Integration of *in-situ* Susceptibility and Petrographic Data in Study of the Magnetic Properties of some Rocks of Parts of Anambra Basin and Southern Benue Trough, Nigeria

Martina O. Eze, Ph.D.* and Ikechukwu B. Ijeh, Ph.D.

Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria.

E-mail: tinamine8@yahoo.com*

ABSTRACT

To provide the basis for a more effective use of aeromagnetic data as a geological mapping tool, a GDD-multi parameter Probe susceptibility meter with a sensitivity of $3x10^{-3}$ SI unit was used to measure the susceptibility of some anomalous rocks on parts of Southern Benue trough and Anambra basin. Magnetic susceptibility measurements performed on rock outcrops on the study area reveal lower magnetic susceptibilities for sedimentary and felsic rocks (granite), Intermediate magnetic susceptibilities for intermediate igneous rocks and metamorphic and higher magnetic susceptibilities for the mafic igneous rocks. The values range from $2 \times 10^{0.001}$ to $39 \times 10^{0.001}$ (SI). The aeromagnetic data interpreted qualitatively gave result for the total magnetic intensity that valued at between negative peak value of -894.0 nT and a minimum of about 404.4 nT. The amplitude of analytical signal peaks on the mafic igneous rocks with the highest susceptibility value at the area. Areas with high anomalous values have high susceptibility values. Petrographic studies revealed that paramagnetic minerals such as biotite, hornblende, Augite and diamagnetic mineral quartz and plagioclase contribute to the source of magnetism in most of the samples measured in the field.

(Keywords: magnetism, magnetic susceptibility, aero-magnetic, Benue trough)

INTRODUCTION

Magnetic susceptibility, k, is a measure of the degree to which a material can be magnetized in an external magnetic field: k = M/H where M is the magnetization in A/m induced in the material by an external field of strength H, also in A/m (Searle, 2008, Hrounda et al., 2009; Da Silva et al., 2009). K is dimensionless scalar entity.

The intensity of induced magnetization is related to the ambient field through the magnetic susceptibility of the rock considered (Hildenbrand et al., 2001). This magnetic susceptibility constant is directly proportional to the chemistry of the rock and modal mineral composition (Waswa et al., 2015). Magnetic field anomalies reflect variations in the magnetic susceptibility of the underlying lithology, which is an essential component of potential field modelling (Elizabeth and Jonathan, 2003).

Susceptibility is the fundamental rock parameter in magnetic prospecting. Magnetic properties vary of rocks and sediments are determined by the quantity of magnetic minerals (iron, nickel and cobalt bearing minerals), the mode and age of the formation and their thermal and geochemical history (Case and Sikora, 1984). The properties vary because they depend on depositional and/or crystallization chemical inhomogeneity and post deformational conditions (Carmichael, 1989). Thus, magnetic susceptibility values can be used in the geological as well as lithological mapping (Hrouda et al., 2009). It is also applied increasingly on sedimentary rocks to constrain stratigraphic correlations, or as a paleo-environmental or paleo-climatic tool (Silva et al., 2015). The aim of this research work is to determine the magnetic susceptibility of some rocks within the study area by in-situ measurement, identify the mineral present by petrographic studies of the rocks to support in the interpretation of airborne aeromagnetic geophysical data within the studied area.

Magnetic properties can only exist at temperatures below the Curie point (temperature at which a material's permanent magnetism changes to induced magnetism). The Curie point temperature is found to be rather variable within rocks but is often in the range 550 to 600°C (Reeves, 1985).

Magnetic susceptibility is a very sensitive indicator of magnetic minerals present in rock or environmental samples because any slight variation in magnetic mineralogy is usually reflected by a profound change of susceptibility (Martin, 2011; Alagarsamy, 2009). Magnetic surveys are based on the assumption that a geological bodies are limited in space and with different physical properties (for example magnetic susceptibility) from the surrounding formation (Waswa et.al 2015). Magnetization for igneous rocks is the thermoremanant magnetization acquired by cooling and solidification of an igneous rock from above the Curie temperature. For sedimentary rocks, primary remanence magnetization is detrital remanence resulting from the alignment of magnetic sediments with the earth's magnetic field (Getting and Bultman, 2014).

GEOLOGY OF SOUTHERN BENUE TROUGH AND UPPER ANAMBRA BASIN

The study area covers parts of Southern Benue trough and Anambra basin. The area is bounded by Longitude 8.00°E to 9.00°E and Latitude 6.00°N to 7.30°N. During the Cretaceous, progressive sea level rise from Albian-Maastrichitian is the main factor responsible for sedimentation within the Benue trough. Three main tectonic phases in the Benue Trough which controlled the basin filling are as follows:

Albian–Cenomanian: Asu River Group represents the first and oldest unit of shallow marine to brackish water sediments deposited on the basement complex. The group occupies the core of the Abakaliki fold belt (Nwajide, 2013). The subdivision of the group into the component formations by Reyment (1965) has been in use. But Nwajide (2013) has repackaged Asu River Group such that the Ogoja Sandstone, Awi Formation, Mamfe Formation, Abakaliki Formation and Mfamosing limestone are all under Asu River Group Formations. Ogoja sandstone is the basal part of the Asu River group and it consists of conglomerates and arkosic sandstones in both Ikom and Ogoja areas (Uzuakpunwa, 1980; Petters et al., 1987). The Awi Formation is the basal, non-calcareous, sandy, conglomeratic unit of the Asu River Group directly overlying the Basement complex (Oban Massif) north of Calabar. The Albian sediment is deposited in a shallow marine environment (Reyment, 1965).

Turonian-Coniacian: These are the "Eze-Aku shale Group" (Murat, 1972). It includes all the stratigraphic units deposited in the Late Cenomanian to Turonian in the southern Benue Trough (Nwajide, 2013). Eze-Aku Formation overlies the Asu River Group and it consists of black calcareous shale, shelly limestone, siltstone and sandstone, which were deposited as a result of renewed transgression in the second depositional cycle of the Benue Trough (Kogbe, 1976). The age has been suggested to be late Turonian through Coniacian to Early Santonian and this is because of the kind of fossil assemblage – mainly planktic foraminifera assemblage.

Campanian-Maastrichtian: This marks the beginning of deposition within the Anambra Basin and the third cycle of marine incursion in the Benue Trough. Nkporo Shale and their lateral/stratigraphic units of the Anambra basin overlies an angular unconformity. Outcrop of Nkporo shale are scarce, but cored boreholes show that the Formation consists of dark shale and mudstone with occasional thin beds of sandy shale and sandstone (Reyment, 1965). Ogugu Shale is deposited conformably on the Agbani Sandstone. It is generally medium to coarse grained and contains pebble bands, occasionally thin silty, or argillaceous, layers are present. Mamu Formation (Lower coal measures) overlies the Nkporo shale. This consists of fine-grained sand, carbonaceous shale and coal with the thickest seam of l km typifying a transitional environment. Its type locality is the Enugu Cuesta. The Ajali Sandstone (Middle coal measures) overlies the Mamu Formation conformably. The Nsukka Formation (Upper coal measures) is the youngest formation from this cycle consisting of interdigitations of very fine-grained sandstones, dark shale and coal indicating a parallic environment of Maastrichtian to Paleocene age.

Paleocene Sequences: These are deposited as a result of the Paleocene transgression and Eocene regression, which led to the deposition of Imo Shale and Ameki Formation respectively, grading to the proximal Niger Delta. (Agagu, et.al 1982). Imo Shales consists of clayey shale, with clay ironstones and sandstone bands. It rests conformably on the Nsukka Formation and forms a down dip continuation of the Akata Shales in the Niger Delta (Reyment, 1965). Ameki Formation overlies the Imo shales and consists of highly fossiliferous greyish–green, sandy clay with calcareous concretions and white clayey sandstones. It displays rapid lateral facies change, with local shale development or inclusions of sandstones; carbonaceous plant remains may be present. The map of geology of study area is shown in Figure. 1.

Anambra Basin: The Anambra Basin was defined by Wright et al. (1985) as the upper Santonian – Maastrichtian to Paleocene depositional area located at the southern end of the Benue trough, within which the Nkporo Group and the younger sediments accumulated, and which extended towards the southwest as the Niger Delta Basin. Anambra Basin is overlying the facies of the southern Benue Trough and consists of Campanian to early Paleocene (Danian) lithofacies. Many authors including Akande and Erdtmann (1998) and Obaje et al. (1999) considered the Anambra basin as part of the Benue Trough on the premise that is a consequence of the compressional history/stage of the trough.

Being a relocated structure that developed after the compressional state, they implied that it was logical to include the Anambra Basin in the Benue trough. However, Nwajide (2013) and some authors disagreed with this proposition and showed that the Anambra basin is a distinct and well demarcated lithostratigraphic entity overlying the southern Benue Trough and is in turn overlain by the Niger Delta basin.

The origin of the basin is generally believed to be linked to the Santonian tectonics of the Abakaliki Benue Basin, during which an N-S compression between the African and Europeans plates folded the Abakaliki Anticlinorium. Prior to the tectonic event, the Anambra Basin was only thinly covered by sediments. The folding of the Anticlinorium laterally shifted the depositional axis into the Anambra platform which then began to accumulate sediments shed largely from the Abakaliki Anticlinorium (Murat, 1972; Hoque and Nwajide, 1985; Amajor, 1989). The Anambra basin-fill comprises over 2500m of sediments that accumulated during the Campanian-Paleocene period.

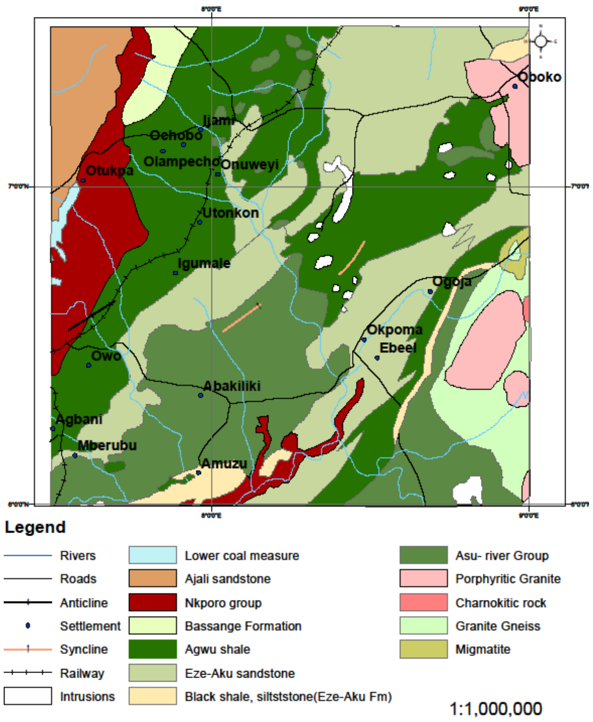

Figure 1: Geology of the Study Area.

MATERIALS AND METHODS

Field and analytical design approaches were employed for this study. The research is divided into three stages: stage one was processing of magnetic data in order to enhance the geologic meaning of the data. Stage two was magnetic susceptibility measurements of the anomalous rocks in the field. The third stage was integration and final interpretation.

Global positioning systems (GPS) have reduced the costs of this field and increased the data accuracy during the field exercise. A massive country-wide airborne geophysical survey commissioned in the year 2006 by the government of the Federal Republic of Nigeria and was awarded to Fugro Airborne surveys of South Africa. While the processing and initial interpretation was contracted to Paterson, Grant and Watson Limited (PGW). The high-resolution magnetic survey flown at 500m Tie-line spacing and 80m terrain clearance; with a flight line spacing of 500m at 135 degrees azimuth flight line trend gave a high-resolution data adequate for this research.

The magnetometer used was Cesium vapor SCINTREX CS2 and the survey was flown along NW-SE direction (i.e., perpendicular to the axis of the basin). The data was generally plotted using Universal Transverse Mercator (UTM) projection method. Data covering nine sheets numbered (228, 289, 290, 269, 270, 271, 301, 302 and 303) was obtained from The Nigerian Geological Survey Agency, 31 Shetima Mangono Crescent Utako District P.M.B 616, Abuja.

Field measurements of in-situ magnetic susceptibility were made on different rocks at twenty locations (Table 1). The susceptibility measurement was made using GDD-Multi parameter Probe portable magnetic susceptibility meter, a hand-held magnetic susceptibility meter, with sensitivity of 1x $10^{0.001}$ SI units (Figure 2). Petrographic studies of major representatives of the rocks were carried out after the field work.

Figure. 2: The hand-held GDD Magnetic Susceptibility Meter is small and easy to use. Measurements are taken first on the rock surface followed by reference reading with another meter.

RESULTS AND DISCUSSION

Correlation of the Magnetic Data with the Rocks Measured in the Field

The study area was selected at the first place by utilizing airborne geophysical data in order to delineate the sources of the anomalies (Rajendra and Kabiraj, 2015; Mertanen and Karell, 2015).

By relating magnetic mineralogy, bulk magnetic properties, petrology and geochemistry to observed magnetic anomalies, an understanding of the geological factors that control magnetic signatures is obtained, which can be used to improve geological interpretation of magnetic surveys (Clark et al., 1992).

Comparison of the susceptibilities values of the rocks with the analytical signal signatures shows that the amplitude of the magnetic anomalies increase with increase in susceptibility values of the rocks (Figure 3 and 4).

Based on the field visitation, the sharp positive anomalies observed on northeastern portion of aeromagnetic map correlate with the ultramafic rocks whereas the lower magnetic anomalies reflect ferruginized ironstone within the Anambra basin.

Magnetic susceptibility measurements provide the hard link between rocks and the features observed in magnetic data (Boyd and Isles, 2007). The smallest amplitude is exhibited by rock in site 1 Ironstone clast (Figure 3).

The susceptibility readings of the visited anomalies are listed in Table 1. Each magnetic susceptibility value in this report represents an average of multiple readings in the field. Generally, the magnetite content and susceptibility of rocks are extremely variable and can be considerable overlap between different lithologies (Kearey, 2002).

Areas where there are high anomalies, have high susceptibility values (see Figures 3 and 4). The susceptibility depends on the amount of ferromagnetic minerals mainly magnetite sometimes titanomagnetite or pyrrhotite and on the paramagnetic and diamagnetic minerals present (Carmicheal, 1982; Hrouda et al., 2010).

Generally, the magnetic susceptibility measurements performed on the rock outcrops reveal lower magnetic susceptibility values for sedimentary, metamorphic, felsic intrusive rocks and pyroclastic rock; moderate susceptibility values for felsic extrusive and intermediate igneous rocks and higher susceptibility values for mafic igneous rocks (Carmichael, 1982). Rocks from the study area reflect this trend.

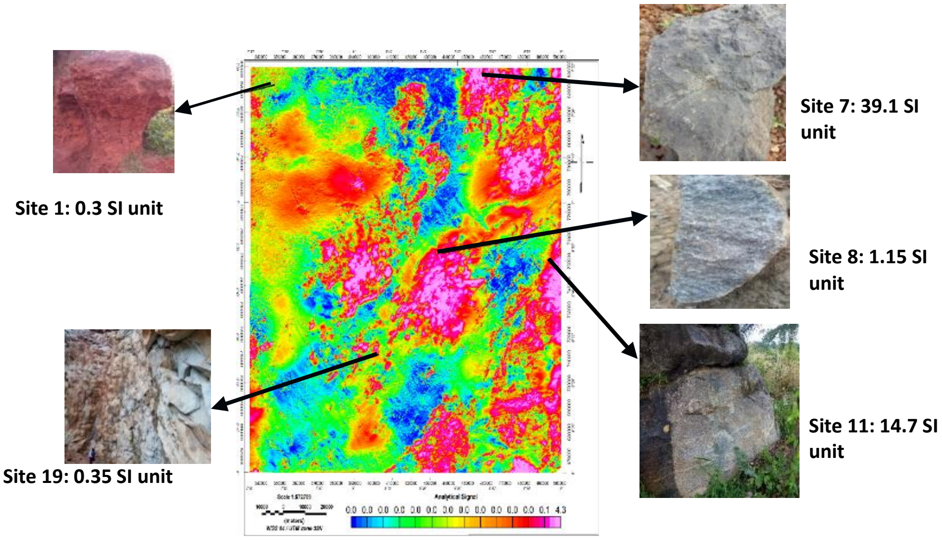

Figure 3: Analytical signal map of the study area showing the signatures of the anomalous rocks on the field with their susceptibility values. Site 1: Ironstone clast; site 7: mafic igneous rock; site 8: Diorite rock; site 11: biotite hornblende gneiss; site 19: pyroclastic rock.

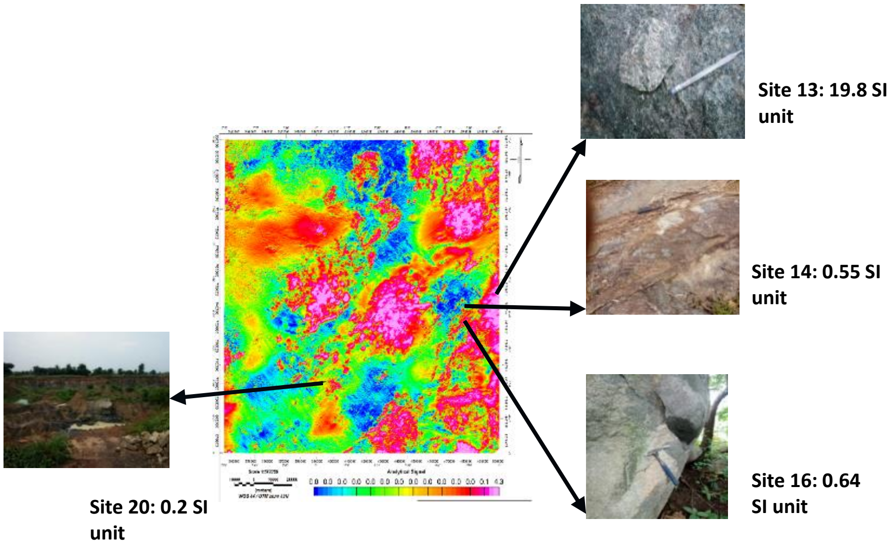

Figure 4: Analytical signal map of the study area showing the signatures of the anomalous rocks on the field with their susceptibility values. Site 13: Charnokitic rock; site 14: weathered granitic rock; site 16: coarse porphyritic granitic rock; site 20 consolidated shale.

Mafic rocks generally have higher magnetic susceptibilities than felsic rocks because mafic rocks are typically more abundant in strongly magnetic minerals such as magnetite. The highest average susceptibility value is exhibited by the mafic igneous rock at site 7 and this reflects the high content of magnetic material in the rock. According to Nielsen and Rasmussen 2002, the higher values reflect the high iron content of the ultramafic rocks.The small susceptibility values of some rocks show magmatic oxides are present in small abundance that do not matter at all (Natlands et al., 2002).

The sedimentary rocks have susceptibility values ranging from 0.12x10^{-3} SI unit to 0.45x10^{-3} SI unit. The magnetic susceptibility of igneous rocks at the study area are variable at site 2 to 7 from intermediate value (Diorite) to high value (Boulders of mafic igneous rock). We categorize susceptibilities less than 1x 10^{-3} SI as “low”, between 1x10^{-3} and 10x10^{-3} SI as “moderate” and greater than 10x10^{-3} as “high” (Altstatt et al., 2002). The lowest occur over some volcanic rocks and gneisses, as well as some sedimentary rocks. The metamorphic rock at location 12 has zero susceptibility value and this could be the effect of metamorphism. The metamorphism could be within granulite gneisses facies (Clark, 1997).

Metamorphism slightly affects the granitic rock at the study area, evident in the susceptibility values of weathered granite at sites 14 and 15 that have susceptibilities value lower than fresh granitic rock at site 17 (see table 1). Other factors such as lithology, depositional environment, tectonic setting, geochemical affinities and hydrothermal alteration influence magnetic properties (Clark et al., 1992).

Figure 5 represents the susceptibility map produced and this is interpreted as a contour presentation of the volume concentration of magnetite (Taha, 2005). According to Hrouda et al., 2009, rocks with susceptibility higher than 5x10^{-3}, means the susceptibility is controlled mostly by the presence of ferromagnetic minerals and paramagnetic minerals. Thus, the susceptibility values of 16.2 x10^{-3}, 28.4 x10^{-3}, 39.1 x10^{-3}, 13.8, 14.7x10^{-3}, and 19.8x 10^{-3} rock in sites 5, 6, 10, 11 and 13 rocks are controlled by ferromagnetic minerals, and much less frequently by diamagnetic and paramagnetic minerals. Abundance of paramagnetic and ferromagnetic minerals result in high magnetic susceptibility signal of a rock (Cricke et al., 1997). This is revealed by the petrographic study of some of the rock samples.

Table 1: Mean Susceptibility Values of the Studied Rocks.

SITES	X	Y	ELEVATION	SUSCEPTIBILITY (10^{-3})	ROCK TYPE
1	19703079	179017	370	0.3	Iron stone
2	19703079	19703079	216	0.12	Sandstone
3	19590773	839538	224	0.31	Sandstone
4	19543859	816132	242	0.45	Sandstone with fragments of dark colored rocks
5	19544087	816206	256	16.2	cobbles of mafic igneous rock
6	19544395	816060	264	28.4	Cobbles of mafic igneous rock
7	19544629	815907	268	39.1	Boulder of mafic igneous rock
8	19303807	548241	166	1.15	Diorite
9	19305295	550128		1.2	Diorite
10	19152990	878925	149	13.8	Biotite hornblende gneiss
11	19152865	879598	148	14.7	Biotite hornblende gneiss
12	19102812	896620	163	0	Biotite hornblende gneiss
13	19079317	910049	177	19.8	Charnokitic rock.
14	19143838	802224	105	0.55	Weathered granitic rock
15	19145755	807909	99	0.648	Weathered granitic rock
16	19135000	785267	70	0.64	Coarse porphyritic rock granite.
17	19121596	785610	86	0.7	Biotite granite.
18	19155506	311323	37	0.35	Pyroclastic rock.
19	19155445	311378	48	0.3	Pyroclastic rock.
20	19164321	242993	89	0.2	Consolidated shale

Site 1 lithology is reddish/lateritic rock ironstone. The ironstone is of Anambra basin (Ajali/Nsukka Formation). The average magnetic susceptibility is 0.3 x 10^{-3}SI unit. Sedimentary and the metamorphic rocks have generally low magnetic susceptibilities.

Petrographic study of site 7 sample revealed it consists of the diamagnetic mineral quartz and paramagnetic minerals plagioclase, biotite, hornblende, augite, and accessory minerals. The rock is augite-hornblende diorite.

Site 9 rock sample is composed of quartz, plagioclase, biotite, hornblende, pyroxene, and accessory mineral. The rock is identified to be hornblende-biotite granodiorite.

The mineral identified in sample 13 (charnokitic rock) rock are well elucidated. Identified mineral include quartz, biotite, and opaque minerals. Quartz consists of elongated grains that are medium size. Biotite is abundant and consists of strides of grains with preferred orientation. Some of the grains have been highly altered. Opaque minerals are sparsely distributed within the sample surface.

Site 16 rock sample has quartz, microcline, biotite and accessory minerals. Zircon and garnet are the identified accessory minerals.

Site 17 sample is biotite granite rock, medium-grained and consists of quartz, plagioclase, biotite, chlorite and accessory minerals. Plagioclase consists of suhedral to euhedral grains with characteristic albite twinning under cross polarized light. Some of the grains have inclusion of accessory minerals. It occurs in association with greenish colored chlorite. Accessory minerals identified are garnet and zircon.

CONCLUSION

The highest average susceptibility value is exhibited by the mafic igneous rock at site 7 at Aliade in Igbor LGA and around Ogoja, Okuku in Cross River state.The lowest occur over some volcanic rocks and basement granites and gneisses, as well as some sedimentary rocks. These areas are found at the western and southern portion of the area.

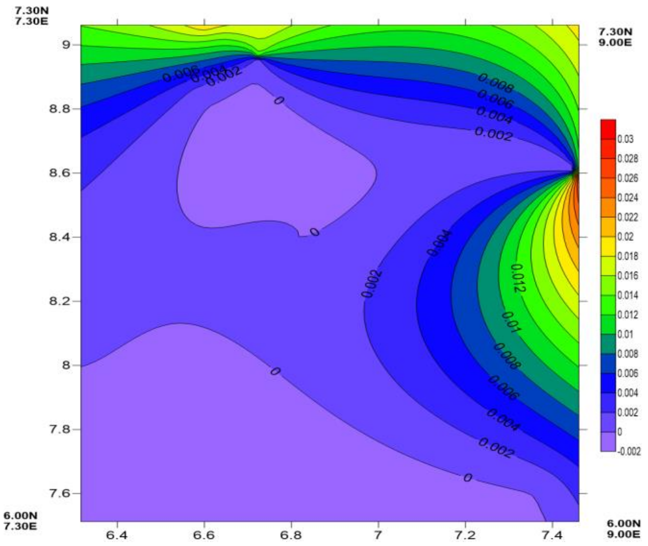

Figure 5: Susceptibility Map of the Area.

Magnetic susceptibility of rocks in the study are controlled by the ferromagnetic minerals (iron oxides or sulphides, represented for instance by magnetite and/or pyrrhotite, respectively) and much less frequently by diamagnetic minerals (calcite, quartz) and paramagnetic minerals (mafic silicates such as olivine, pyroxenes, amphiboles, micas, tourmaline, garnets). Areas on the aeromagnetic map with high amplitude have high susceptibility values.

REFERENCES

1. Agagu, O.K, and C.M. Ekweozor. 1982. “Source Rock Characteristics of Senonian Shales in the Anambra Basin of Eastern Nigeria”. *J. Mining and Geol.* 19:132-140.

2. Akande, S.O. and B.D. Erdtmann. 1998. “Burial Metamorphism (thermal maturation) in Cretaceous Sediments of the Southern Benue Trough and Anambra Basin, Nigeria”. *Geol. en Mijnbouw.* 7:131 – 144.

3. Alagarsamy, R. 2009 “Environmental Magnetism and Application in the Continental Shelf Sediments of India”. *Marine Environmental Research*. 68(2):49. 10.1016/j.marenvres.2009.04.003 hal-00563074.

4. Altstatt, A.A, R.W. Saltus, R.L. Bruhn, and R. Hacusslern. 2002. “Magnetic Susceptibilities Measured Non-Rocks of the Upper Cook File, Alaska”. USGS open file Report 02-0139. -9.

5. Amajor, L.C. 1989. “Geological Appraisal of Groundwater Exploitations in the Eastern Niger Delta”. In: C.O Ofoegbu (Ed.). *Groundwater and Mineral Resources of Nigeria.* Friedr Vieweg and Sohn: Braunschweig/Weisbaden, Germany. 85-100.

6. Boyd, D.M. and D.J. Isles. 2007. “Geological Interpretation of Airborne Magnetic Surveys-40 Years”. *Proceedings of Exploration 07. Fifth Decennial International Conference on Mineral Exploration.* B. Milkereit (ed.). 491-505.

7. Carmichael, R.S. 1989. *Practical Handbook of Physical Properties of Rocks and Minerals*. CRC Press: Boca Raton, FL.

8. Case, J.E. and R.F. Sikora. 1984. *Geologic Interpretation of Gravity and Magnetic Data in the Salida Region, Colorado*. US Geological Survey Open-File Report, 46, 84-372.

9. Chadima, M. 2011. “Application of Magnetic Susceptibility as a Function of Temperature, Field and Frequency”. *Latinmag Letters*.1, Special Issue (2011), E03:1.

10. Clark, D.A., D.H. French. M.A. Lackie and B.W. Schmidt. 1992. “Magnetic Petrology Application of Integrated Rock Magnetic Petrological Techniques to Geological Interpretation of Magnetic Survey”. *Exploration Geophysics*. 23:65-68.

11. Clark, D.A. 1997. “Magnetic Petrophysics and Magnetic Petrology Aids to Geological Interpretation of Magnetic Survey, A950”. *J. Aust. Geol. Geophysics*. 17(2):83-103.

12. Crick, R.E., B.B. Ellwood, A. El Hassani, R. Feist, and J. Hladil. 1997. “Magnetosusceptibility Event and Cyclostratigraphy (MSEC) of the Eifelian–Givetian GSSP and Associated Boundary Sequences in North Africa and Europe”. *Episodes*. 20:167–175.

13. da Silva. A.C., K. Potma; J.A.W. Weissenberger, M.T. Whalen; C. Mabille and F. Boulvain. 2009. “Magnetic Susceptibility Evolution and Sedimentary Environments on Carbonate Platform Sediments and Atolls, Comparison of the Frasnian from Belgium and Alberta, Canada”. *Sedimentary Geology*. 214: 3–18.

14. da Silva, A.C.. M.T. Whalen, L. Hladil, D. Chadimova, S. Chen, F. Spassov, F. Boulvain and X. Devleeschouwer. 2015. Geological Society, London, Special Publications, 414, 1-13, 24 June 2015, https://doi.org/10.1144/SP414.12

15. Getting, M.E. and M.W. Bultman. 2014. “Magnetic Susceptibility Data for some Exposed Bedrock in the Western Conterminous United States”. U.S. Geological Survey Data Series 804, 5 p., with graphical user interface, http://dx.doi.org/10.3133/ds804.

16. Hildenbrand, T.G., W.D. Stuart, and P. Talwani. 2001. “Geological Structures Related to New Madrid Earthquakes near Memphis, Tennessee, Based on Gravity and Magnetic Interpretations”. *Environment Geology*, 62:105-121. http://dx.doi.org/10.1016/S0013-7952(01)00056-4

17. Hoque and Nwajide. 1985. “Application of Markov Chain and Entropy Analysis to Lithologic Successions: An Example from the Cretaceous of the Benue Trough (Nigeria) Geology”. *Rundschau* 74:165-172.

18. Hrouda, F., M. Chlupacova, M. Chadima. 2009. “The use of Magnetic Susceptibility of Rocks in Geological Exploration”. *Terraplus-Case Study*. 6: 1-25.

19. Kearey, P., and M. Brooks. 2002. *An Introduction to Geophysical Exploration*. Blackwell Science: London, UK.. 262 pp.

20. Kogbe, C.A. 1965. *Geology of Nigeria*. Rock View: Nigeria (limited): Lagos, Nigeria. 536p.

21. Mertanen, S. and F. Karell. 2015. “Petrophysical and Rock Magnetic Studies to Aid Au Exploration – Case Studies from the Häme Belt, Southern Finland”. *Geological Survey of Finland, Special Paper*. 58: 89–106.

22. Murat, R.C. 1972. “Stratigraphy and Paleography of the Cretaceous lower Tertiary in Southern Nigeria”. In: Dessauvagie, T.F.J. and Whiteman, A. (eds.). *African Geology*. UI Press: Ibandan, Nigeria. 635-641.

23. Natland, J.H. 2002. “Magnetic Susceptibility as an Index of the Lithology and Composition of Gabbros, ODP Leg 176, Hole 735B, Southwest Indian Ridge”. In: J.H. Natland, H.J.B. Dick, D.J. Miller, and R.P. Von Herzen (eds.). *Proc. ODP, Sci. Results*, 176, 1–69 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/176_SR/VOLUME/CHAPTERS/SR176_11.PDF>. [Cited YYYY-MM-DD] Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami FL.

24. Nielsen, B.M. and T.M. Rasmussen. 2002. “Geological Correlation of Magnetic Susceptibility and Profiles from Nordre Strømfjord, Southern West Greenland”. *Geology of Greenland Survey Bulletin*. 191:48–56.

25. Nwajide, C.S. 2013. *Geology of Nigeria Sedimentary Basins*.CSS press 565pp.

26. Obaje, N.G., I.I. Funtua, B. Ligouis, and S.I. Abaa. 1999. "Organic Maturation and Coal-Derived Hydrocarbon Potentials of Cretaceous Coal Measures in the Middle Benue trough of Nigeria". *J. Mining and Geol*. 34(1): 7-18.

27. Oniku, S.U., I.B. Osazuwa, and O.C. Meludu. 2008. "Preliminary Report on Magnetic Susceptibility Measurements on Rocks within the Zaria Granite Batholith, Nigeria". *GEOFISIKA*. 25(2).

28. Peters, S.W. and C.S. Okereke. 1987. "Geology of the Mamfe Rift, S.E. Nigeria". In: G Mathes and H.S. Schandelmeier (eds.). *Current Research in African Sciences*. A.A Balkema: Rotherdam. 299-302.

29. Rabeh. T. 2005. "Prospecting for the Ferromagnetic Mineral Accumulations using the Magnetic Method at the Eastern Desert, Egypt". *J. Geophysics Eng*. 6:401-411.

30. Rajendra, A. and P. Kabiraj. 2015. "Magnetic Susceptibility as a Tool of Lithological Mapping: A Case Study from Malekhu-Damauli Area of Central Nepal, Lesser Himalaya". *Nepal Journal of Science and Technology*. 16(1):49-58.

31. Reeves, C., R. Macnab, and S. Maschenkov. 1998. "Compiling all the World's Magnetic Anomalies". *EOS, Transactions of the American Geophysical Union*. 79:338.

32. Reyment, R.A. 1965. *Aspects of Geology of Nigeria*. Ibandan University Press: Ibandan University Press, Nigeria, p.133.

33. Searle, R.C. 2008. "Magnetic Susceptibility as a Tool for Investigating MIgneous Rocks—Experience from IODP Expedition 304". *Scientific Drilling*. dio:10.2204/IODP.sd.6.08.2008

34. Telford, W.M., L.P. Geldart, and R.E. Sheriff. 1990. *Applied Geophysics 2nd edn*. Cambridge University Press Cambridge: Cambridge, MA.

35. Uzuakpunwa, A.B. 1980. "Petrography Differentiation of Tectonically Controlled Cretaceous Sedimentary Cycles Southeastern Nigeria". *Sedimentary Geology*. 17:234 – 245.

36. Waswa, A.K., C.M. Nyamai, E. Mathu, and D.W. Ichang'I. 2015. "Application of Magnetic Survey in the Investigation of Iron Ore Deposits and Shear Zone Delineation: Case Study of Mutomo-Ikutha Area, SE Kenya". *International Journal of Geosciences*. 6: 729-740. http://dx.doi.org/10.4236/ijg.2015.67059

37. Wright, J.B., D.A. Hastings, W.B. Jones, and H.R. Williams. 1985. *Geology and Mineral Resources of West Africa*. George Allen and Union. 188.

ABOUT THE AUTHORS

M.O. Eze, Ph.D., is a Lecturer 1 at the Michael Okpara University of Agriculture, Umudike, Abia State. She is a registered Geologist and is a member Nigerian Association of Petroleum Explorationists (NAPE), Nigeria Mining Geosciences Society (NMGS) and Society of Exploration Geophysicists (SEG). She holds a Ph.D. degree in Applied Geophysics from the University of Nigeria, Nsukka. Her research interests are in reservoir characterization, mineral exploration, basin analysis/modelling, and GIS application in geology/geophysics.

Ikechukwu B. Ijeh, is a senior Lecturer at Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria. He is a geophysicist with interest in assessment of pollution status and vulnerability of water supply aquifers, groundwater quality, aero-magnetic applications and investigation of subsurface resistivity. He holds a Ph.D. in Geophysics from the Federal University of Technology, Owerri, Imo State, Nigeria.

SUGGESTED CITATION

Eze, M.O. and I.B. Ijeh. 2019. "Integration of in-situ Susceptibility and Petrographic Data in Study of the Magnetic Properties of some Rocks of Parts of Anambra Basin and Southern Benue Trough, Nigeria". *Pacific Journal of Science and Technology*. 20(2):387-395.

Pacific Journal of Science and Technology