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ESTIMATION OF GROUND DEPTH OF RADIOELEMENTS SOURCES IN OGUN STATE, SOUTHWESTERN NIGERIA USING GRADIENT TECHNIQUES

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ABSTRACT

Radioelement exploration has gained economic interest recently due to its usefulness in the detection and delineation of mineral deposits. In this study, the airborne radiometric data were analysed for depth estimation of the radioelement deposit in Ogun state, Nigeria. Three enhancement gradient techniques, namely; Analytical Signal Amplitude (ASA), Horizontal Gradient Magnitude (HGM) and Local Wave Number (LWN) were employed to estimate the possible depth of radioelements for mineralization. Geosoft's (Oasis Montaj) software and Potential Field's (PF) software were used to conduct the estimations. The result obtained revealed shallow sources of 0.584 km (LWN) and 0.387 km (ASA), and deep-seated sources of 5.950 km (ASA) and 5.880 km (ASA) for uranium and thorium, respectively. The shallow source and deep source for potassium are 0.259 km (ASA) and 2.540 km (ASA), respectively. In this study, the position and depth of the source were automatically estimated using linear equations based on derivatives without the use of any a priori knowledge. The three gradient methods are therefore found suitable in estimating the depth to radioelement anomalous source.

Keywords: Depth of radioelement, Enhancement, Gradient techniques, Ogun State.

INTRODUCTION

Numerous derivative-based automatic techniques have been created to ascertain the source parameters, such as location boundaries and depth estimation of mineral deposits (Blakely, 1995; Nabighian *et al.,* 2005). Some of the techniques that are primarily used for potential field issues are Wener deconvolution (Ku and Sharp, 1983), Euler deconvolution (Paterson *et al.*, 1991; Keating, 1998; Mushayandebvu *et al.,* 2004), Analytic Signal (Keating and Sailhac, 2004), Tilt derivatives (Fairhead, 2008; Oruc, 2010), Balanced horizontal derivatives (Ma *et al.*, 2014), Enhanced local wave (Salako, 2014).

In order to interpret and estimate the source parameters of either potential or non-potential field data, other authors, including Cordell, (1979); Thompson (1982); Cordell and Grauch, (1985); Reid *et al.* (1990); Millar and Singh (1994); Verduzo *et al.* (2004); Cooper and Cowan, (2006); Abderahman *et al.* (2007); Salem *et al.* (2007); Ma and Li, (2012); Beamish (2016); Ogunsanwo *et al.* (2022), have used one or more enhancement and filtering procedures. Many potential field studies have used gradient techniques to determine the potential depth of contrast (Salem *et al.,* 2007; Badmus *et al.,* 2013).

Various gradient techniques have been employed by many authors to display the depth of both shallow and deep sources Miller and Singh, 1994; Rajagopalan and Milligan, 1995; Verduzco *et al.,* 2004; Wijns *et al.,* 2005; (Cooper and Cowan, 2006; Ma and Li, 2012; Ma, 2013a). Edge detection filters' maxima automatically delineate the sources' edges (Cooper and Cowan, 2008; Ma, 2013b). The edge of the zones connected to contrast in flux behaviour is primarily estimated using the enhancement procedures.

Some authors (Cordell, 1979; Hood and Taska, 1989; Thurston and Smith, 1997; Smith *et al.* (1998); Thurston *et al.,* 2002; Smith *et al.,* 2005; Salem and Smith, 2005) opined that the maxima of the total horizontal derivatives and the zero of the vertical derivatives correspond to the edge of the source. It is used to distinguish the source detector response due to the action of the metamorphic and secondary geological processes like supergene alteration and leaching that may be indicated by variation in radioelement concentration within the bedrock geological units.

All of the earlier research relied on automated techniques to interpret potential field issues. Therefore, this study considers the application of derivative techniques to radiometric data (non-potential field data) using the Blakely (1995) method. According to Nabighian *et al.* (2005), the processing used on potential field data sets has been well-developed and documented in numerous literatures. According to Beamish (2012) research, non-potential field data can be transformed in the same way as a potential field as long as the necessary inherent filtering procedures are taken into account. Three-stage processes as outlined by Blakely (1995) were used to successfully complete the transformation. These were carried out in an effort to determine the depth from the anomalous source of the radioelement in Ogun state, south-western, Nigeria.

STUDY AREA

The study area is situated between latitudes 6.2° to 7.8° and longitude 3.0° to 5.0°, in the tropical rainforest, south-western, Nigeria. Its geological formation consists of Precambrian basement which is found to be overlaid by the Sedimentary terrain. The identified rock units associated with the study area are Granite, Migmatite, Undifferentiated Schist, Granodiorite, Muscovite, Quartzite schist, Coarse Porphyritic biotite; Sands, clay and Shale, Sandstone and Limestone. Akinrinde and Obigbesan (2006), Badmus and Olatisun (2009) and other authors with different geophysical approaches have established the presence of mineral deposits such as bitumen, phosphate, limestone, mica and kaolin to be dominant in the study area. Generally, granitic areas have been found to have great emissions of uranium and thorium which are also attributed to the deposition of mineral deposits.

To determine which of the bedrock units enhance radioelement the most and to what degree, geological identification of the rock units present in the study area is of utmost importance.

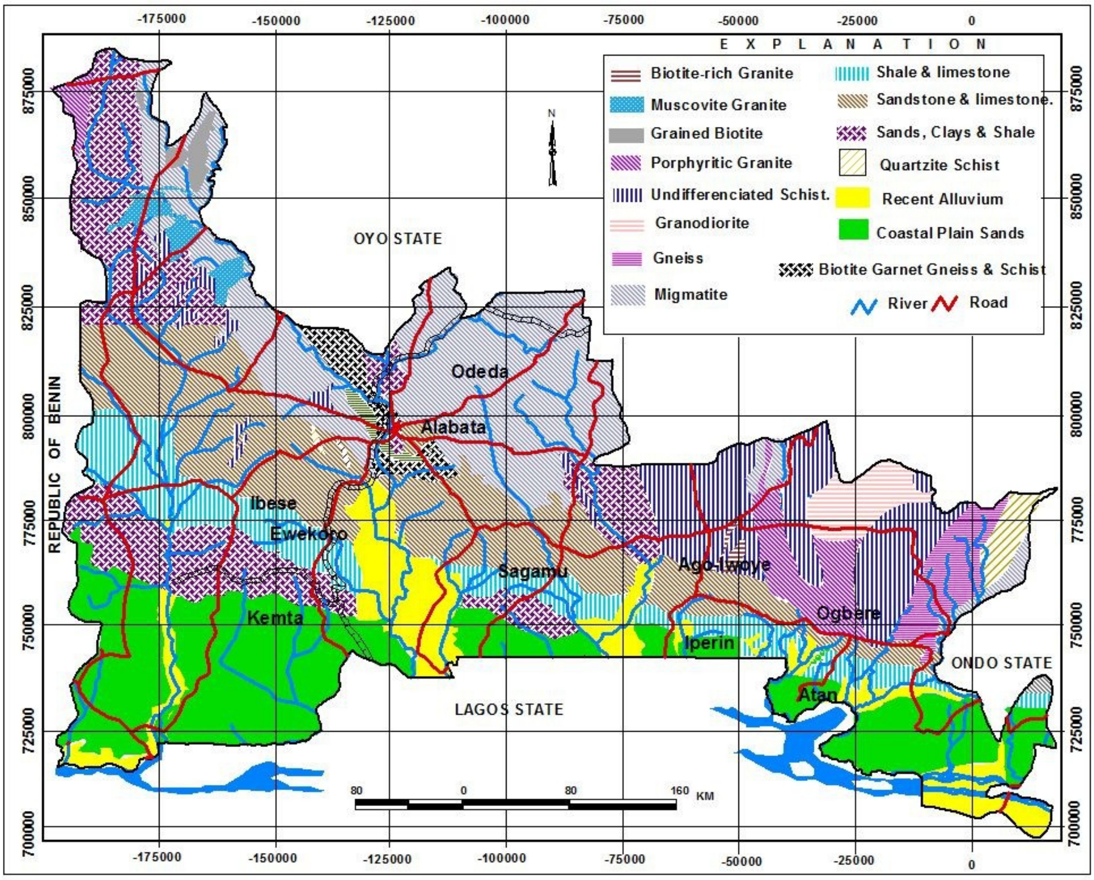

Figure 1: The rock unit map of the study area (Adapted from Nigerian Geologic Survey Agency, 2006).

MATERIALS AND METHODS

Airborne radiometric data

The airborne radiometric data for the study area (Ogun state) which consists of uranium, thorium and potassium was obtained from the Nigeria Geological Survey Agency. The collected radiometric data were analysed and interpreted in line with the geological map, which gives baseline information about the lithological bedrock composition and their responses to the radiometric parameters. The airborne radiometric survey was carried out such that a very high resolution gamma spectrometer containing Sodium Iodide (NaI) detector was flown across the study area at altitude range between 200 and 500 m with horizontal terrain interval of 120 m. The radiometric data were collected, analysed and subjected to different corrections in order to eliminate and reduce the noise associated with the radiometric anomalous flux to minimal. ^{238}U and ^{232}Th were then estimated from their decay daughter chain ^{214}Bi and ^{206}Tl, respectively, while potassium is obtained directly at energy 1.461MeV. The energy window used for each radioelement was in accordance with that of IAEA (2003) and Grasty (1991) procedure.

Gradient techniques

In this study three of the gradient techniques namely, Analytical Signal Amplitude (ASA), Horizontal Gradient Magnitude (HGM) and Local wavenumber (LWN), were put to test for radioelements depth estimation.

Analytic signal amplitude

The analytical signal amplitude was applied to the gridded observation of the radiometric field (T) using the relation proposed by Roest *et al.* (1992) as defined in Equation (1).

$$ASA = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \qquad (1)$$

where, $\partial T/\partial x$, $\partial T/\partial y$, $\partial T/\partial z$ are the first derivatives of the radiometric field T in the x,y and z directions.

Horizontal gradient magnitude

Horizontal gradient magnitude (HGM) has been found to produce more accurate and reliable result when used for both edge and depth estimation (Grauch *et al.,* 2001). In view of this, the gridded radiometric field data sets were subjected to HGM analysis using the relation proposed by Grauch *et al.* (2001) in Equation (2)

$$HGM = \sqrt{(dx)^2 + (dy)^2} \qquad (2)$$

Local wave number

The radiometric data sets were analysed using the local wave number or source parameter imaging method to estimate the anomalous source bodies and possible depth to radiometric flux contrast. In order to estimate the depth, the local wave number, k_1, need to be determine using the Thurston and Smith (1997) procedure.

The local wave number k_1 is defined in Equation (3) given by Thurston and Smith (1997) as

$$k_1 = \frac{\partial}{\partial x}\tan^{-1}\left[\frac{\partial T}{\partial z} \Big/ \frac{\partial T}{\partial x}\right] \qquad (3)$$

Then, the depth (h) is obtained in Equation (4) as

$$h = \frac{1}{k_1} \qquad (4)$$

RESULTS AND DISCUSSION

Distribution of the radioelements

Figures 2, 3 and 4 show the surface map of the potassium, thorium and uranium across the study area. The maps depict the trend of the radioelements distribution across the study area. Potassium was found in the range of 0.0 – 3.0% while thorium was in the range of 0.0 – 150.0 ppm. Uranium concentrations exist in the range -1.0 – > 13.0 ppm. Three distinct levels were shown by the radioelement surface maps; low, moderate and high concentration levels.

Potassium concentrations distribution (Figure 2) are presented in the order of low (< 0.0 – 0.2%), moderate (2.1 – 1.3%) and high (1.4 – > 13.0%). Moderate potassium concentration (green) is shown in the central and North Eastern part of the study area being weathered basement terrain. High concentrations were found to overlap on the moderate concentrations in form of intrusion. The area with low potassium concentrations (gray) is that associated with recent alluvium and coastal plain region.

Thorium distributions are in the range of < 0.0 – 26.9 ppm for low concentration, 27.0 – 120.0 ppm for moderate concentration and > 120.0 for high concentration (Figure 3). The study area is predominantly with low thorium concentrations except at the central part where moderate and relatively high thorium trending NE and SE is experienced.

Uranium concentrations distribution (Figure 4) are classified in the order of low (< -1.0 – 1.7 ppm), moderate (1.8 – 10.5 ppm) and high (10.6 – > 13.0 ppm). Moderate uranium concentration (green) is found predominantly across the study area. Low concentrations are found in trace amount especially around the coastal plain region. Uranium is mobile in nature and might have been depleted as a result of water bodies, soil moisture and vegetation in that region. Highly peak uranium concentration was experienced in the NE part of the study area being a basement terrain.

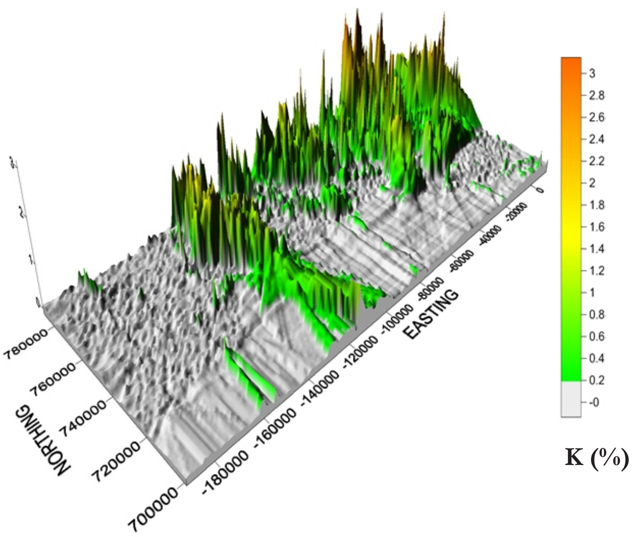

Figure 2: Surface map of potassium deposition in Ogun State.

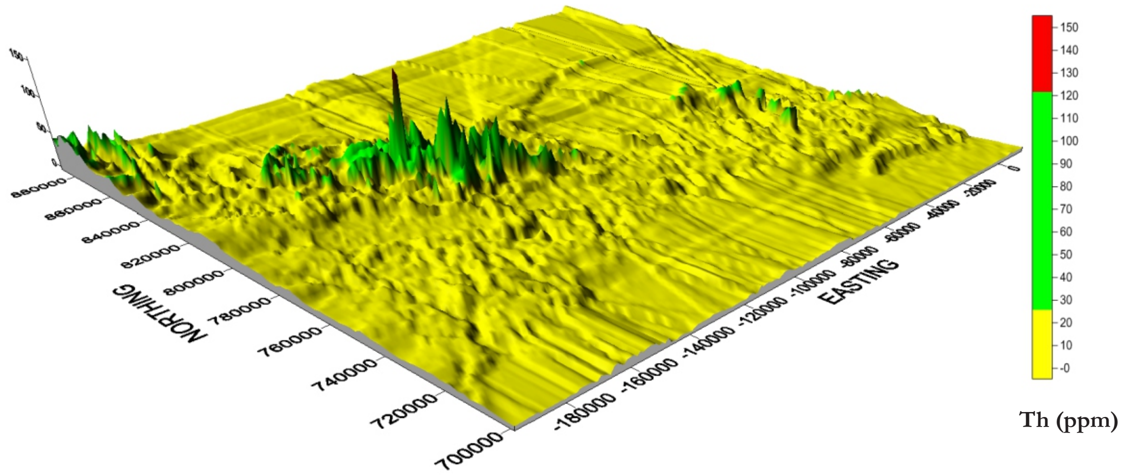

Figure 3: Surface map of thorium deposition in Ogun State.

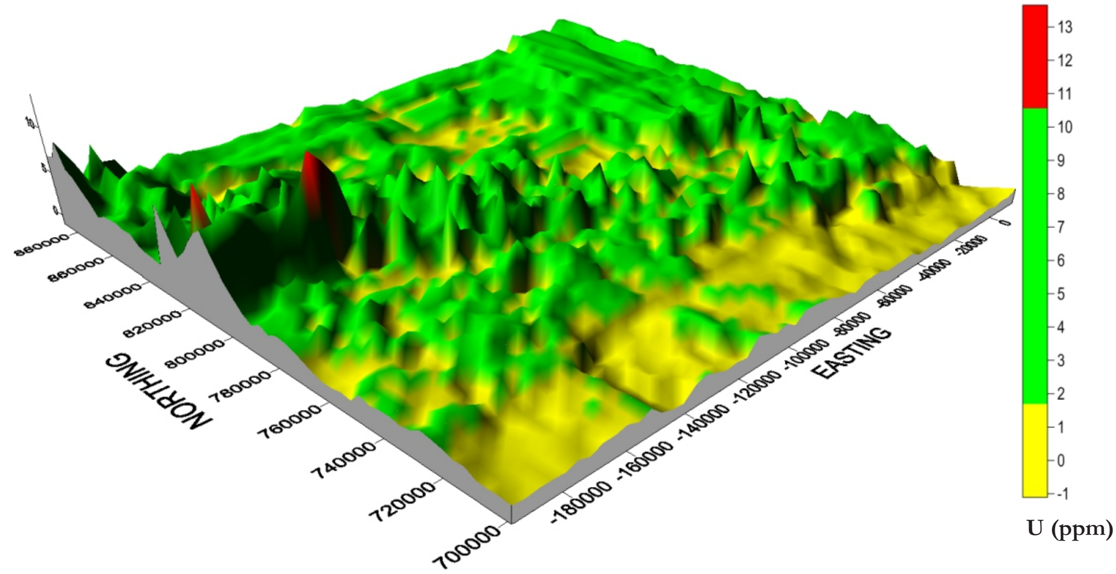

Figure 4: Surface map of uranium deposition in Ogun State.

Depth estimation result

The horizontal gradient method, the analytical signal method, and the local wave number method are three similar interpretation methods based on depth estimation of radioelement data that are compared in this section. The depth of the radioelements deposit were deduced as shown in Figures 5, 6 and 7, for the three gradient techniques; LWN, HGM and ASA, respectively. From the potential field (PF) software; Local wave number depth (Loc-dep), Horizontal gradient depth (H-dep) and Analytical signal depth (As-dep) were obtained for the radiometric data set following sequential procedures and transformations.

The result obtained for LWN depth estimate accounted for same depth for the three radioelements ranging from 0.584 – 2.090 km. The result obtained from LWN is questionable and may not be reliable as it gives no account of disparity in the depth estimate of the three radioelements. Although, the shallow source was obtained as 0.584 km and deep seated source was found to be 2.090 km for uranium, thorium and potassium, respectively in Figure 5. In case of ASA and HGM, there exists variation in depth obtained for the radioelements deposits (Table 1).

Table 1: Radioelement depth and edge source.

Radioelements	Depth Estimation (km)						Source Edge	
	ASA		**HGM**		**LWN**		**Minima**	**Maxima**
	Min	**Max**	**Min**	**Max**	**Min**	**Max**		
K	0.259	2.540	0.710	2.130	0.584	2.090	-0.625	0.597
Th	0.387	5.880	0.485	2.180	0.584	2.090	-0.057	0.044
U	0.736	5.950	0.804	5.070	0.584	2.090	-0.002	0.002

Uranium mineralization was found in the depth range of 0.804 – 5.070 km and 0.736 – 5.950 km for HGM and ASA respectively while thorium were in the depth range of 0.485 – 2.180 km for HGM and 0.387 – 5.880 km for ASA (Table 1). In a similar manner, potassium mineralization depth was within the range of 0.710 – 2.130 km and 0.259 – 2.540 km for HGM and ASA, respectively. The result obtained revealed two anomalous sources, namely; the shallow source and deep seated. For mineral exploration and exploitation, depth estimate of 1 km is recommended for shallow source while depth above 1 km is deep source (Philips, 2000; Salem *et al.,* 2005). LWN, HGM and ASA accounted for uranium shallow depth of 0.584, 0.804 and 0.736 km, respectively, which are found to be comparable. Thorium shallow depth as well gives the values of 0.584, 0.485 and 0.387 km for LWN, HGM and ASA respectively. The result shows proximity in the shallow source obtained for thorium. Potassium shallow source have the values of 0.584, 0.710 and 0.259 km for LWN, HGM and ASA respectively. Unlike uranium and thorium, potassium results revealed a wide range of disparity between the value obtained for HGM and ASA.

The apparent contact of ASA appears to be less continuous than the HGM method, making it structurally and geologically more noise sensitive. The results of quantitative depth analysis carried out were presented in Figures 5–7. The maxima are located in the centre of the circle, while its diameters show the estimated depth of the radioelement anomalous source for LWN, HGM and ASA gradient techniques for the three radioelements.

In the result obtained for LWN, there is an overestimation tendency of anomalous depth sources due to perturbations in the data set which may be consequence of near-surface seated interference. The result obtained shows that the three gradient techniques are good depth estimator of both the shallow and deep seated radiometric anomalous sources.

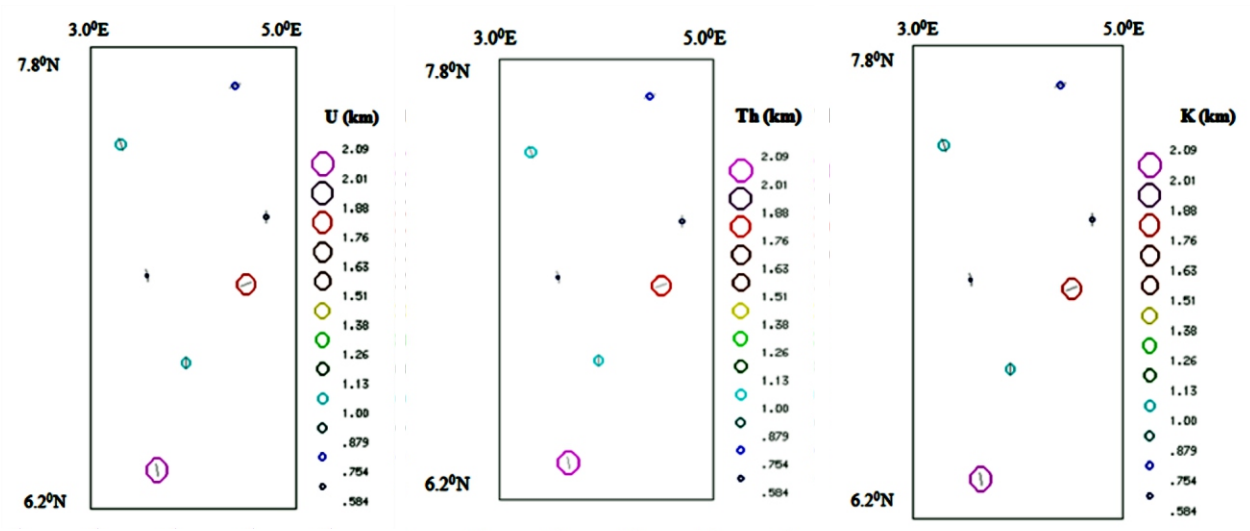

Figure 5: LWN Depth and mineral source location for (a) Uranium (b) Thorium (c) Potassium.

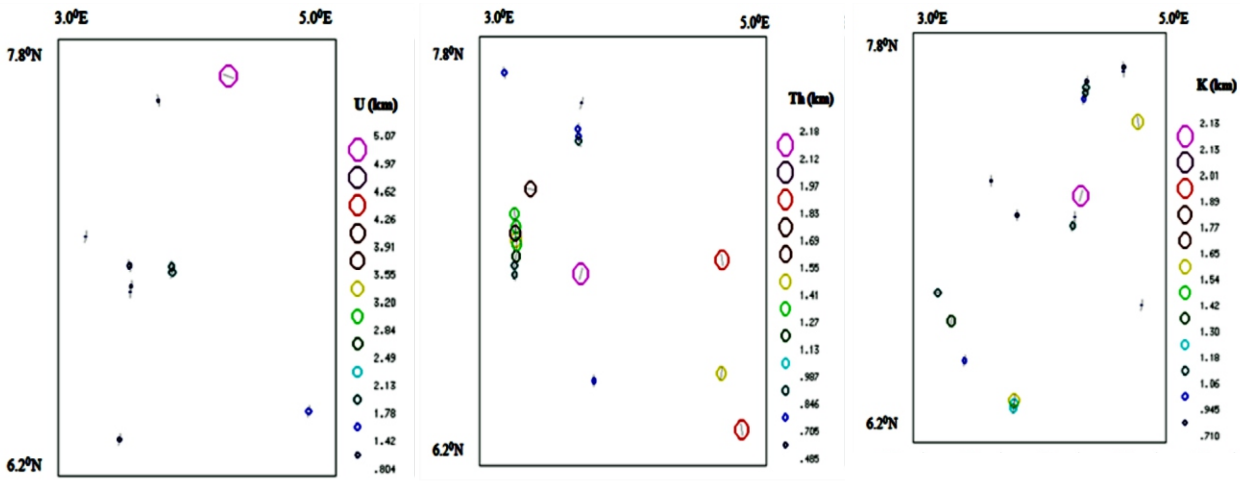

Figure 6: HGM Depth and mineral source location for (a) Uranium (b) Thorium (c) Potassium.

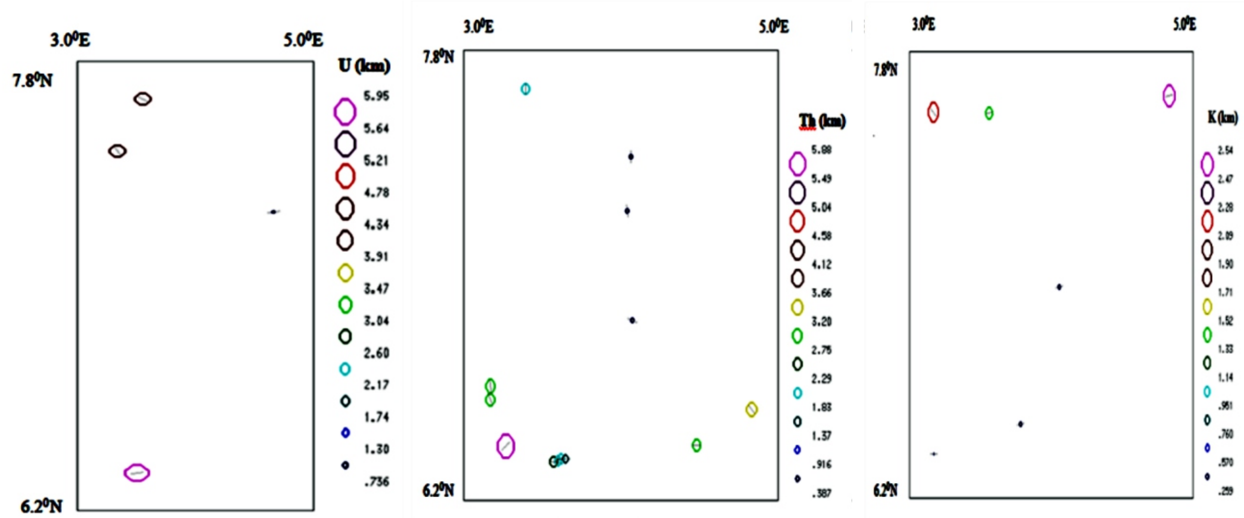

Figure 7: ASA Depth and mineral source location for (a) Uranium (b) Thorium (c) Potassium.

Edge source detector

The horizontal gradient magnitude (HGM) of the observed data was used to improve our capacity to resolve the edges of non-uniform source regions. Bi-directional gridding and the minimum curvature technique are the two algorithms that are most frequently used when mapping radioelement data. The minimum curvature algorithm was used in this study to produce a smooth grid of data. After obtaining the horizontal gradient magnitude (HGM) gridded data set, the usual processing step is to extract the HGM maxima as described by Blakely and Simpson (1986).

The peak or maxima of HGM of the radiometric field was to locate the causative source bodies represented by the edge of thin horizontal sheet. HGM provides causative sources bodies that are highly continuous, for this reason, the HGM method was applied. Using potential field (PF) software, series of program codes was developed for the radioelements (eU, eTh and K) in line with that of Open- File report (92-18-A-G), which are majorly used in geophysical map interpretation of potential field, radiometric and remote sensing data set (Philip, 1997).

The edges of the anomalous region could be recognized as maxima in the HGM response. The Potassium (Figure 8) was found to have maxima edge of 0.597 and minima edge of -0.625. Thorium and uranium maxima edge source were found (Figures 9 and 10) to be 0.044 and 0.002 respectively, while the minima values are -0.057 and -0.002, respectively.

The method provides improved resolution of the lateral contributions to changes in flux behaviour as a result. The radiometric anomalies' steepest and flattest portions are where the horizontal gradient maxima and minima are found. The extent of small scale contributions to the response is revealed by the high resolution HGM analysis, and there is a clear correlation between the radiometric anomalous response and the major bedrock types. These effects are widespread and include contributions from bedrock lithologies, modifications to soil characteristics, artificial soil removal (quarrying), water bodies, and specific types of vegetation.

Thorium and Uranium were observed to be discrete while potassium has intruded in the lineament edge enhancement which is continuously embedded towards the coastal region. Potassium has a continous pattern (Figure 8) due to the fact that it is one of the radioelement found in abundance on and within the earth's crust unlike uranium and thorium. The behaviour of the anomalous response characteristics suggests that the scale length of the anomalous region controls the lateral scale of the source response. The anomalous sharp decrease in radioelement response of background value, which marks the source region's edges, is easy to spot. Many of the localized responses, according to Beamish (2015), are probably soil-related which depends on factors such as density and wetness. In uranium, thorium, and potassium, the HGM edge detection filter recognizes edges that are more accurate and noise-resistant.

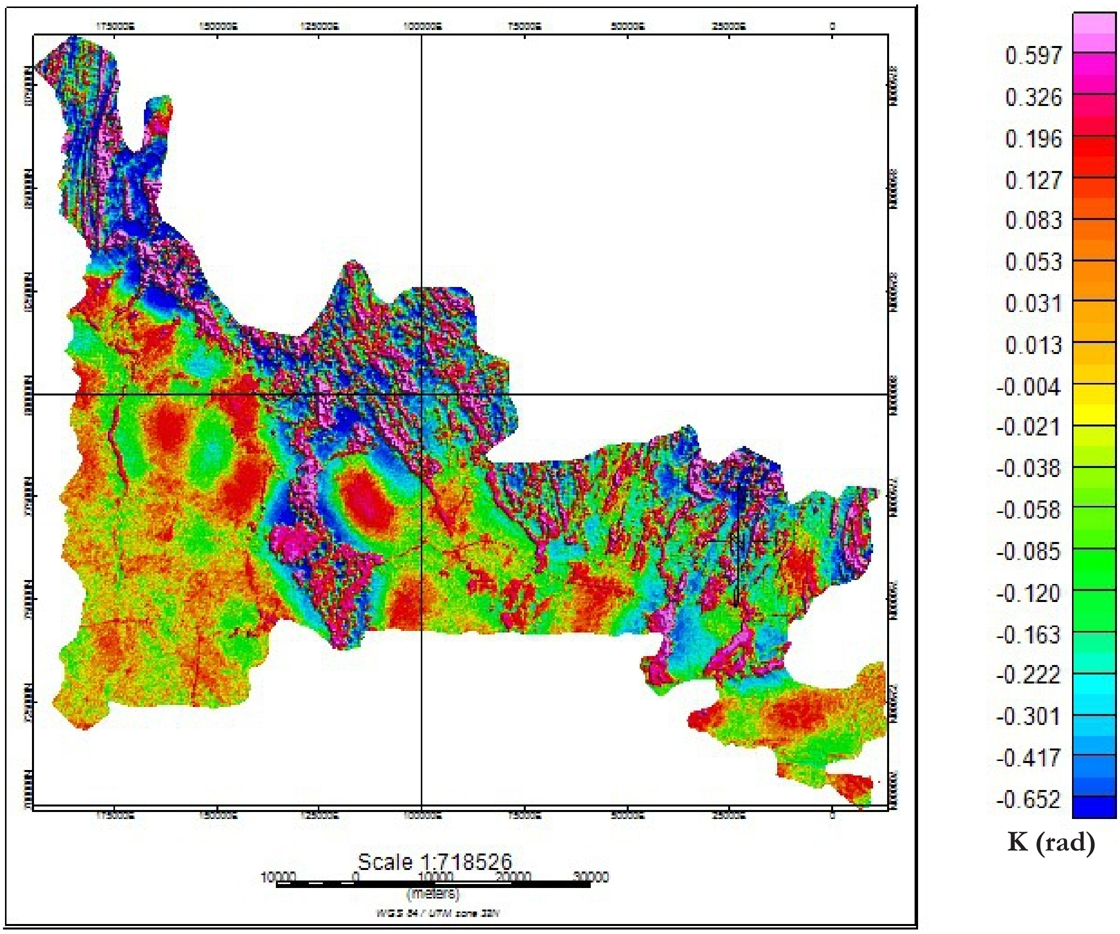

Figure 8: Potassium edge source in radian.

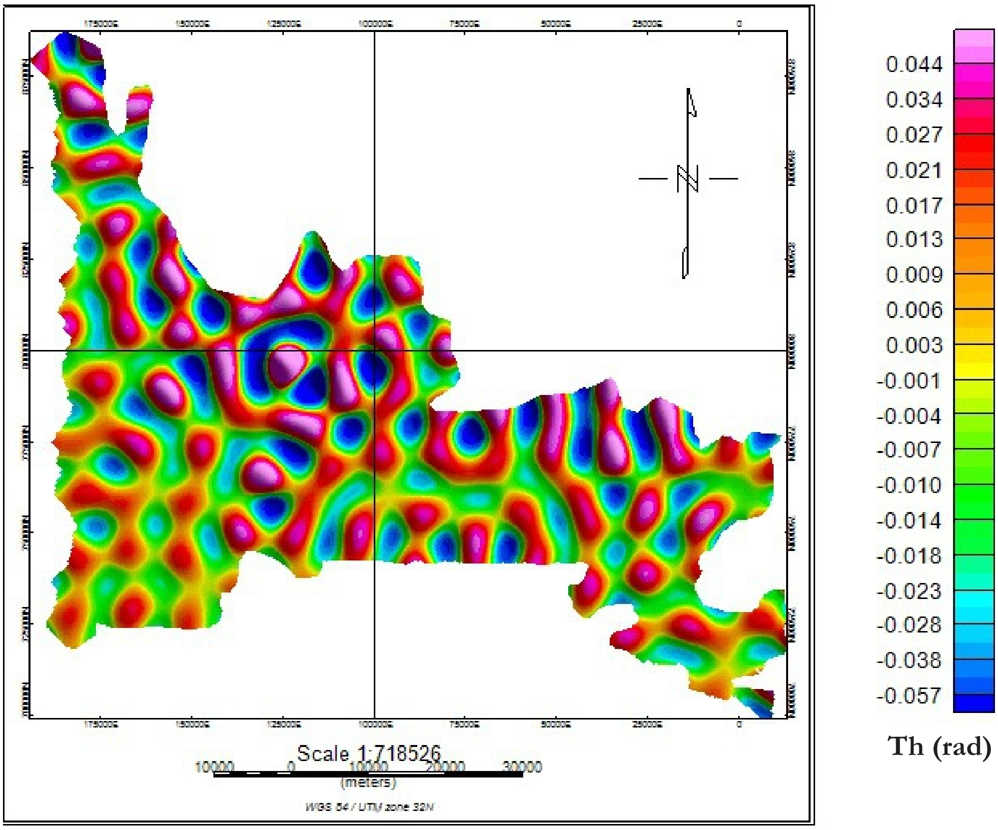

Figure 9: Thorium edge source in radian.

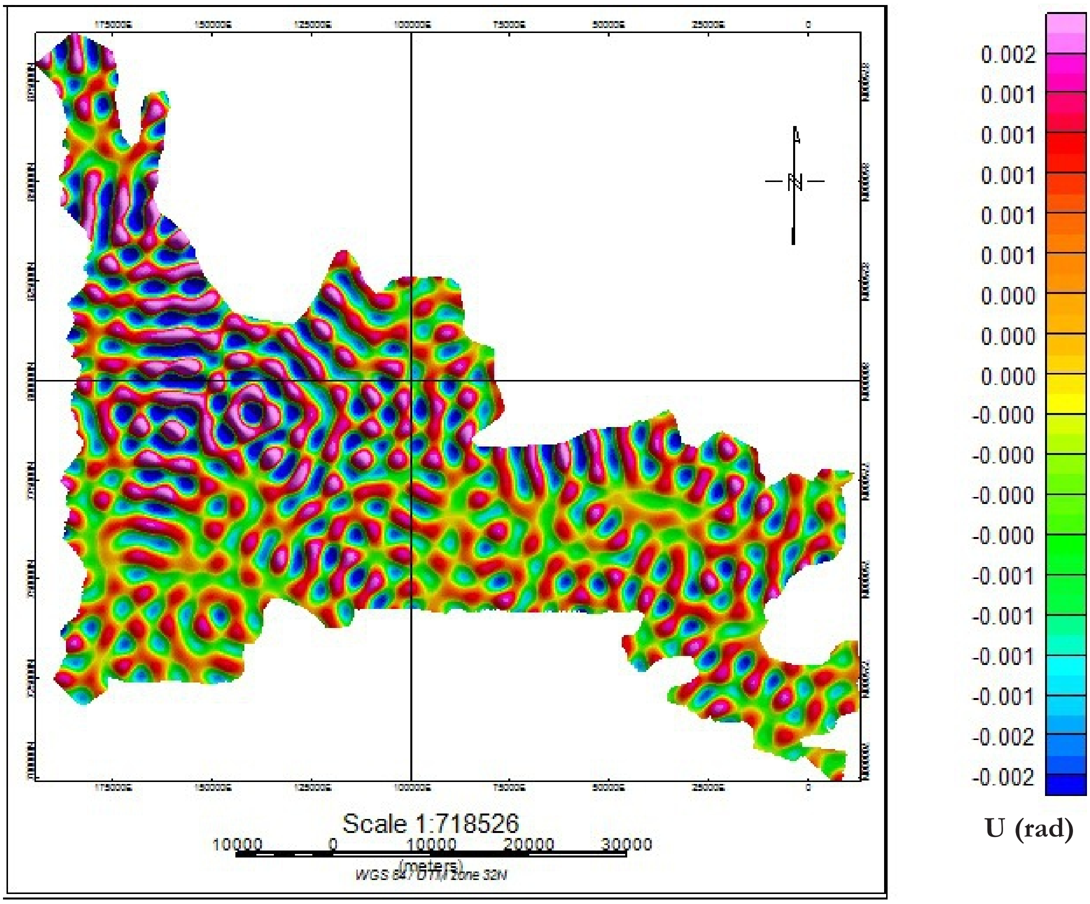

Figure 10: Uranium edge source in radian.

CONCLUSION

In this study, HGM, ASA and LWN have been used for depth estimation of the radioelements source. The depth estimate of HGM and ASA are found to be more reliable compared to that of LWN. In contrast to other edge detection filters that produce no results, the HGM filter was able to identify the edges more precisely and clearly. The edge estimate and depth of the source in this study were obtained without any a priori information about the source. Of the three gradient techniques utilized, HGM was therefore found suitable as it accounts for both depth and edge estimation of the radioelement mineralization of the study area. Conclusively, in this study, the three gradient techniques HGM, LWM and ASA have therefore been found to be mathematically efficient and effectively utilized to estimate the shallow and deep seated anomalous source of the radioelement deposit in Ogun state.

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CONFLICT OF INTEREST

The authors affirm that they have no known financial or interpersonal conflicts that might have appeared to have an impact on the research presented in this paper.

AUTHORS' CONTRIBUTION

Dr. F.O. Ogunsanwo conceived the idea and is the principal investigator; Dr. F.O. Ogunsanwo, Dr. O.T. Olurin and Dr. Ganiyu worked on filtration and depth estimation analysis of aeroradiometric data; Dr. J.D. Ayanda and Prof. A. O. Mustapha edited the manuscript. All authors read and approved the final manuscript.

REFERENCES

Abdelrahman E.M, Ammar A.A, Hassanein, H.I and Soliman, K.S. 2007. Separation of anomalous aerial radiospectrometric zones using least squares method on a sample area in Egypt. *The Arabian Journal for Science and Engineering,* 32(1): 19–35.

Akinrinde, E.A. and Obigbesan, G.O. 2006. Benefits of phosphate rocks in crop production: experience in benchmark tropical soil areas in Nigeria. *J. Biol. Sci.,* 6 (6): 999–1004.

Badmus, B.S. and Olatinsu, O. B., 2009. Geoelectric mapping and characterization of limestone deposits of Ewekoro formation, southwestern Nigeria International Journal of Physical Sciences. *Journal of Geology and Mining Research,* 1(1): 8–18.

Badmus, B,S., Awoyemi, M.O., Akinyemi O.D., Saheed, G.A. and Olurin, O.T. 2013. Magnetic Gradient Techniques on Digitized Aeromagnetic Data of Ibadan Area, South-Western Nigeria, *Central European Journal of Geoscience,* 5(3): 387–393. doi: 10.2478/s13533-012-0136-5

Beamish, D., 2012. The application of spatial derivatives to non-potential field data. *Geophys. Prospect,* 60: 337–360. doi: 10.1111/j.1365-2478.2011.00976.x

Beamish, D., 2015. Relationships between gamma-ray attenuation and soils in SW England. *Geoderma,* 259-260, 174–186. doi: 10.1016/j.geoderma.2015.05.018

Beamish, D. 2016. Enhancing the resolution of airborne gamma-ray data using horizontal gradient. *Journal of applied geophysics,* 132: 75–86. doi: 10.1016/j.jappgeo.2016.07.006

Blakely R.J. and Simpson R.W. 1986. Approximating edges of source bodies from magnetic or gravity anomalies. *Geophysics,* 51: 1494–1498. doi: 10.1190/1.1442197

Blakely, R.J., 1995. Potential Theory in Gravity and Magnetic Application. Cambridge University Press.

Cooper, G.R.J. and Cowan, D.R., 2006. Enhancing potential field data using filters based on the local phase. *Comput. Geosci.,* 32: 1585–1591. doi: 10.1016/j.cageo.2006.02.016

Cooper, G.R.J. and Cowan, D.R. 2008. Edge enhancement of potential-field data using normalized statistics. *Geophysics,* 73: 1– 4. doi: 10.1190/1.2837309

Cordell, L. 1979. Gravimetric expression of graben faulting in Santa Fe Country and the Espanola Basin, New Mexico. New Mexico Geol. Soc. Guidebook, 30th Field Conf, pp. 59–64. doi: 10.56577/FFC-30.59

Cordell, L., and Grauch, V.J.S. 1985. Mapping basement magnetization zones from aeromagnetic data in the San Juan Basin, New Mexico. In: Hinzc, W.J. (Ed.), The Utility of Regional Gravity and Magnetic Anomaly. Society of Exploration Geophysicists, pp. 181–197. doi: 10.1190/1.0931830346.ch16

Fairhead, J.D., Salem, A.S., William, S. and Samson, E. 2008. Magnetic interpretation made easy: The Tilt-Depth-Dip- ΔK method, SEG Technical Program Expanded Abstracts 27(1). doi: 10.1190/1.3063761

Grasty, R.L., Mellander, H. and Parker, M. 1991. Airborne gamma-ray spectrometer surveying. IAEA Technical Reports Series, 323.

Grauch,V. J. S. Hudson, M. R and Minor, S. A. 2001, Aeromagnetic expression of faults that offset basin fill, Albuquerque basin, New Mexico. *Geophysics,* 66: 707–720. doi: 10.1190/1.1444961

Hood, P.J., and Teskey, D.J. 1989. Aeromagnetic gradiometer programof the Geological Survey of Canada. *Geophysics,* 54: 1012–1022. doi: 10.5636/jgg.44.367

International Atomic Energy Agency (IAEA) 2003. Guidelines for radioelement mapping using gamma ray spectrometry data. Technical Report Series International Atomic Energy Agency, Vienna, Austria (No. 136) 14 p.

Keating, P. B. 1998. Weighted Euler deconvolution of gravity data. *Geophysics,* 63: 1595–1603. doi: 10.1190/1.1444456

Keating, P., and Sailhac, P. 2004. Use of the analytic signal to identify magnetic anomalies due to kimberlite pipes. *Geophysics,* 69(1): 180–190. doi: 10.1190/1.1649386

Ku, C. and Sharp, J. 1983. Werner Deconvolution for Automated Magnetic Interpretation and Its Refinement Using Marquart's Inverse Modelling. *Geophysics,* 48: 754–774. doi: 10.1190/1.1441505

Ma, G. and Li, L. 2012. Edge detection in potential fields with the normalized total horizontal derivative. *Comput. Geosci.,* 41: 83–87. doi: 10.1016/j.cageo.2011.08.016

Ma, G. 2013a. Edge detection of potential field data using improved local phase filter. *Explor. Geophys.* 44: 36–41. doi: 10.1071/EG12022

Ma, G. 2013b. Combination of horizontal gradient ratio and Euler (HGR-EUL) methods for the interpretation of potential field data. *Geophysics,* 78: 53–60. doi: 10.1190/geo2012-0490.1

Ma, G., Liu, C. and Li, L. 2014. Balanced horizontal derivative of potential field data to recognize the edges and estimate location parameters of the source. *Journal of Applied Geophysics,* 108: 12–18. doi: 10.1016/j.jappgeo.2014.06.005

Miller, H. G. and Singh, V. 1994. Potential field tilt-a new concept for location of potential field sources. *Jour of Appl. Geophysics,* 32: 213-217. doi: 10.1016/0926-9851(94)90022-1

Mushayandebvu, M. F., Lesur,V.P., Reid, A.B. and Fairhead, J.D. 2004. Grid Euler deconvolution with constraints for 2D structures. *Geophysics,* 69, 489–496. doi: 10.1190/1.1707069

Nabighian, M.N., Grauch, V.J.S., Hansen, R.O., LaFehr, T.R., Li, Y., Peirce, J.W., Philips J.D and Ruder, M.E. 2005. The historical development of the magnetic method in exploration. *Geophysics,* 70: 33ND–61ND. doi: 10.1190/1.2133784

Nigeria Geologic Survey Agency (2006) Geological map of Nigeria. Federal Republic of Nigeria

Ogunsanwo F.O, Olurin, O.T, Ozebo, V.C, Ganiyu, S.A, Ayanda, J.D, Ogunsanwo, B.T, Olowofela, J.A, Okeyode, I.C and Mustapha, O.A. 2022. Application of Enhancement and Filtering technique to Aeroradiometric data of Ogun State, South-Western, Nigeria. *Journal of Mining and Geology,* 58 (1): 63-73.

Oruc, B. 2010. Edge Detection and Depth Estimation Using a Tilt Angle Map from Gravity Gradient Data of the Kozaklı-Central Anatolia Region. Turkey. *Pure and Applied Geophysics, Springer, Basel AG*. doi: 10.1007/s00024-010-0211-0

Paterson, N. R., Kwan, K.C.H., and Reford, S.W., 1991. Use of Euler Deconvolution in Recognizing Magnetic Anomalies of Pipelike Bodies. *Extended Abstract G/M2.6,* p 642-645*, SEG Annual Meeting, Houston.* doi: 10.1190/1.1888827

Phillips, J.D. 2000. Locating Magnetic Contacts; A Comparison of the Horizontal Gradient, Analytic Signal, and Local Wavenumber Methods. *Society of Exploration Geophysicists, Abstracts with Programs, Calgary,* pp. 402–405. doi: 10.1190/1.1816078

Phillips, D. J. 1997. Potential-field geophysical software for the PC version 2.2.U.S.G.S. Open-File Report 97-725, pp. 34.

Rajagopalan, S. and Milligan, P. 1995. Image enhancement of aeromagnetic data using automatic gain control. *Explor. Geophys.,* 25: 173–178. doi: 10.1071/EG994173

Reid, A. B., Allsop, J. M., Granser, H., Millett, A. J. and Somerton, I. W. 1990 Magnetic interpretation in three dimensions using Euler deconvolution. *Geophysics,* 55, 80-91. doi: 10.1190/1.1442774

Roest, W.R., Verhoef, J. and Pilkington, M., 1992. Magnetic interpretation using the 3-D analytic signal. *Geophysics,* 57: 116–125. doi: 10.1190/1.1443174

Salako, K. A. 2014. Depth to Basement Determination Using Source Parameter Imaging (SPI) of Aeromagnetic Data: An Application to Upper Benue Trough and Borno Basin, Northeast, Nigeria. *Academic Research International,* 5: 74-86.

Salem, A., Ravat, D., Smith, R and Ushijima, K. 2005. Interpretation of magnetic data using an enhanced local wave number (ELW) method. *Geophysics,* 70: 7–12. doi.org/10.1190/1.1884828

Salem, A., Williams, S., Fairhead, J. D., Ravat, D. and Smith, R. 2007. Tilt-depth method: A simple depth estimation method using first order magnetic derivatives. *The Leading Edge,* 26: 1502–l505. doi: 10.1190/1.2821934

Salem, A. and Smith, R.S. 2005. Depth and structural index from the normalised local wavenumber of 2D magnetic anomalies. *Geophysical prospecting,* 53: 83-89. doi: 10.1111/j.1365-2478.2005.00435.x

Smith, R.S., Salem, A. and Lemiuex, J. 2005. An enhanced method for source parameter imaging of magnetic data collected for mineral exploration. *Geophysical prospecting,* 53: 155-165. doi: 10.1111/j.1365-2478.2005.00494.x

Smith, R.S., Thurston J.B., Dai, T. and MacLeod I.N. 1998. ISPI™ – The improved source parameter imaging method. *Geophysical Prospecting,* 46, 141 – 151. doi: 10.1046/j.1365-2478.1998.00084.x

Thompson, D.T. 1982. EULDPH: a new technique for making computer-assisted depth estimates from magnetic data. *Geophysics,* 47: 31–37. doi: 10.1190/1.1441278

Thurston, J. B., and. Smith, R. S. 1997. Automatic conversion of magnetic data to depth, dip, and susceptibility contrast using the SPI™ method. *Geophysics,* 62: 807–813. doi: 10.1190/1.1444190

Thurston, J. B.,. Smith, R. S and Guillon, J.C. 2002. A multi-model method for depth estimation from magnetic data. *Geophysics,* 67: 555–561. doi: 10.1190/1.1468616

Verduzco, B. Fairhead, J. D., Green, C. M. and MacKenzie, C. (2004) New insights into magnetic derivatives for structural mapping. *The Leading Edge,* 23: 116–l19. doi: 10.1190/1.1651454

Wijns, C., Perez, C. and Kowalczyk, P. 2005. Theta map: edge detection in magnetic data. *Geophysics,* 70: 39–43. doi: 10.1190/1.1988184