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ORIGINAL RESEARCH ARTICLE

Multi-Step Filtering of High Resolution Aeromagnetic Data for Geological Delineation over Sokoto Basin, Northern Nigeria

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ABSTRACT
The aeromagnetic survey provides a means for prospecting subsurface structures based on the magnetic susceptibility contrast of the underlying materials. It is applied in hydrocarbon study, mineral exploration, environmental monitoring, unexploded ordinance, and geological mapping. In this research, high-resolution airborne magnetic data over Sokoto Basin were acquired, analysed, and interpreted using some selected filters applied in steps to delineate the geologic boundary of the study area. The data, which were acquired in the form of $0.5^{0} \times 0.5^{0}$ square grids, were first knitted to form the composite total magnetic field intensity map of the study area. A hierarchical combination of four carefully selected enhancement filters was then applied to the composite total magnetic field intensity map to enhance regional features. The filters were reduction to the equator, Butterworth, vertical integration, and upward continuation – the algorithms are available in the Oasis Montaj environment. The results obtained showed four distinct regional fields – very high (>100 nT) at the northern part corresponding to the Sokoto Group, high (60-100 nT) at the north-western part corresponding to the Gwandu Formation, moderate (40-50 nT) at the mid part indicting the Rima Group and low (< 40 nT) in the south-eastern part of the area resulting from Continental Intercalaire. It is concluded that the multi-step filter has reasonably delineated the stratigraphic successions in the Nigerian sector of the lullummeden Basin (Sokoto Basin). The filtering was efficacious in resolving the geologic structures, which were not resolved when a single technique was applied in isolation.

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INTRODUCTION
The application of magnetic enhancement techniques – vertical derivatives, horizontal gradient, analytical signal, tilt derivative, reduction to the pole/equator, vertical integration, or upward continuation – for transforming magnetic data effectively detects and highlights magnetic anomalies linked to the edges of simple geological bodies. This makes them valuable for mapping or delineating simple structures, volcanic rock bodies, and other igneous intrusions that are emplaced and concealed within sedimentary rocks in sedimentary basins. These methods have been utilized worldwide to identify surface and subsurface faults, shear zones, and fractures. These structures can potentially host various minerals and serve as guides for exploring epigenetic, stress-related mineralization in the surrounding rocks. Additionally, subsurface structures may act as migration pathways and/or traps for petroleum, including oil and gas. However, a single technique may not resolve a complex geological setting, such as the Sokoto basin, with various sedimentary formations and volcanic rocks, when applied in isolation (Sheu *et al.,* 2004; Shehu et al., 2017; Ibe et al., 2018; Ezekiel et al., 2019).

A multi-step filter can be developed and applied based on careful selection and hierarchical combination of some of these techniques. The algorithms required are readily available in the Oasis Montaj environment. This study, therefore, aims to demonstrate the efficacy of stepwise combination reduction to the equator (RTE), vertical integration (VI), and upward continuation (UC), selected and applied to aeromagnetic data to study the geologic architecture of Sokoto Basin, located at north-western Nigeria (Figure 1). This study was motivated by the fact that images obtained from previous investigations of geomagnetic data of the Sokoto basin (Sheu *et al.,* 2004; Shehu et al., 2017; Ibe et al., 2018; Ezekiel et al., 2019) did

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not sufficiently delineate the different geologic formations of the basin, making them hard to interpret without recourse to previously established detailed geological maps of the area.

The basin is the southeastern part of the big Iullemmeden Basin (Shehu et al., 2017). Metamorphic rocks underlie the Sokoto Basin and have an average elevation ranging from 250 to 400 meters above sea level (Sheu *et al.,* 2004; Ezekiel et al., 2019). The basin may be subdivided into the following: the Gwandu Formation, which is popularly referred to as the Continental Terminal; the Sokoto Group, comprising of Gamba, Kalambaina, and Dange Formations; the Rima Group, which consists of Wurno, Dukamaje and Taloka Formations and finally the Continental Intercalaire consisting the Gundumi and Illo Formations (Obaje, 2009). Aside from Nigeria, other countries with significant portions of the Iullemmeden Basin are the Republic of Benin, Niger Republic, Algeria, and Libya (Obaje *et al.,* 2013; Kamba et al., 2018; Ibe et al., 2018).

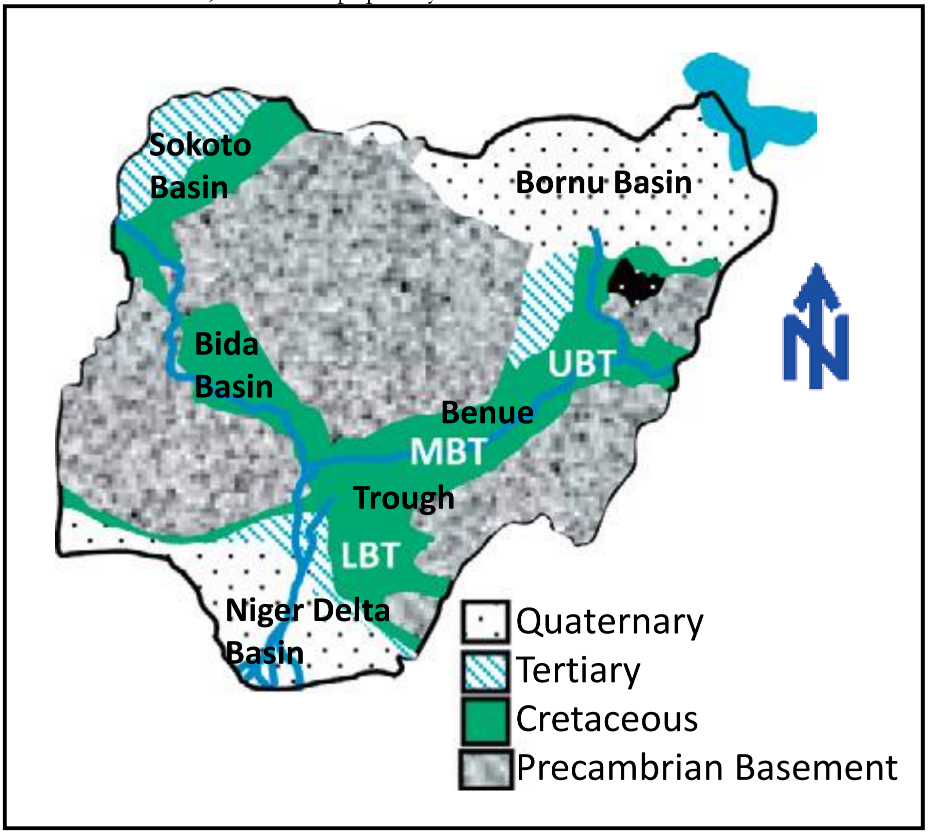

Figure 1: Geologic Map of Nigeria showing the Sokoto Basin (Anudu *et al.,* 2014)

METHODOLOGY

The digital aeromagnetic data utilized in the research were sourced from the recent high-resolution national datasets flown by Fugro Airborne Surveys for the Nigerian Geological Survey Agency (NGSA). Equipment used for data acquisition are: a fixed-wing aircraft, Sintrex CS3 Caesium Vapour magnetometer, FASDAS magnetic counter, KING KR 405/KING KR 405B radar altimeter, and ENVIRO BARO/DIGIQUARTZ barometric altimeter. The aeromagnetic survey was flown along a series of NW–SE flight lines (i.e., perpendicular to dominant regional geological strike), spaced 500 m, with 2000 m tie-line spacing in a NE–SW direction and 80 m nominal flight height. Data were recorded at 0.1 s intervals. Since the aeromagnetic survey was flown closer to the ground (80 m flight height) with narrow line spacing and very small recording intervals, the resolution of the anomalies is vastly superior to that of conventional high-altitude aeromagnetic surveys.

All necessary magnetic data corrections were carried out. The geomagnetic gradient was removed using the International Geomagnetic Reference Field (IGRF) model referenced to the World Geodetic System 1984 ellipsoid. The aeromagnetic data were geo-referenced to the Universal Transverse Mercator (UTM) coordinate system for comparative study with a geological map of the area.

The aeromagnetic (total magnetic intensity, TMI) data of the area were gridded using the bi-directional gridding method, which is well-suited for parallel or nearly parallel data orientations to enhance trends perpendicular to the flight lines. This method employs Akima splines to interpolate data readings along and across the lines to determine values at the grid nodes. A grid cell size of 100 by 100 meters was selected, equivalent to one-fifth (1/5) of the survey or flight line spacing, to minimize short-wavelength errors that could appear as lines perpendicular to the flight direction. According to Anudu et al. (2014), grid cell size (i.e., the distance between interpolated locations or positions) should be 1/3 to 1/5 of the survey line spacing.

The filtering process commenced with the transformation of the TMI grid data using the reduction to the equator (RTE) filter rather than the reduction to the pole (RTP) filter. This choice was necessitated by the study area's location within low magnetic latitudes (i.e., regions with a geomagnetic inclination of less than 15°), where achieving an accurate reduction to the pole (RTP) of magnetic data is not feasible (GETECH, 2007). Additionally, a Butterworth low-pass filter was implemented during the RTE transformation to suppress high-wavenumber noise present in the data. This enhancement refined the TMI anomaly map, yielding a more accurate representation of magnetization directions and the ambient magnetic field. In the subsequent stage of analysis, the Vertical Integration (VI) technique was employed to further interpret the data. The MAGMAP two-dimensional Fast Fourier Transform (2-D FFT) filters package in the Oasis Montaj software (Geosoft Inc., 2015) contains the required algorithms employed. Upward Continuation (UC) was applied at 20 km to further refine the vertically integrated data at the third filtering stage (Ezekiel et al., 2019). Since the magnetic field, as a potential field, adheres to Laplace's equation, it enables the determination of the field over any arbitrary surface, provided that the field is fully known over another surface. This principle underpins the process known as continuation (Telford *et al.,* 2004).

RESULTS AND DISCUSSION

The composite total magnetic field intensity (TMI) map is depicted in Figure 2. The TMI values generally ranged from -65 to 100 nT after removing a constant value of 33000 nT. The anomalies are distinguished by short-wavelength (high wavenumber), medium-wavelength (moderate wavenumber), and long-wavelength (low wavenumber) variations. Low magnetic values are coloured blue while high magnetic values red to pink, with green to yellow being intermediate. The background field is generally perceived to be low, typical for the sedimentary basin, with the north-western part being magnetically higher than its south-eastern counterpart. Most of the observable anomalies are mostly oriented in the northeast-southwest and along east-west.

The initial step in the filtering process involved reducing the total magnetic field intensity map to the magnetic equator (RTE), rather than performing a reduction to the pole (RTP), due to the study area's location in low latitudes (10.5° to 13.5°), which are closer to the equator than the pole. A Butterworth low-pass filter was subsequently applied to further attenuate high-wavenumber noise in the data during this phase of filtering. These procedures resulted in subtle enhancements and shifts in the magnetic anomalies on the original TMI anomaly map, ultimately transforming the TMI into a more accurate representation of magnetization directions and the ambient magnetic field. Hence, the reduced to equator total magnetic intensity (RTE-TMI) anomaly map has shown nearly centred magnetic anomalies directly over their respective causative geological bodies, which are visually more accurate to interpret (Figure 3).

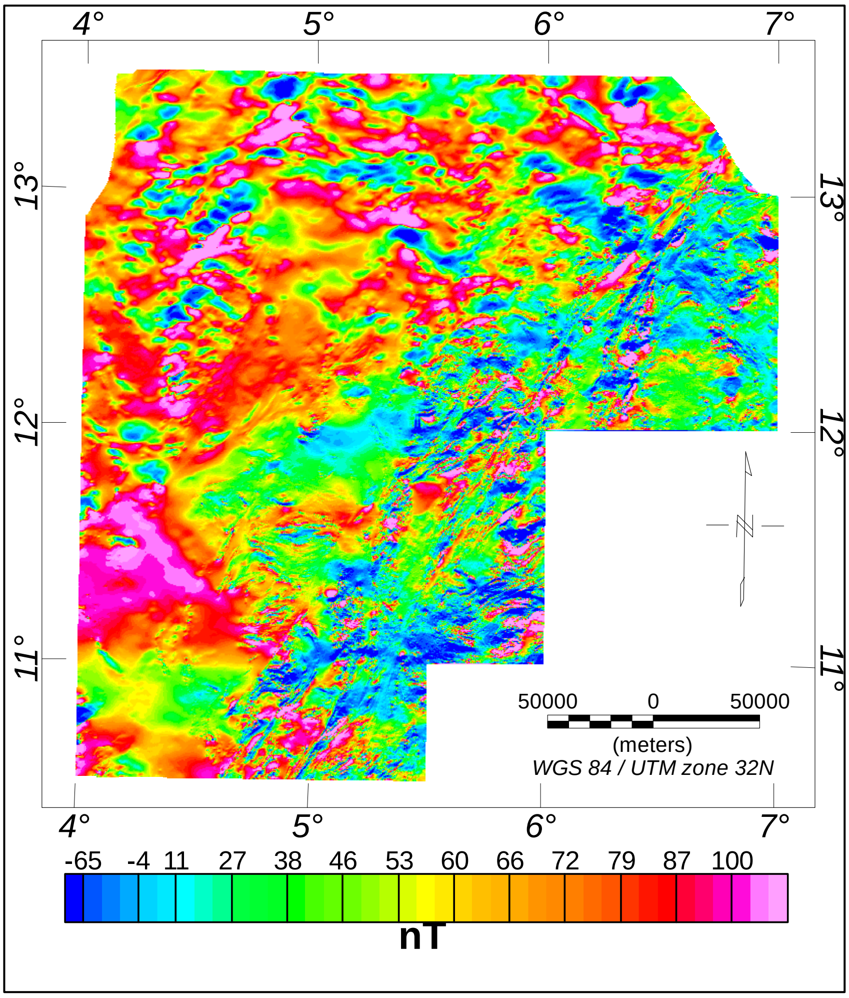

Figure 2: Total magnetic field intensity map (TMI) of the study area

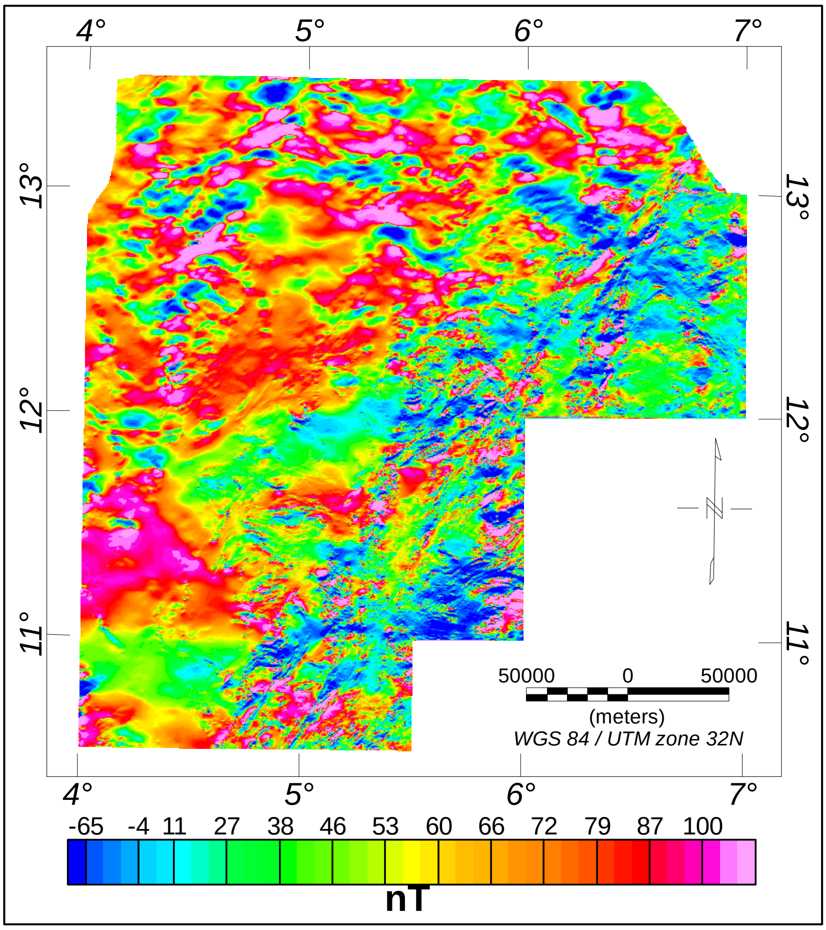

Figure 3: Reduced to equator of total magnetic field intensity (RTE-TMI) map of the area

In the second step, the application of vertical integration has further enhanced the data by mitigating the influence of shallow ensembles and suppressing noise. The resulting map has fairly shown major geologic boundaries, which would further be enhance in the last stage (Figure 4).

To minimize the influence of short-wavelength features caused by shallow sources and noise in the grids, thereby enhancing large-scale geological features and ensuring the representation of a valid regional field, upward continuation was applied to the vertically integrated total magnetic field intensity anomaly of the study area at a height of 20 km. The method tends to accentuate anomalies caused by deep sources at the expense of anomalies caused by shallow sources (Mekonnen, 2004). The result obtained delineated the stratigraphic successions in the Nigerian sector of the lullummeden Basin (Sokoto Basin), showing four distinct regional fields – very high (>100 nT) at the northern part, high (60-100 nT) at the north-western part, moderate (40-50 nT) at the mid part and low (< 40 nT) in the south-eastern part (Figure 5).

The result (Figure 5) agrees with established geologic findings in the area (Obaje, 2009), in which the very high magnetic anomaly observed at the northern part of the area corresponds to the iron-rich oolites recorded as the main deposits of the Sokoto Group (Gamba, Kalambaina and Dange Formations) which is of the Paleocene series (66-56 Ma). The Gwandu Formation in the north-western part of the study area is of the Eocene series (56-33.9 Ma). Previous studies have shown that the formation contained several prominent ridges and clusters of flat-topped, steep-sided hills capped with ironstone, which possesses a highly magnetic origin. This could be the reason why the area is also highly magnetic. The moderately magnetic sediments observed at the central part of the study area belong to the Rima Group, comprising of Wurno, Dukamaje, and Taloka Formations, which extend north towards the Niger Republic. Studies have shown that these sediments contain sandstones, siltstones, and mudstones (Ozumba, 2018). The Illo Formation represents a lateral equivalent of the Gundumi Formation, exhibiting the lowest observable magnetic values within the study area. Collectively, these formations constitute the Continental Intercalaire. Similar to the Gundumi sediments, the Illo Formation unconformably overlies the basement. The deposits are of continental origin, ranging from fluviatile to fluvio-lacustrine environments, and comprise shale and limestone. They dip gently in the N-E direction, striking in the NE–SW direction (Obaje, 2009). These formations contain structures that can potentially host various minerals and serve as guides for exploring epigenetic, stress-related mineralization in the surrounding rocks. Additionally, subsurface structures may act as migration pathways and/or traps for petroleum, including oil and gas. The final filtering step has shown remarkable improvements compared with the first step's result. Similar improvement can also be seen when compared with the results of previous aeromagnetic studies in the area (Lawal et al., 2020; Rabo et al., 2022a; Rabo et al., 2022b).

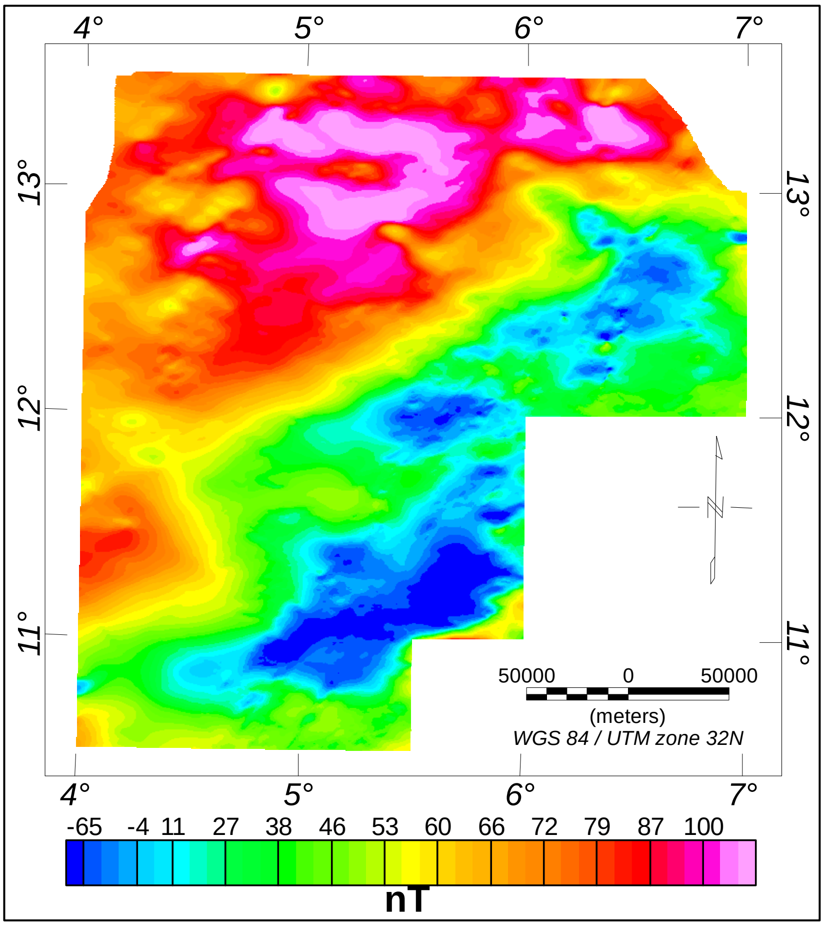

Figure 4: Vertically integrated reduced to equator TMI (VI-RTE-TMI) map of the area

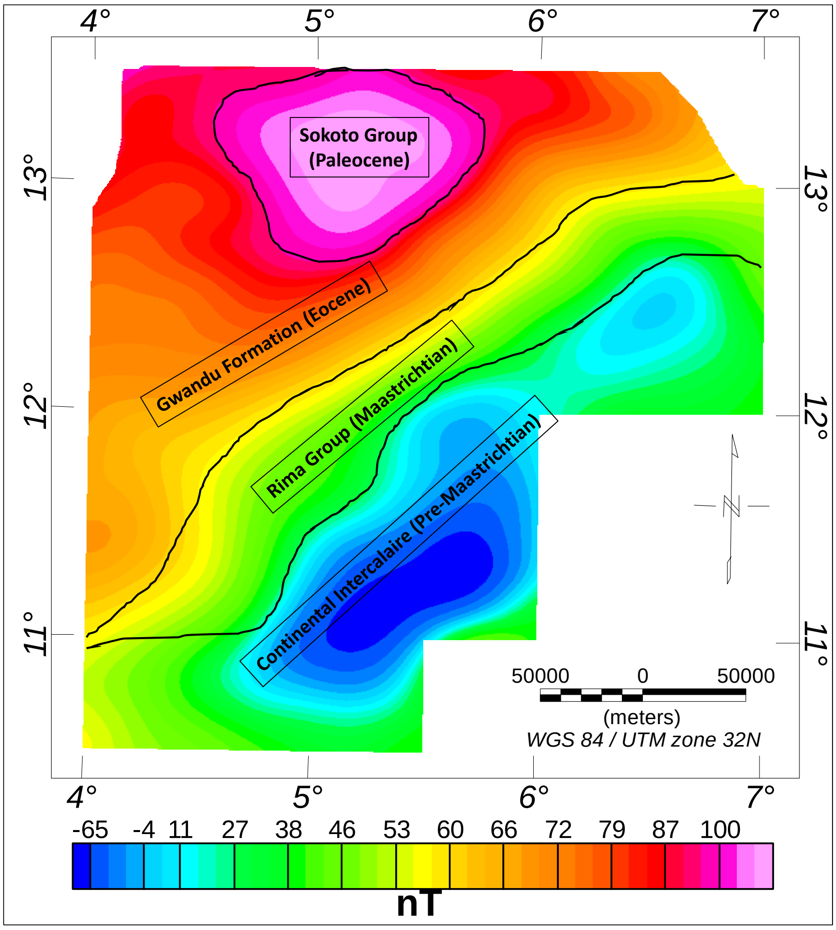

Figure 5: Upward continued vertically integrated reduced to equator TMI (UC-VI-RTE-TMI) map of the area

CONCLUSIONS

Reduction to the Equator, Butterworth, Vertical integration, and Upward Continuation are among the qualitative data enhancement techniques used to analyse magnetic data. The techniques have been proved handy when applied exclusively to locate and examine simple linear and nonlinear geologic features, which are indicative of hydrocarbon and mineral resources potential. However, a single technique may not satisfactorily resolve a complex geological setting, such as Sokoto basin, with various sedimentary formations and volcanic rocks. Multi-step filtering based on hierarchical combination of those techniques was applied. The result showed four distinct regional fields – very high (>100 nT) at the northern part corresponding to the Sokoto Group, high (60-100 nT) at the north-western part corresponding to the Gwandu Formation, moderate (40-50 nT) at the mid part indicting the Rima Group and low (< 40 nT) in the south-eastern part of the area resulting from Continental Intercalaire. It is concluded that the multi-step filtering has reasonably delineated the stratigraphic successions in the Nigerian sector of the lullummeden Basin (Sokoto Basin).

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