Journal of Mining and Geology Vol. 58(1) 2022. pp. 109 - 116 0022-2763

Integrating both Air and Ground Magnetic Data in Evaluating the Magnetic Properties of the Ironstone Deposits in Lokoja Area, North Central Nigeria

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Abstract
Both air and ground magnetic data were integrated into determining the magnetic character of the ironstone deposits in Lokoja area, northcentral Nigeria. The result of the analysis indicates that their susceptibilities in residual aeromagnetic data range from 146.68 – 168.17 nT. The susceptibility of the ores varies between those in the basement section and those in the sedimentary environment within the study area. Those in the basement section have a lower residual magnetic susceptibility range (194.410 – 292.99 nT) as compared with their counterparts in the sedimentary area (375.46 – 631.27 nT). This implies that the ores in the sedimentary basins are richer in metalliferous materials than those hosted by the basement rocks. The influence of the host rocks on the residual susceptibility anomalies in the study area is quite minimal. The popular trend of the iron ores in the basement section is east-west direction, while those in the sedimentary basin trend majorly in the north-south direction. The significant difference in the residual susceptibilities of the ores from the two geologic environments, coupled with differences in their orientations suggests that they are of different geologic ages, and could have been formed under different geologic conditions. An analysis of the depth of occurrence of the ores indicates that they are shallow sited (≤150 m).

Keywords: *Iron ore; Magnetic method; Anambra Basin; Basement Complex; Lokoja, Nigeria.*

Introduction

The earth crust is substantially enriched with iron and is present in various concentration levels in most rocks (Ojo et al., 2021). Some rocks are so enriched with iron in different forms that they can be practically harnessed from them in economic quantities. These rocks are known as iron ores. Such ores include hematite, magnetite, limonite and pyrite among others. On inception of mining activities globally, the outcropping ores were primarily developed and mined as major sources of metallic minerals (Cheng et al. 2017). Depletion of outcropping metallic ores has led to the search for the ores in their concealed forms using appropriate geophysical means (Jianfei et al., 2020).

The two broad types of iron ore deposits in Nigeria are the Banded Iron Formation (BIF), which occurs in folded bands and lenses associated with the Precambrian meta-sedimentary schist belts, and the Cretaceous sedimentary (oolitic) deposits (Oyedele et al., 2016). The Banded Iron Formation (BIFs) is a chemical sedimentary rock comprising layers of iron-rich and silica-rich minerals whose deposition requires anoxic and iron rich (ferruginous) sea water (Rasmussen et al., 2012). The BIF type of the iron ores is the world′s highest source of iron (Jianfei et al., 2020). Discussions on the origin of iron-bearing sediments, that is much richer in iron minerals than usual have been of interest and received attention among researchers (Afify et al., 2018; Akinlotan, 2019). Their occurrence in some parts of the country is highly essential for the growth of the nation′s economy. It has been reported that prior to the discovery of hydrocarbon in Nigeria, the mining of iron ores contributed immensely to Nigeria′s economy (Olorunfemi and Waziri, 2018). They occur in both the Basement Complex terrain (in the form of the Banded Iron Formation), and in the sedimentary basins (as oolitic and pisolitic ironstones) (Anike et al., 1993; Olorunfemi and Waziri, 2018). It is expected that these deposits will be a major source of supply of raw materials to the steel company that is currently under construction in Ajaokuta when completed. An estimated reserve of about 2.3 billion tones has been reported from parts of Kogi, Niger, Nasarawa, Bauchi, Oyo Kebbi, Kaduna, Borno, Benue and Anambra states (Bamalli et al., 2011; Ohimain, 2013). The Lokoja area represents a true picture of the occurrence of the iron ores in Nigeria in the sense that it hosts the ores both in sediments and in basement rocks. They outcrop in such communities as Itakpe,Agbaja, Patti, Bassa Nge, Ate, Sakpe, Batati, Lokoja, Koton Karfe, Ajabanoko, Ochokochoko, and Tajimi, among others within the study location (Bayowa et al., 2016; Imrana and Haruna, 2017). It is therefore expected that data derived from these areas would give reasonable information on the response of the iron ore deposits to a given geophysical method in both terrains. Geochemical studies on samples from some of the deposits from these areas and beyond (Imrana and Haruna, 2017; Adekoya, 1998; Adekoya et al., 2012) have proven that the Nigerian iron ores are very rich in iron content. They occur mostly as lenses, with majority of them not outcropping to the surface. Hence, there is need to infer their occurrence through geophysical means. If an insitu ore body is successfully delineated from surface through any known geophysical means, it ensures cost effectiveness and environmental sustainability, as well as encourages more investment in mining (Bukola et al., 2021).

The magnetic method has played a major role in the delineation of iron ores deposits (Gunn 1993; Gunn and Dentith, 1997; Oyedele et al., 2016; Adebisi, 2018; Sehah and Raharjo, 2017). Exploration for iron ore based on its magnetic effects represents the earliest use of geophysics in mineral exploration (Gunn and Dentith, 1997). Airborne magnetic surveys have been able to identify many valuable ore deposits under thick sedimentary fill because of the strong magnetic anomalies associated with iron formations (Schmidst et al., 2007). It is sometimes integrated with other geophysical methods like resistivity or electromagnetic methods in the delineation of concealed iron ores (Wang et al., 2017; Jianfei et al., 2020). The magnetic signature of iron deposits are dependent on if their major mineralogical composition tilts towards magnetite or hematite (Gunn and Dentith, 1997). Elsewhere, a correlation of the susceptibility property of the iron ores from Hermasley Basin, western Australia (Clark and Schmidst, 1994) with that from southern Australia (Schmidst et al., 2007), and China (Jianfei et al., 2020) tends to suggest that their susceptibilities differ from one region to another across the globe. Within the study area, many of the ore bodies are yet to be located underneath due to their mode of occurrence, hence, the need to establish their susceptibility within the region. Field study of the existing mines tries to suggest a regional trend in occurrence of deposits. Establishment of their regional trend using aeromagnetic data is expected to assist in locating new deposits.

The geology and geochemistry of the iron formations in the northcentral region of Nigeria has been extensively studied (eg., Anike et al., 1993; Adekoya, 1998; Adekoya et al., 2012; Bayowa et al., 2016; Olorunfemi and Waziri, 2018; Bolarinwa, 2018). There are pockets of previous works on geophysics in the area (eg., Ayodele et al., 2016; Obi et al., 2018; Bukola et al., 2020) and so could not look at the occurrence and distribution of the ores in the area on a regional scale. They were unable to establish the magnetic character of the deposits by integrating outcrop samples with field data. Therefore, there is need to measure the magnetic susceptibility of the iron ores in the Lokoja area, north-central Nigeria using both the air and ground magnetic methods. The outcome will enhance the generation of a standard reconnaissance tool for mapping of these deposits in the region and similar environments globally and also help to locate several other deposits yet to be identified. To achieve this, both the air and ground magnetic data of the area were acquired, separated into their regional-residual components, and further enhanced using relevant special filters.

Site Description and Geologic Setting

The study area is Lokoja and its environs. It is located on the confluence of River Niger and River Benue. It is about 165 km southwest of Abuja as the crow flies. It lies between latitudes $07^{0}00^{l}$ N– $08^{0}30^{l}$N and longitude $6^{0}00^{l}$ E– $7^{0}30^{l}$ E in the north-central part of Nigeria (Fig. 1). It covers an area of about 22500 km^2 and is easily accessible through a network of roads. The study area comprises the Basement Complex and the sedimentary basins. Basement Complex is made up of narrow low-grade schist belts, with each belt separated from adjacent ones by migmatites and gneisses or granites (Ajibade et al., 1989), while the sedimentary basin is made up of Anambra and Bida basins (Fig. 1). Within the study area, the sediments of the Bida Basin ranges from Campanian – Maastrichtian, and comprises of the Lokoja Sandstone, the Patti Formation, and the Agbaja Ironstone; while that of the Anambra Basin comprises of sediments of Mamu, Ajali, and Nsukka formations, which also belong to Campanian – Maastrichtian (Nwajide, 2013). The Bida Basin occupies the left-hand side of the Basement Complex, while the Anambra Basin occupies the right-hand side.

Materials and Methods

Magnetic Methods

Data acquisition

Two forms of magnetic data were applied in this work namely: the aeromagnetic and ground magnetic data. The aeromagnetic data was sourced from the Nigeria Geological Survey Agency (NGSA). It was part of the data generated by the agency as a high-resolution national dataset flown by Fugro Airborne Surveys between 2006 and 2009. Equipment employed during the aero data acquisition includes a fixed-wing aircraft, 3x Sintrex CS3 Alkali Vapour magnetometer, FASDAS magnetic counter, KING KR 405/KING KR 405B radar altimeter and ENVIRO BARO/DIGIQUARTZ barometric altimeter. The flight was flown perpendicular to dominant regional geological strike along with a series of NW–SE flight lines spaced 500 m, with 2000 m tie-line spacing in a NE–SW direction and 80 m nominal flight height. Magnetic data were recorded at 0.1 s intervals. A total of nine aeromagnetic

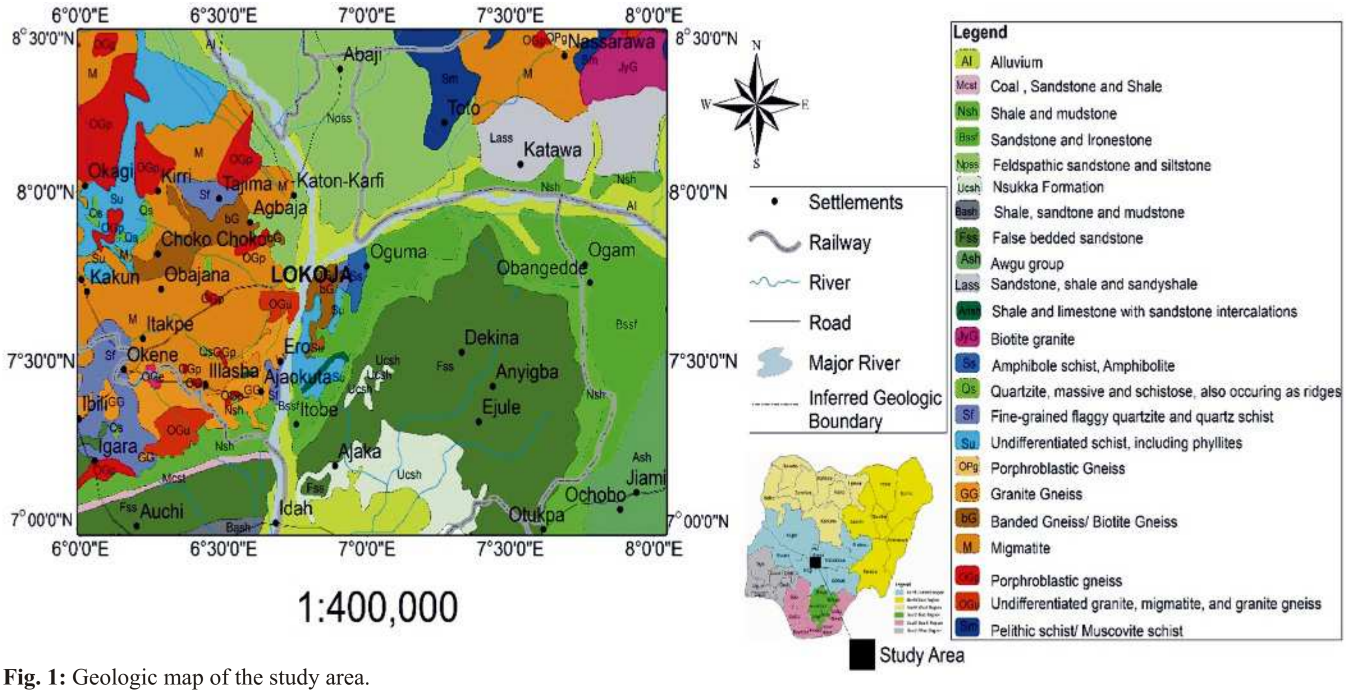

Fig. 1: Geologic map of the study area.

maps (i.e. 9 geologic sheets according to NGSA distribution sheets 226, 227, 228, 246, 247, 248, 266, 267, and 268) were used in this work, on a scale of 1: 100,000. It covers the southern part of the Bid Basin, northern Anambra Basin and parts of the Basement Complex.

Ground magnetic surveys of the study area were carried out at two designated points namely: Itakpe and Agbaja. The choice of the areas was guided by the fact that they are popularly known for the occurrence of the ores in them, coupled with the fact that the former is located in the basement part while the latter is part of a sedimentary basin. The ground magnetic survey measurements were taken with GEM-19 v7.0 Overhauser Instrument manufactured by GEM SYSTEMS, Canada. It is made up of two major components, a magnetic recording machine that is always stationed at a base, and a second machine that can be moved from one point to another (The Rover). It also has an in-built global positioning system (GPS) which records the coordinates of each measurement station. Its capacity for fast measurement and high accuracy made it suitable for this work. A total of 33 east-west trending profiles, with an inter-profile spacing of 100 m, were covered in the two locations. 24 profiles were measured in Itakpe, while 9 profiles were measured at the Agbaja Ironstone field. Readings were taken per minute along the profile. With two recording machines, one served as a base and was kept at a magnetically quiet location, while the rover was used to acquire data along the profiles. At the end of the fieldwork, all acquired field data was transferred to the computer for processing.

Data Processing and Interpretation

All the necessary magnetic data corrections meant to be done on the aeromagnetic data were carried out by Fugro Company, which led to the generation of the air-borne TMI data. For the ground magnetic data, the base station method was applied in diurnal correction through the correlation of field data from the base recorder with that of the rover. A micro leveling or decorrugation method was used to remove line-to-line leveling errors of magnetic data, using Butterworth and Cosine directional filters. To estimate the geometry of geologic structures and depths to causative bodies of both the airborne and ground magnetic data, mathematical functions were applied to the total intensity magnetic field data. These were regional-residual calculations (Eqn. 1, Obasi et al., 2016), source parameter imaging (SPI) (Eqn. 2, Thurston and Smith, 1997), first and second vertical derivatives (Eqns. 3 and 4), and analytic signal (Eqn. 5). The magnetic data was processed using the Oasis Montaj software produced by the Geosoft Limited. The processed data will be analyzed both qualitatively and quantitatively. Qualitative interpretation involved visual inspection of the colour band (spectrum) and contour maps. From these, inferences were drawn on both the geology of the area, basin boundaries, lithologic boundaries, and magnetic susceptibility variations across the area. The quantitative interpretation will involve the calculation of depth to anomaly sources across the study area. This was achieved by drawing profile and generating 2D models along such profiles.

$$\Delta g_R = ax_i + by_j + c \quad \text{(1)}$$

$$Depth = \frac{1}{K_{\max}} = \frac{1}{\sqrt{(\partial \mathrm{Tilt}/\partial x)^2 + (\partial \mathrm{Tilt}/\partial y)^2}} \quad \text{(2)}$$

$$FVD = -\frac{dT}{dZ} \quad \text{(3)}$$

$$SVD = \frac{d^2T}{dZ} \quad \text{(4)}$$

Where FVD is First Vertical Derivative
SVD is Second Vertical Derivatives

$$/AS/ = \sqrt{\left(\frac{dT}{dx}\right)^2 + \left(\frac{dT}{dy}\right)^2 + \left(\frac{dT}{dZ}\right)^2} \quad \text{(5)}$$

Where AS is the analytic signal and T is the observed total magnetic field at (x, y).

Result and Discussion

Aeromagnetic Data

The total magnetic intensity map of the aeromagnetic data (Fig. 2) indicates susceptibility values which range from 32992.63 – 33408.60 nT. The highest susceptibilities occurred predominantly in the northeastern end, with few occurring towards the eastern end and in Lokoja area at the centre. The values were reducing southwards, with the least values occurring in the southern end of the map. This arrangement could be attributed to probably older geologic structures occurring in the north – eastern end of the study area, with more magnetic properties, while the whole area is younging towards the south. The residual magnetic data (Fig. 3) indicates high susceptibility responses majorly around Lokoja with very few scattered in few other locations in the study area. These highest values are suspected to be associated with the iron ores in the area. They are seen around Itakpe, Okene, Kabba, Choko-Choko, and Lokoja areas which are popular for the occurrence of iron ores. Their susceptibility range is from 146.68–168.17 nT. They are also seen in some sections of the Anambra Basin, around Ejule and Dekina. The deposit around Ejule appear quite massive and is of a large extent, however, it is not exposed to the surface. There may be a need for further studies in that location to ascertain its in-situ occurrence. The deposits of the ores within the Bida Basin (e.g., around Koton Karfe, Agbaja, and Tajima) appear not to be as pronounced, massive, and continuous as those in the basement section and the Anambra Basin. They seem to be highly localized and occur as rounded to semi- rounded bodies of very low quantity. That could explain why they are not as visible as others based on the scale of the map (Fig. 3). However, a critical view of the map will reveal that there are some dot-like occurrences of the highest susceptibility values around the aforementioned communities. Previous studies (Bayowa et al., 2016; Imrana and Haruna, 2017) have also confirmed their occurrence in nature in those areas. The magnetic character of the iron ores is the same, both in the Basement Complex and in the sedimentary environments. Figure 3 also suggests that majority of the ores are striking in the east-west direction, with others trending northeast-southwest. Those trending northeast-southwest tend to be restricted to the Anambra Basin section of the map (around Ejule and Dekina), while the East-west trending ones seems to be restricted to the Basement Complex, around Lokoja and Itakpe areas. The ores seems to have a general trend of northeast– southwest within the Basement rocks and southern Bida Basin, having its lower boundary at about latitudes $07^0 00'00''$ N (i.e. between Igarra and Auchi) and latitudes $08^0 05'00''$ N. Notably, its boundary in the northeastern end occurs between latitudes $08^0 15'00''$ N and $08^0 30'00''$ N (i.e. around katawa and Toto communities). The trend continued in that northeast direction up to Muro hill, somewhere outside the study area. The suspected loads in the Anambra Basin sector in this study needs to be subjected to further confirmation through core samples as no active mining is currently ongoing in that area.

Ground Magnetic Data

Itakpe Iron Ore Field

To ascertain that the observed highest susceptibility values are associated with the ore deposits, magnetic readings were taken within active mine sites where the ores outcrop commonly and their coordinates on ground location in the field were measured and geo-referenced in the maps. It can be established that the highest susceptibility values in the study area are associated with the iron ore deposits (Fig. 5). The total magnetic field of the Itakpe Iron ore field (Fig. 4) indicates that the ores are scattered in the area and has a susceptibility

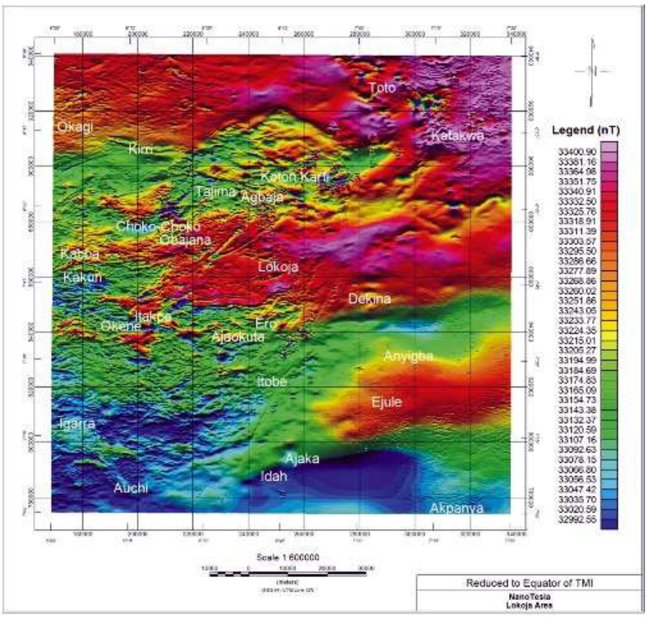

Fig. 2: Reduced to equator of total magnetic intensity (RTE-TMI) anomaly map of the area.

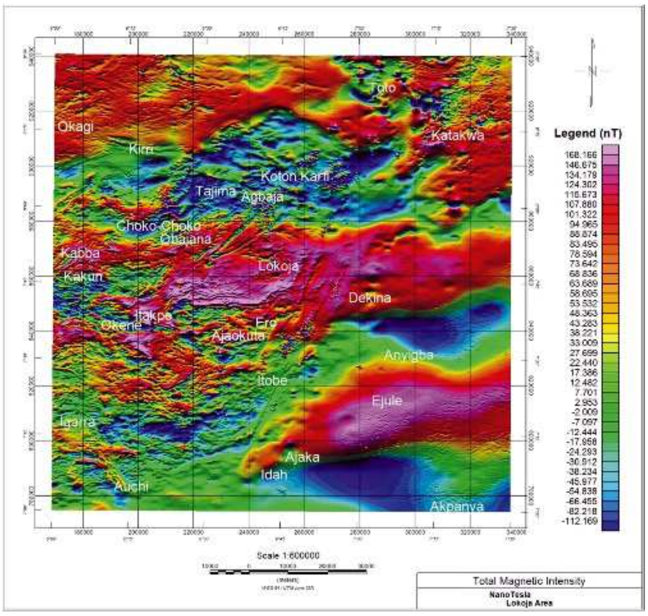

Fig. 3: Residual-TMI anomaly map of the area.

range of 36918.42 – 38071.27 nT. This value is relatively higher than the values of the aeromagnetic TMI data (32992.63 – 33408.60 nT) discussed earlier. This could probably be due to the proximity of the equipment to the deposits. Even its susceptibility value in the residual anomaly map (Fig. 5) are also higher (194.410 – 292.99 nT) than that of the aeromagnetic data (146.68 – 168.17 nT). The residual magnetic data from the Itakpe mining field (which is part of the Basement Complex) also agrees with the aeromagnetic data which indicates that most of the ore deposits are trending east–west, while few others are trending in the north-south directions. These differences in orientation are suggestive of more than a single phase in the formation and deposition of the lodes.

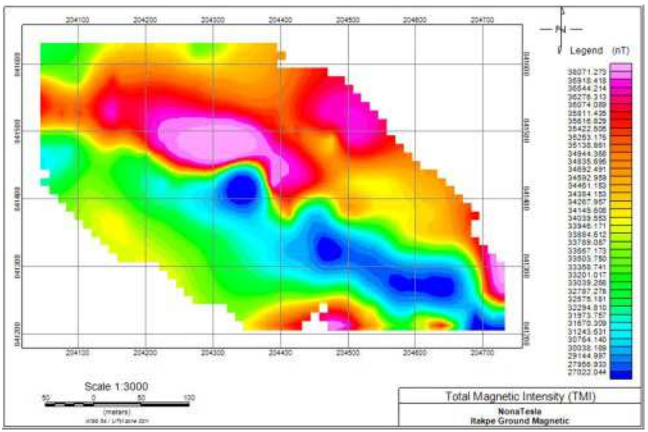

Fig. 4: Total magnetic intensity map of the Itakpe iron ore field.

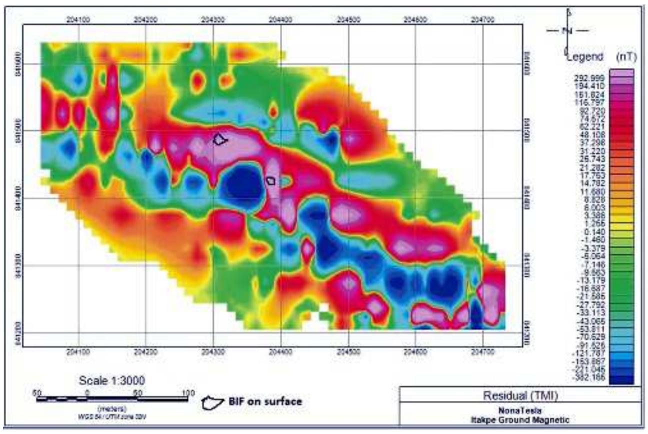

Fig. 5: Residual Magnetic intensity map of the Itakpe iron ore field.

Agbaja Iron Ore Field

The TMI map of the Agbaja Iron ore field (Fig. 6), in the Bida Basin, shows a magnetic susceptibility range (35219.36 - 35774.74 nT) that is more than that of the aeromagnetic data values (32992.63 – 33408.60 nT), but lower than that of the Iron ore in Itakpe mine field, which is part of the Basement Complex (36918.42 – 38071.27 nT). Since the data from both the Itakpe and Agbaja Iron ore fields are ground magnetic data taken at under the same field condition, the higher values observed from the Itakpe field when compared with those of Agbaja units could be either attributed to the influence of their host rocks or that the ironstones in Itakpe area have more magnetic minerals in concentration than those in the Agbaja area. The residual magnetic map of the Agbaja Iron ore field (Fig. 7) attempted to address the somewhat underlying concerns. It agrees perfectly with others that the highest values represent the locations of the iron ore deposits in the field. Contrary to the results of the TMI data from both locations, the result of the residual anomaly from the Agbaja area shows a very high susceptibility range for the iron ores (375.46–631.27 nT) compared to those in Itakpe Field (194.410 – 292.99 nT). This suggests that the Agbaja deposits have a higher concentration of magnetic materials compared to their Itakpe units. Sanni et al. (2016) reported a very low concentration of magnetic minerals in the sediments of the Agbaja Formation which hosts the Agbaja Iron ore. Hence, the impact of the host rock on the susceptibility is likely not a factor in this case. The predominant orientation of the ores in the Agbaja minefield is north-south (Fig. 7). This is quite different from those of Itakpe which is predominantly east-west. The significant difference in the residual susceptibilities of the ores from the two geologic environments, coupled with differences in their orientations suggests that they are of different geologic ages and could have been formed under different geologic conditions.

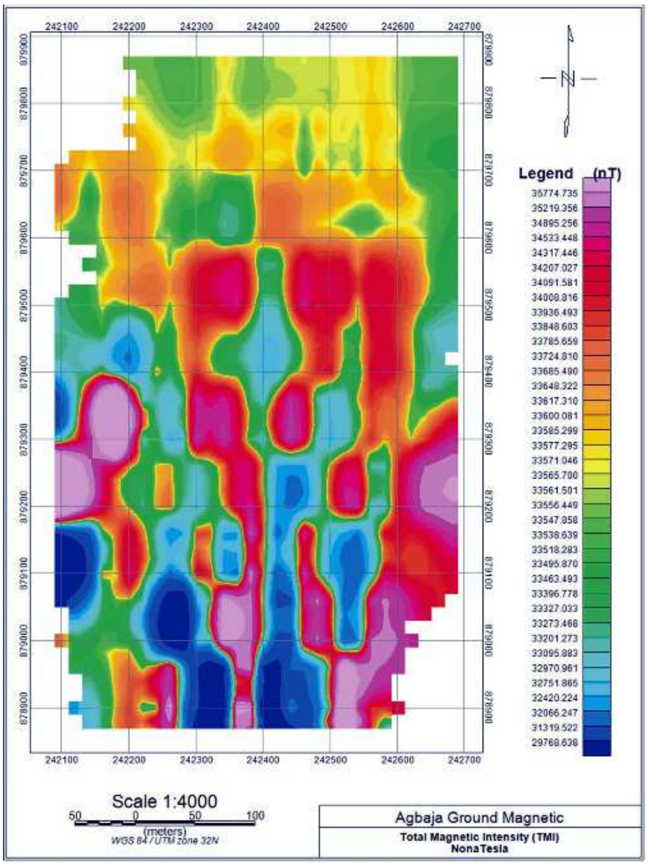

Fig. 6: Total magnetic intensity map of the Agbaja iron ore field.

The result of Source Parameter Imaging (SPI) carried out on the residual aeromagnetic data in the study area (Fig. 8) suggests that the ore deposits in the study area are shallow sited (≤ 150 m). This can be inferred from the colour legends around Itakpe, Agbaja, Choko-Choko, and Tajima where they are currently being mined. Previous study corroborated the result of the present research by stating that the depth to the ore deposits varied from the surface up to about 200 m (Oyedele et al., 2016).

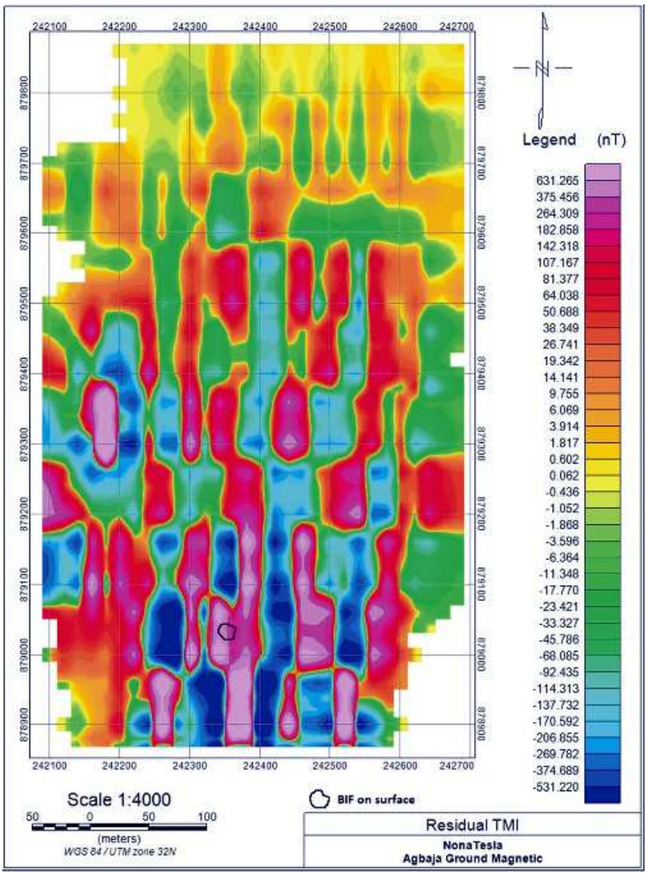

Fig. 7: Residual magnetic intensity map of the Agbaja iron ore field.

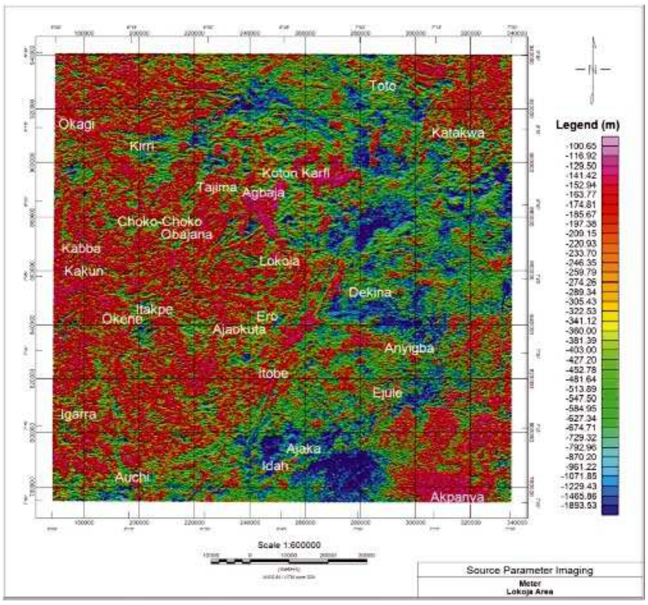

Fig. 8: Source Parameter Image anomaly map of the Lokoja area.

Conclusion

The application of magnetic methods in the study of the ironstones in the Lokoja area has revealed their magnetic characters within the entire region. The present work has shown that there are significant lodes of the deposits that occur in the Anambra Basin section of the study area, around Ejule, that was previously unidentified. The differences in the results of the aeromagnetic and ground magnetic data have further emphasized the relevance of the ground magnetic data in exploration work. The result of this work will serve as a good reconnaissance tool for the mapping of iron ores, both in sedimentary terrain and in the Basement Complex.

Disclosure Statement

We state clearly, that we have no conflict of interest to declare.

References

Adebisi, M. A. (2018). Ground Magnetic Survey for the Investigation of Iron Ore Deposit at Oke-Aro in Iseyin East, South-Western Nigeria. International Journal of Geosciences, 9, 415-427.

Adekoya, J. A. (1998). The geology and geochemistry of the Maru Banded Iron-Formation, northwestern Nigeria. Jour. Afri. Earth Sci. 27 (2), 241-257.

Adekoya, J. A., Okonkwo, C. T. and Adepoju, M. O. (2012). Geochemistry of Muro Banded Iron-Formation, Central Nigeria. Inter. Jour. of Geosci, 3, 1074-1083.

Afify, M. A., Sanz-Monteroa, M. E. and Calvoa, J. P. (2018). Differentiation of ironstone types by using earth elements and yttrium geochemistry – a case study from Bahariya region, Egypt. Ore Geol. Rev. 96, 247–261.

Ajibade, A. C., Woakes, M. and Rahaman, M. A. (1989). Proterozoic crustal development in the Pan-African regime of Nigeria. In. Kogbe, C. A. (Ed.), Geology of Nigeria. Rock view (Nig) Ltd, Jos, 57-69.

Akinlotan, O. (2019). Sideritic ironstones as indicators of depositional environments in the Weald basin (early cretaceous) SE England. Geological Magazine, 156(3), 533 – 546.

Anike, L. O., Umeji, A. C. and Orajaka, I. P. (1993). Geology of Precambrian Formation from Muro Hill, Nigeria," *Economic Geology* 88(5), 1237-1241

Bamalli, U. S., Moumouni, A. and Chaanda, M. S. (2011). A review of Nigerian metallic minerals for technological development. *Natural Resources* 2, 89-91.

Bayowa, O., Ogungbesan, G., Majolagbe. R. and Oyeleke, E. (2016). Geophysical prospecting for iron ore deposit around Tajimi village, Lokoja, North–Central Nigeria. *RMZ – M & G,* 63, 151–0160.

Bolarinwa, A. T. (2018). Petrography and Geochemistry of the Banded Iron Formation of the Gangfelum Area, Northeastern Nigeria. Ear. Sci. Res 7(1), 25-34.

Bukola, A. B., Ibeneme, S. I., Osizemete, A. G., Obioha, Y. E, Abba, A. U. (2020). Quality Assessment and Reserve Estimation of the Egnaeja Iron Ore Deposit, North-Central Nigeria using Integrated Approach. Inter. Jour. Earth Sci. Geophy. 1-12.

Cheng, H. J., Chen, C., Zhan, X.Z., Chang, J.Y., Ding, Y.L., Kuwanixibieke, M., Yang, R.H., Jia, N.E., Fu, H.Z. (2017). New progress in the prediction theory and prospecting method for concealed deposits. Geol. Explor. 53, 456–463.

Clark, D. A. and Schmidt, P. W. (1994). Iron: Magnetic properties and magnetic signatures of BIFs of the Hamersley Basin and Yilgarn Block, Western Australia, ASEG Extended Abstracts, 1994:1, 341-354, DOI: 10.1071/ASEGSpec07_26.

Gunn, P. J. (1993). The Causes of Magnetic Responses in Massive Sulphide Ore Bodies and Their Horst Rocks. AGSO Journal of Australian Geology and Geophysics, 17(2), 145–158.

Gunn, P. J. (1997). Application of aeromagnetic surveys to sedimentary basin studies. AGSO Journal of Australian Geology and Geophysics, 17(2), 133–144.

Gunn, P. J. and Dentith, M. C. (1997). Magnetic Responses Associated with Mineral Deposits. AGSO Journal of Australian Geology and Geophysics 17(2), 145–158.

Jianfei, F., Sanshi, J. and Ende, W. (2020). Combined Magnetic, Transient Electromagnetic, and Magnetotelluric Methods to Detect a BIF-Type Concealed Iron Ore Body: A Case Study in Gongchangling Iron Ore Concentration Area,Southern Liaoning Province, China. Minerals, 10, 1044. 1-17.

Imrana, A. and Haruna, I. V. (2017). Geology, Mineralogy and Geochemistry of Koton-Karfe Oolitic Iron Ore Deposit, Bida Basin. Kogi State, Nigeria. Inter. Jour. Sci. & Techn. Res 6(08), 415-426.

Nwajide, C. S. (2013). Geology of Nigeria's sedimentary basins. CSS Bookshop Ltd., Lagos 565p

Obasi, A. I., Onwuemesi, A. G. and Romanus, O. M. (2016). An enhanced trend surface analysis equation for regional – residual separation of gravity data. J. Appl. Geophys. 135, 90–99.

Obasi, A. I., Onwa, N. M. and Igwe, E. O. (2021). Application of the resistivity method in characterizing fractured aquifer in sedimentary rocks in Abakaliki area, southern Benue Trough, Nigeria. Environmental Earth Sciences 80:24. https://doi.org/10.1007/s12665-020-09303-w

Obi, D. A., Oyonga, A. O. and Morphy, M. (2018). Application of Electrical Resistivity and Ground Magnetic Investigation of Ironstones Deposits in Abiati Akamkpa LGA, Cross River State, Nigeria. Journal of Environment and Earth Science 8(6), 133-139.

Ohimain, E. I. (2013). The challenge of domestic iron and steel production in Nigeria. *Greener Journal of Business and Management Studies*, 3(5), 231-240.

Ojo, O. J., Bamidele, T. E., Adepoju, S. A. Akande, S. O. (2021). Genesis and paleoenvironmental analysis of the ironstone facies of the Maastrichtian Patti Formation, Bida Basin, Nigeria. Journal of African Earth Sciences, 174. https://doi.org/10.1016/j.jafrearsci.2020.104058

Olorunfemi, T. O and Waziri, N. M. (2018). Geochemical and Mineralogical Characteristics of Sakpe Ironstone aroundJima, Northern Bida Basin, Nigeria. *IOSR Journal of Appl. Geol. and Geophy* 6(3), 24-29

Oyedele, K., Oladele, S. and Salami, A. (2016). Geophysical investigation of banded iron ore mineralization at Ero, North – Central Nigeria. RMZ – M&G, 63, 109–118.

Rasmussen, B., Fletcher, I. R., Bekker, A., Muhling, J. R., Gregory, C. J. and Thorne, A. M. (2012). Deposition of 1.88-billion-yearold iron formations as a consequence of rapid crustal growth. Nature, 484, 498–501.

Sanni, Z. J., Toyin, A., Ibrahim, A. and Ayinla, H. A. (2016). Provenance studies through petrography and heavy mineral analysis of part of Agbaja-Lokoja Formation, Bida Basin, NW Nigeria. *Ife Journal of Science,* 18(1), 203-212.

Sehah, Raharjo, S. A. (2017). Application of magnetic survey to explore the iron ore deposits in the Nusawungu coastal regency of Cilacap central Java. *Jurnal Penelitian Fisika dan Aplikasinya (JPFA),* 7 (2), 79-88.

Schmidt, P. W., McEnroe, S. A., Clark, D. A. and Robinson, P. (2007). Magnetic properties and potential field modeling of the Peculiar Knobmetamorphosed iron formation, South Australia: An analog for thesource of the intense Martian magnetic anomalies? Jour. of Geophys Res, 112, B03102, 1-19. doi:10.1029/2006JB004495

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

Wang, Q., Wang, X. B., Yang, J., Min, G. and Guo, J. (2017). Locating of the concealed skarn iron ore deposit basedon multivariate information constraints: A case study of the Beiya gold mine in Yunnan province. Chin. J. Geophys. 60(1), 84–96. https://doi.org/10.1002/cjg2.30029