural trends of fracture systems in the study area. Consequently, these zone defines the potential fracture zones worthy of further investigation as to the possibility of mineralization or otherwise within the fracture systems.

On the final analyses integrating and synthesizing the results of all the EM-VLF and HRP profiles together, a number of isolated potential fracture zones, with high current density, as interpreted from both EM and resistivity surveys were identified as highlighted in Figure 12. As shown in Figure 12, it is possible to order and link the distribution of the potential fracture zones together resulting in a more or less N–S trends. This is consistent with the trends observed for the HRP profiles as presented in Figure 11.

In terms of possible gold mineralization potential, it can be concluded that zones with high current density identified on the VLF-EM profiles as well as regions of low resistivity as identified on the HRP profiles are potentially structurally controlled fracture zones that are likely to be mineralized with gold or related mineral deposits. Therefore, a follow-up geochemical exploration involving pitting and sampling at those zones as well as geochemical analyses can be recommended as parts of the next phase of the exploration strategy for gold mineralization enrichment in the study area. Such follow-up geochemical study will be required to understand the grade of the mineralization of the suspected fracture zones and the possible geochemical control. This will serves as basis for estimation of possible cut-off grade.

Furthermore, the presence of cross joints within suspected shear zones around the south-west portion of the study area (Figure 12), should be examined further to ascertain their positions more accurately and their potential for hosting mineralization. This may however, warrants additional geophysical investigation specifically targeted at determination of the geometrical parameters and disposition of the mineralized fracture zones.

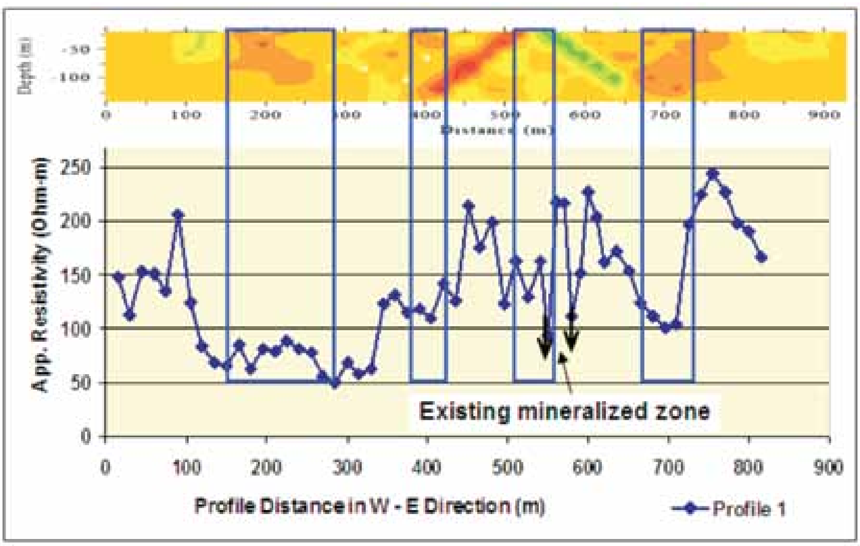

Figure 10. Combined plot of the EM-VLF and HRP results for profile 1 showing the zones of high current density and low resistivity as potentials fracture/mineralized zones

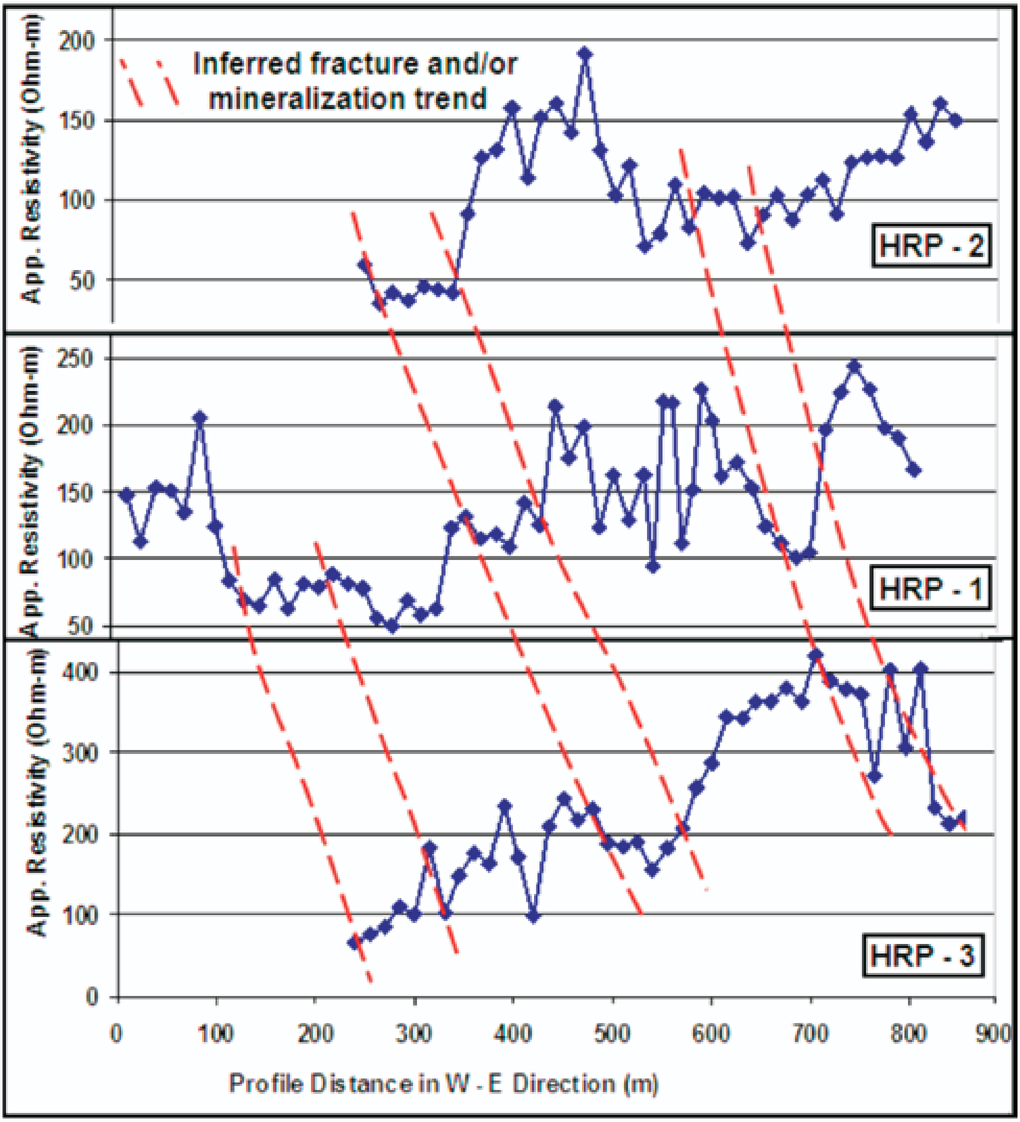

Figure 11. Combined plots of the HRP profiles showing inferred potential fracture/ mineralized zones

The interpretation and recommendation presented here are based on the field geophysical measurements and observations as well as both manual and computer-aided interpretation therefrom. However, in view of a number of field limitations, it should be noted that the respective estimated location of

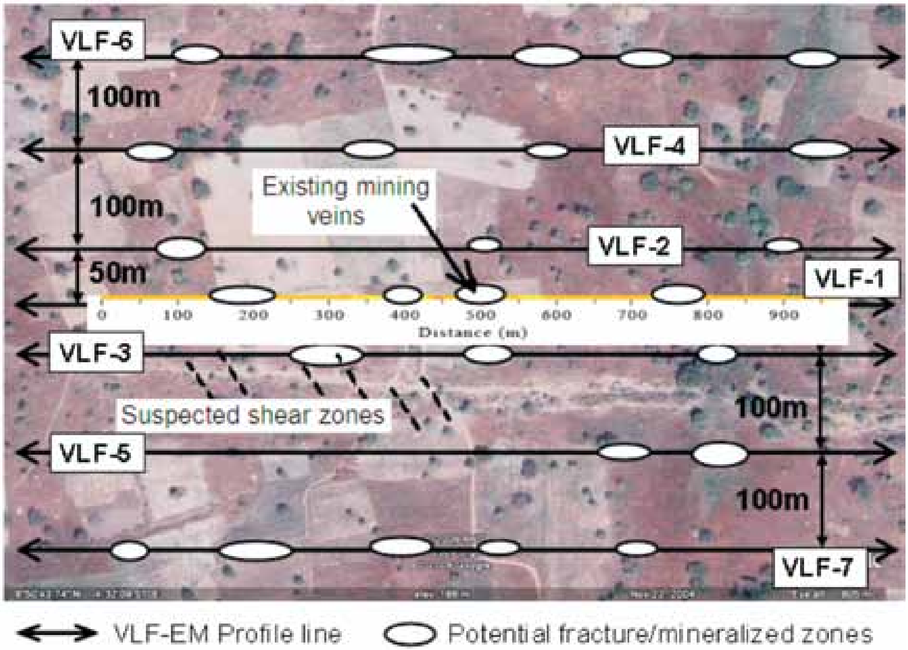

Figure 12. Isolated potential fracture zones with high current density as interpreted along the VLF-EM profiles. (NOTE: It is possible to order and link the distribution of these isolated zones together to form a more or less N–S trending fracture zones)

the identified potential fracture / mineralized zones are approximations within some margin of error of ±5 m. This can be attributed to non-linearity of the profile lines due to lack of properly cut survey lines, topographic variation along the profile lines etc. Nonetheless, irrespective of such field limitations, the results and interpretation presented herein provide enough geophysical basis for delineation of the potential fracture and/or gold mineralization zones on one hand, and on the other hand, provide basis for follow-up detail geological-geochemical exploration studies.

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References

Al-Tarazi, E., Abu Rajab, J., Al-Naqa, A. & El-Waheidi, M. (2008): Detecting leachate plumes and groundwater pollution at Ruseifa municipal landfill utilizing VLF-EM method *Jour. Appl. Geophysics;* Vol. 65, pp. 121–131.

Aristodemu, E., Thomas-Betts, A. (2000): DC resistivity and induced polarization investigations at a waste disposal site and its environments. *Jour. Appl. Geophysics; Vol.* 44, pp. 275–302.

Babu, R. V., Ram, S. & Sundararajan, N. (2007): Modeling and inversion of magnetic and VLF-EM data with an application to basement fractures: A case study from Raigarh, India. *Geophysics;* Vol. 72**,** B133–B140.

Benson, A. K., Payne, K. L., Stubben, M. A. (1997): Mapping groundwater contamination using DC resistivity and VLF geophysical methods - a case study. *Geophysics*; Vol. 62, pp. 80–86.

Bernstone, C., Dahlin T., Ohlsson T. & Hogland, W. (2000): DC-resistivity mapping of internal landfill structures: two pre-excavation surveys. *Environ Geol;* Vol. 39, pp. 360–371.

Chouteau, M., Zhang, P., Chapellier, D. (1996): Computation of apparent resistivity profilesfrom VLF-EM data using linear filter. *Geophysical Prospecting; Vol.* 44, pp. 215–212.

Dahlin, T. (1996): 2D resistivity surveying for environmental and engineering applications. *First Break;* Vol. 14, pp. 275–284.

Draskovits, P., Vero, L. (2005): Indication of groundwater contamination with the induced –polarization (IP) method. In: Butler, Dwain K. (Ed.), *Near-Surface Geophysics*. SEG Tulsa, OK, pp. 551–561.

Fraser, D. C. (1969): Contouring of VLF-EM data. *Geophysics*; Vol. 34, pp. 958–967.

Frohlich, R. K., Parke, C. D. (1989): The electrical resistivity of the vadose zone – field study. *Groundwater;* Vol. 27, No. 4, pp. 524–530.

Frohlich, R. K., Urish, D. W., Fuller, J., O'Reilly, M. (1994): Use of geoelectrical methods in groundwater pollution surveys in a coastal environment. Jour. Appl. Geophysics; Vol. 32, pp. 139–154.

Gharibi, M., Pedersen, L. B. (1999): Transformation of VLF data into apparent resistivities and phases. *Geophysics;* 64, pp. 1393–1402.

Gokturkler, G., Balkaya C., Erhan, Z. & Yurdakul, A. (2008): Investigation of a shallow alluvial aquifer using geoelectrical methods: a case from Turkey. *Environ Geol*ogy; Vol. 54, pp. 1283–1290.

Jones, H. A., and Hockey, R. D. (1964): The Geology of part of Southwestern, Nigeria. *Geol. Surv. of Nigeria Bull.*, No. 31, 101p.

Karlik, G. & Kaya, M. A. 2001. Investigation of groundwater contamination using electric and electromagnetic methods at an open waste-disposal site: a case study from Isparta, Turkey. *Environ Geology*; Vol. 40, pp. 725–731.

KAROUS, M. R. & HJELT, S. E. (1983): Linear filtering of VLF dip angle measurement, *Geophysical Prospecting*; Vol. 31, pp. 782–794.

KELLER, G. V. & FRISCHKNECHT, F. C. (1966): *Electrical Methods in Geophysical Prospecting.* Pergamon Press.

LIGAS, P., PALMOBA, M. (2006): An integrated application of geological–geophysical methodo-logies as a cost-efficient tool in improving estimation of clay deposit potential: Case study from South-Central sardine (Italy). *Ore Geology Reviews;* Vol. 29, pp. 162–175.

MCNEILL, J. D., LABSON, V. F. (1991): Geological mapping using VLF radio fields. In: Nabighian, M.C. (Ed.), *Geotechnical and Environmental Geophysics, Review and Tutorial*, Vol. 1, Society of Exploration, Tulsa, pp. 191–218.

MILSOM, J. (1989): *Field Geophysics*. Geological Society of London Handbook. Publ. Open University Press.

NGSA (2006): Lineament and Geological Map of Nigeria, Scale 1:100 000

NOBES, D. C. (1996): Troubled waters: environmental application of electrical and electro-magnetic methods. *Surveys in Geophysics;* Vol. 17, pp. 393–454.

ODEYEMI, I. B. (1976): Preliminary report on the field relationships of the Basement of Complex rocks ground Igarra, Midwest. In Kogbe, C.A. (1976 Ed.), *Geology of Nigeria*. Elizbethan publishers, Lagos, Nigeria, pp. 59–63

ODEYEMI,. I. B. (1981): A review of orogenic events in the Precambrian Basement of Nigeria, West Africa. *Geologische Rundschau;* Vol. 70, No. 3, pp. 897–909

OLORUNFEMI, M. O. & MESIDA, E. A. (1987): Engineering geophysics and its application in engineering site investigation – Case study from Ile-Ife area. The Nigerian Engineer, Vol. 22, pp. 57–66.

OSKOOI, B., PEDERSEN, L. B. (2005): Comparison between VLF and RMT methods. A combined tool for mapping conductivity changes in the sedimentary cover. Jour. Appl. Geophysics; 57, pp. 227–241.

OYAWOYE, M. O. (1970): The Basement Complex of Nigeria, In: T. F. J. Dessauragie, and Whiteman (Eds), African Geology. Ibadan University Press. Nigeria, pp. 67–78.

RAHAMAN, M. A. (1976): Review of Basement Geology of South western Nigeria. In Kogbe, C.A. (Ed.) Geology of Nigeria, Elizabethan Publ. Co., Lagos, pp. 41–58.

ROY, A. & APPARAO. A. (1971): Depth of investigation in direct current resistivity prospecting. *Geophysics*; Vol. 36, pp. 943–959.

SAYDAM, A. S. (1981): Very low-frequency electromagnetic interpretation using tilt angle and ellipticity measurements. *Geophysics;* Vol. 46, pp. 1594–1605.

SHARMA, P. V. (1997): *Environmental and Engineering Geophysics*, Cambridge University Press, 173p.

SHARMA, S. P., BARANWAL, V. C. (2005):

Delineation of groundwater-bearing fracture zones in a hard rock area integrating very low frequency electromagnetic and resistivity data. *Jour. Appl. Geophysics*; Vol. 57, pp. 155–166.

SPORRY, R. (2004): Geophysical techniques in groundwater Investigations. In: V. S. Kovalevsky, G. P. Kruseman, and K. R. Rushton (Eds.); *Groundwater studies - An international guide for Hydrogeological investigations.* UNESCO IHP-VI, Series on Groundwater No.3, pp. 133–183.

STEEPLES, D.W. (2001): Engineering and environmental geophysics at the millennium. *Geophysics;* Vol. 66, pp. 31–35.

TELFORD, W. M., GELDART, L. P., SHERIFF, R. E. (1990): *Applied Geophysics*. Second Edition, Cambridge University Press.

WRIGHT, J. L. (1988): VLF interpretation manual. EDA Instrument, Toronto, Ontario, Canada.