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APPRAISAL OF THE MAGNETIC AND GEOTHERMAL ANOMALIES OF BORNU BASIN NORTHEAST NIGERIA INVOLVING AERO-MAGNETIC DATA

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ABSTRACT

The Bornu Basin in northeast Nigeria was studied using high-resolution airborne magnetic data with the objective of improving the reliability of mapped magnetic and geothermal anomalies, and depth solutions. Necessary enhancement operations like analytic signal (ASIG), upward continuation, depth assessment methods involving standard Euler deconvolution (SED) and source parameter imaging (SPI) as well as spectral analysis applying the centroid technique were applied. The middle and southern parts are dominated by high frequency anomalies as revealed by the ASIG map. Furthermore, the magnetic data, when upward continued to 5 km, revealed avalanche of deeply buried igneous intrusions that created near-surface magnetic sources and geologic structures. Maximum thicknesses of sedimentary series estimated from SED and SPI, are respectively ~5974.7 and ~5885.3 m. These values correlate correlated relatively well with depth to the top boundary (Z_t) of ~6550 m obtained from the centroid technique. These depth estimates reveal sequence of thick sediments overlying igneous intrusions and falls under the prospective geothermal anomaly zones characterised by high geothermal gradient (GG) (>55 °C/km) and heat flow (HF) (>130 mW/m^2) values. Areas characterised by high geothermal anomalies correspond to igneous intrusion-dominated shallow Curie point depths (CPD or Zb).

KEYWORDS: Magnetic Method; Source Parameter Imaging; Standard Euler Deconvolution; Curie Point Depth; Geothermal Gradient; Heat-Flow, Bornu Basin, Nigeria

INTRODUCTION

The Bornu Basin is a southward extension of Chad Basin that runs into several African countries including Central African Republic, Chad, Niger, and Cameroon, into northeastern Nigeria (Okosun, 1995). Several researchers have studied the geology (Okosun, 1995; Okosun, 1992; Avbovbo, *et al.,* 1986; de Klasz, 1978; Matheis, 1976, and some references therein), stratigraphy (Nwankwo and Ekine, 2009; Okosun, 2000; Petters and Ekweozor, 1982), tectonic evolution and regional framework (Genik, 1992) of the Bornu Basin. Geophysical and geological evidence suggests the coexistence of igneous rocks with some horst and graben structures that are overlain by somewhat thick sediments (Nwankwo *et al.*, 2012). Heat-flow, Bouguer gravity, and seismic results reveal the existence of structural and stratigraphic traps (Nwankwo *et al.,* 2012). Recently, the Federal Government of Nigeria commissioned geoscientists to conduct integrated investigation involving seismic, magnetic, geochemical, paleoclimatography, rock facies assessments, aerial photography, magnetic investigation, gravity prospecting and exploratory boreholes in the mainly Cretaceous inland basins of Nigeria (Ekwok *et al.,* 2021a; 2019). Sedimentary basin analysis, tectonics and tectono-sedimentary framework (Ofoegbu, 1984; Burke *et al.,* 1971), and geophysical characterization of mineral deposits (Eldosouky et al., 2022; Ekwok *et al.,* 2022a; 2022b; 2022c; 2022d; 2022e; 2021b; 2020a) can be mapped from the analysis and interpretation of potential field dataset.

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On the whole, magnetic method provides a quick way of exploring depocentres, estimating sediment thicknesses, assessing mineralised areas (Ekwok *et al.,* 2021a; 2020a), delineating horst and graben structures (Ekwok *et al.,* 2021b), as well as geothermal systems/structures (Abraham *et al.,* 2019). Also, it is reported that geologic structures determine the location, concentration, and pattern of hydrothermal mineralization (Eldosouky and Elkhateeb, 2018), polymetallic anomalies, Copper-Uranium mineralization (Ekwok *et al.,* 2021c; Boadi *et al.*, 2013) including, the character and orientation of groundwater movement (Ekwok *et al.,* 2020b).

Currently, reconnaissance hydrocarbon exploration, minerals and geothermal energy investigations in the inland basins of Southern of Nigeria are being conducted employing the recent high-resolution magnetic data. These data plus improvement in technology have made it progressively feasible to delineate subtler magnetic anomalies/structures, offer a better understanding of the buried geothermal systems/structures (Abraham *et al.,* 2019) and simplify interpretations (Eldosouky and Elkhateeb, 2018). In general, the main applications of airborne magnetic data are to enhance detection of targets, resolve the position and depth to magnetic and geothermal anomalies.

Essential enhancement operations like analytic signal (Nabighian, 1972), upward continuation (Nabighian, 1984; Gunn, 1997), depth assessment methods (such as standard Euler deconvolution and source parameter imaging) (Thurston and Smith, 1997) as well as spectral analysis involving the centroid method (Bhattacharyya and Morley, 1965) were applied. The magnetic dataset were subjected to spectral analysis using the enhanced centroid method (Bhattacharyya and Morley, 1965) to generate CPD, GG and HF maps. Curie depth results from magnetic data can be used to generate reliable geothermal information in geologic basins characterized by intrusions, such as the Bornu Basin (Bansal et al., 2016; 2013; 2011). The modified centroid technique permits depths to the top and centroid of the magnetic body to be estimated (Bansal et al., 2011). This procedure, which has an advantage over traditional methods, allows convenient computation of basal depths of the magnetic bodies (Bansal et al. 2016). To improve the reliability of the mapped magnetic and geothermal anomalies, as well as depth solutions, several techniques including spectral analysis, enhanced depth estimation methods, and better-quality filtering, were applied to the same magnetic anomalies.

Location and geology

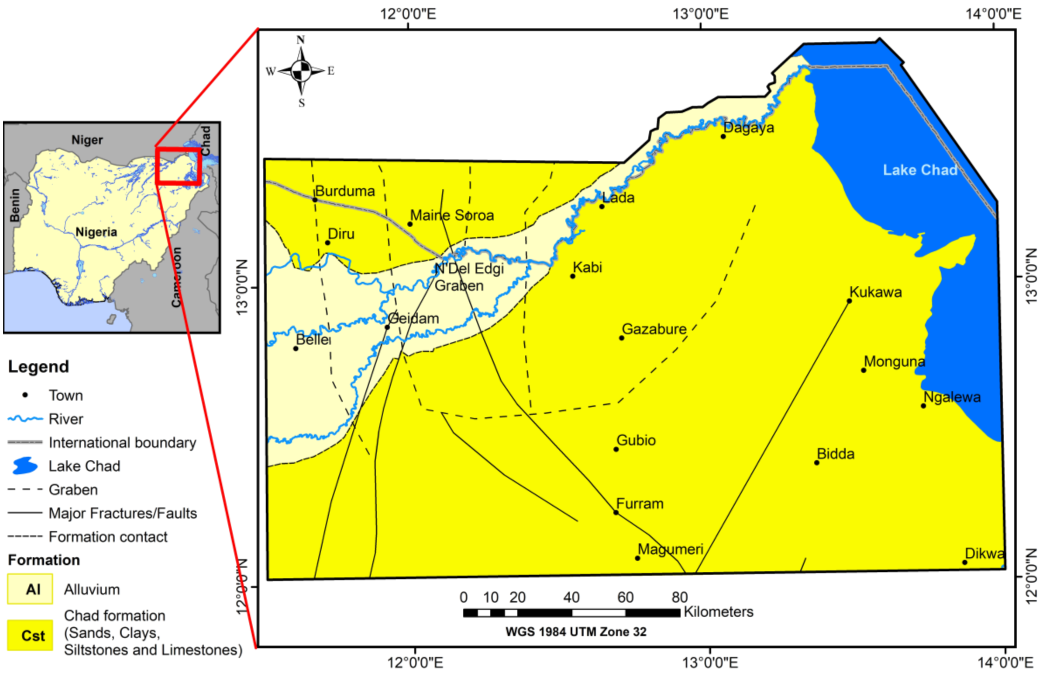

Figure 1: Geologic map of the study area

Bornu Basin (Figure 1) is located between longitudes 11°30′and 14°00′E of the Greenwich Meridian and latitudes 12°00′ and 14°00′N of the Equator in Nigeria's northeastern border with Chad, Cameroon, and Niger Republics. It is a southward extension of the Chad Basin, (Kingston et al., 1983) into northeastern Nigeria (Genik, 1993). With variable elevations above sea level (200-500 m), its dominant structures consist of a system of physically disconnected but contemporaneous and genetically connected CARS (Central African Rift System and WARS (West African Rift System) (Hamza and

Hamidu, 2011). According to Fairhead and Green (1989), the WARS and CARS originated from the breakup of the Gondwana, and the consequent creation of Indian and South Atlantic Oceans at about 120-130 Ma. Information regarding the development and tectonic structure of the Bornu Basin have been properly documented (Genik, 1993; Genik, 1992; Fairhead and Green, 1989). Evidence gathered from geological and geophysical investigations show a diverse sequence southwest ward stretching of Cretaceous grabens from the Benue Trough in central Nigeria (Nwankwo et al., 2012). These findings point to the existence of shallow igneous intrusions coexisting with horst and graben structures (Genik, 1993).

AGE	FORMATION	LITHOLOGY	THICKNESS (m)	SEDIMENTTHICKNESS FROM SEISMIC DATA (m)	MEAN THICKNESS (m)	DEPOSITIONAL ENVIRONMENT
Pliocene, Pleistocene	Chad Formation	Clay, Sand	Not investigated	800	400	Continental
		(Unconformity)				
Palaeocene (?)	Kerri-Kerri Formation	Coarse Sandstone, Clay stone, Sandstone	Not investigated		130	Continental
		(Unconformity)				
Maastrichtian	Gombe Sandstone	Shale, Sandstone, Siltstone,	Not investigated	0 - 1000	315	Deltaic Estuarine
Turonian-Santonian	Fika Shale	Blue-Black Shale	840 - 1453	0 - 900	430	Marine
Turonian	Gongilla Formation	Sandstone, Shale	162 - 420	0 - 800	420	Marine, Estuarine
Cenomanian	Bima Formation	Sandstone	716 - 850	2000	3050	Continental
		(Unconformity)				
Crystalline Basement						

Figure 2: The stratigraphic succession, average thicknesses of formations and thicknesses recorded in the studied wells in the Nigerian sector of the Chad Basin (Carter et *al.,* 1963; Avbovbo *et al.,* 1986).

Okosun (2000), and Petters and Ekweozor, (1982) described the stratigraphic settings of the Southern Chad Basin (Figure 2). Within the basin, the underlying Precambrian basement is overlain by Bima Formation characterised by poorly sorted, continental, sparingly fossiliferous, and feldspathic, medium-coarse grained sandstones. Bima sandstone (characterised by shale intercalations) is overlain by a transitional calcareous deposit (Gongila Formation), composed mainly of calcareous shale and sandstone deposits (Nwankwo *et al.*, 2012; Carter *et al.,* 1963). The piling of sediments that formed the Gongila Formation provides primary evidence of marine incursion into the Chad Basin. The Albian-Turonian marine transgression resulted in the deposition of Fika-Shale Formation (Olugbemiro *et al.*, 1997) that continued into Senonian. A regressive depositional phase followed the Turonian-Senonian deposits. The estuarine/deltaic Maastrichtian Gombe Sandstone is composed of siltstones, shales and ironstones intercalations. Between Late Maastrichtian to the end of the Cretaceous, extensional deformations were witnessed in the Chad Basin. This tectonic event caused the formation of an elongated graben system in the Northeast-Southwest direction. According to Carter *et al*. (1963), the relic basin that followed this distortion created the location for the Tertiary Kerri-Kerri Formation that unconformably overlie the Cretaceous sediments. The Chad Formation continental (lacustrine) deposits were deposited unconformably over the Kerri-Keri Formation during the Pleistocene and perhaps the Pliocene. Its central and southern areas witnessed widespread volcanic activities in the Tertiary-Recent period (Burke, 1976). Sand dunes are currently building up in the Chad Basin with river alluvium, and deltaic and lagoonal clays being the youngest deposits, which cover some of Lake Chad's south and southwest shores (Olugbemiro et al., 1997).

METHODS

The analytic signal method (Nabighian, 1984; Nabighian, 1972) generates peak responses over high anomaly gradient. As a result of the inherent problem connected with reduced-to-pole process, the ASIG is usually applied to magnetic data obtained at low magnetic latitude. The long wave-length anomalies emanating from deeply buried magnetic bodies were appraised using the upward continuation technique (Telford et al., 1990). SED and SPI techniques, which, unlike several other computer-assisted depth estimation methods, do not assume any specific geologic model (Casto, 2001; Thompson, 1982), were used to generate imageries from which depths to basement and various magnetic sources were determined (Reid et al., 1990; Thurston and Smith, 1997; Smith et al., 1998).

The analysis can yield an appropriate geologic model, depth estimates, and interpretable results, particularly when the geology of the study area is well understood (Thurston and Smith, 1997). Furthermore, the centroid method of spectral analysis, another powerful tool for estimating depths to top (Z_t), bottom (Z_b) and the centroid (Z_c) of the magnetic layer (Tanaka et al., 1999, 2017; Wang and Liu, 2018; Okubo, 1985), GG and HF (Abraham et al., 2019; Bouligand et al., 2009; Ross et al., 2006), was also implemented. It is frequently employed in conjunction with the azimuthally average power spectrum procedure (Wang and Liu, 2018). Ross et al. (2006) reported that the spectral peak technique is focused mainly on determining the exact wavenumber at the peak of the anomaly. However, Bouligand et al. (2009) showed from experimental results that most logarithmic power spectra generated from magnetic anomalies do not have peaked anomalies. Thus, instead of spectral peaks, the slope matching procedure of the centroid technique can be used to make optimal estimates. Details of this procedure can be found in Tanaka et al. (1999).

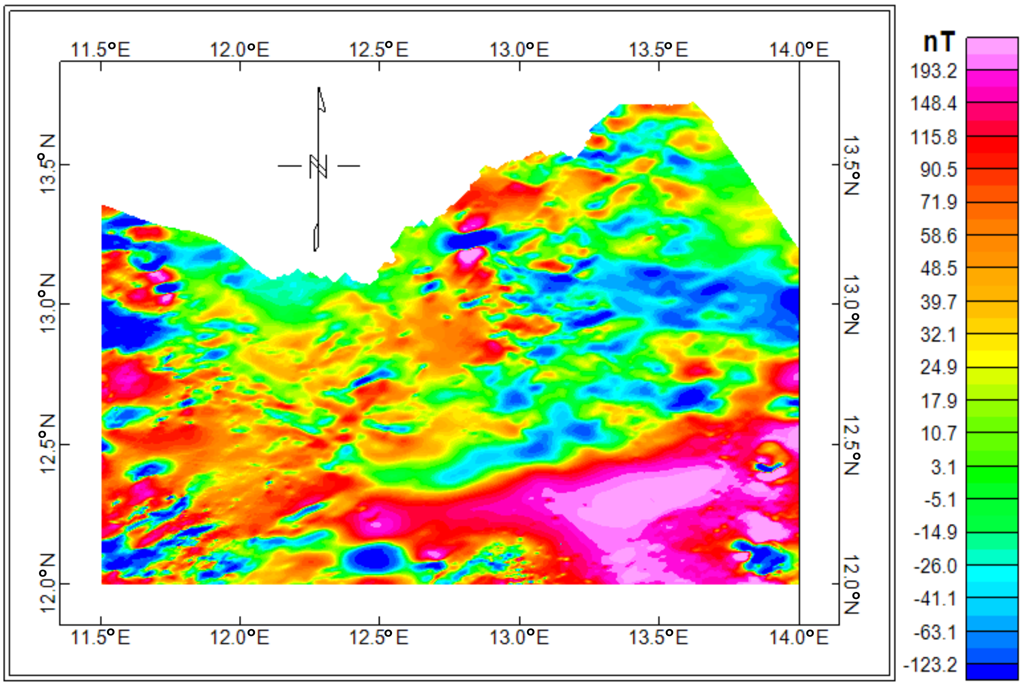

Figure 3: Reduced-to-equator total magnetic intensity map.

Data acquisition, reduction and processing

The high-resolution aeromagnetic data used in this study was acquired by Fugro Airborne Surveys (FAS), Canada, using a Flux-Adjusting Surface Data Assimilation System. Basic flight parameters comprising flight-line, tie line, and terrain clearance were generally kept low at 0.1, 0.5, and 0.08-0.1 km, respectively. Furthermore, FAS carried out the necessary corrections and subsequently, reduced the regional field to total magnetic intensity (TMI) data, which were then displayed in color raster format (Figure 3). Because the data were measured at a low latitude, the magnetic data were reduced-to-equator (RTE) because TMI subjected RTE filter generates more reliable results, especially at middle and lower latitudes (Jain, 1988; Leu, 1981).

RESULTS

Airborne magnetic data have been qualitatively interpreted for long wave-length magnetic anomalies, structures controlling mineralisation (Ekwok *et al.,* 2019), tectonic influence on groundwater yield (Ekwok *et al.,* 2020b) and polymetallic-magmatic hydrothermal deposits (Ekwok *et al.,* 2021c). In the Benue Trough, magnetic data have been used to quantitatively assess sediment thicknesses (Ekwok *et al.,* 2021a; 2019), tectonic evolution (Ajakaiye and Burke, 1973; Ofoegbu, 1984; Fairhead and Green, 1989), basement framework (Ekwok *et al.,* 2021b; Agagu and Adighije, 1983; Genik, 1993; Genik, 1992), and geothermal anomalies (Abraham *et al.*, 2019).

Peak responses are produced by the ASIG (Nabighian, 1972) over discrete magnetic sources. The direction of the magnetic body has no effect on the amplitude of magnetization produced by ASIG (Nabighian, 1972). Different sources of magnetisations delineated as low (blue colour) -0.003421-0.008461 nT/m^2, intermediate (lemon green-yellow colours) -0.009898-0.017579 nT/m^2, and high (red-pink colour) -0.019647-0.093958 nT/m^2 were mapped (Figure 4a). Regions with high magnetisation are coincident with near-surface intrusive bodies/basement highs coexisting with the horst/graben structures that characterised the Bornu Basin (Nwankwo *et al.*, 2012; Genik, 1993). To elucidate the main crustal blocks and igneous intrusions responsible for near-surface magnetisations and geologic structures, the TMI data were upward continued (Gunn, 1997) up to 5 km so as to attenuate short wave-length magnetic sources (Figure 4b). Figure 4b shows deeply buried ridge-like intrusive body described as **A-B** characterised by red-pink colour (that runs through Belle, Geidam, Furam, Magumeri, Bidda, Ngalewa and Dikwa) which trends in E-W direction. Also in the middle and northern portions of Figure 4b, imprints of tectonic origin were identified along **C-D**. the upward continued map reveals tectonic signatures in the central and towards the northern portions of the investigated area described as **C** and **D**. These observed anomalies related to the basin horst of the study area are bordered by synclines (grabens) defined by lemon green-blue colours. In addition, Figure 4b clearly showed the E-W weak zone (denoted by blue color) that is deeply buried.

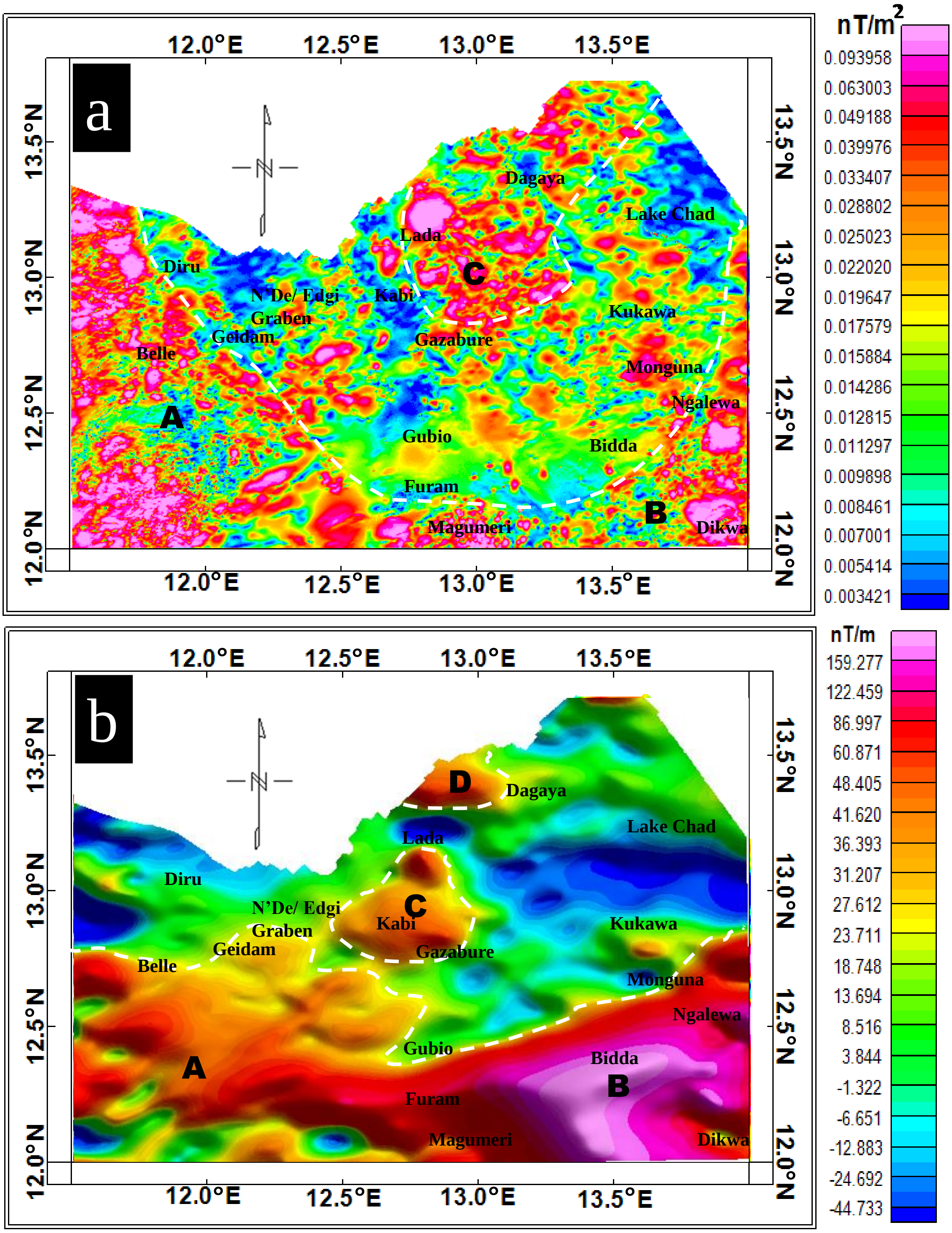

Figure 4: (a) Analytic signal and (b) total magnetic intensity data upward continued 5000 m maps.

To assess the locations and various depths to magnetic sources, depth determination methods involving SED and SPI were used. These techniques are suitable for delineating isolated/multiple magnetic source geometries and vertical contact, as well as magnetic susceptibility disparity (Telford et al., 1990). Figure 5 depicts the mean depths derived from TMI data. The approximated depths to shallow, intermediate and deep magnetic bodies are shown in Figure 5a, ranging from 130.2 - 917.6 m (red-pink), 1044.1 -1572.3 m (yellow-red), and 1725.5 - 5974.7 m (lemon green-blue), respectively. Similarly, depth estimates generated from the SPI procedure (Figure 5b) range from 286.1 - 615.2 m (red to pink) for shallow, 695.5 - 1038.7 m (yellow to red) for intermediate, and 1145.0 - 5885.3 m (lemon-green to blue) for deep-seated magnetic bodies. Furthermore, the undulating configuration of the underlying basement topography was elucidated by the wide-ranging depths (Figure 5) of magnetic sources. From the results (Figure 5), areas characterized by intermediate-high magnetization (yellow-pink) are attributed to localised high residual magnetisations linked to ferruginous sediments, igneous intrusions and associated horst/graben structures (Nwankwo *et al.*, 2012) of the area. Burke (1976) reported that the middle and southern portions of Bornu Basin experienced widespread volcanic activities in late Tertiary-Recent times. The Precambrian and sedimentary rocks within these regions are metamorphosed and characterised by various geologic structures. The area has been described by Olugbemiro *et al.* (1997) to be blanket by sand dunes, river alluvium, and deltaic and clay sediments. Furthermore, the predominance of blue (Figure 5) in the black polygon (Gubio, Furam, and Bidda) indicates that the region is characterised by comparatively thickest pile of sediments, with approximate thickness of of 5974.7 m and 5885.3 m obtained from SED and SPI methods, correspondingly.

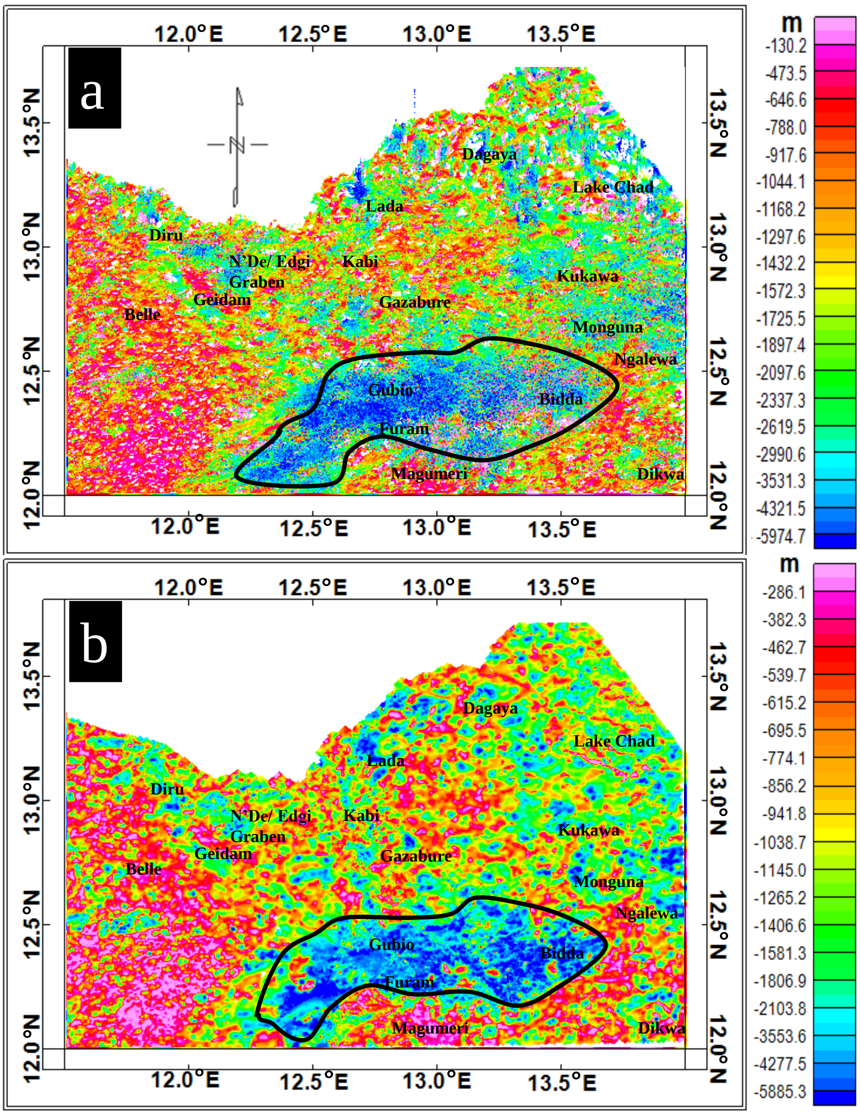

Figure 5: (a) Standard Euler deconvolution (structural index=1.0; max. % depth tolerance=15.0, window size=10) and (b) source parameter imaging maps.

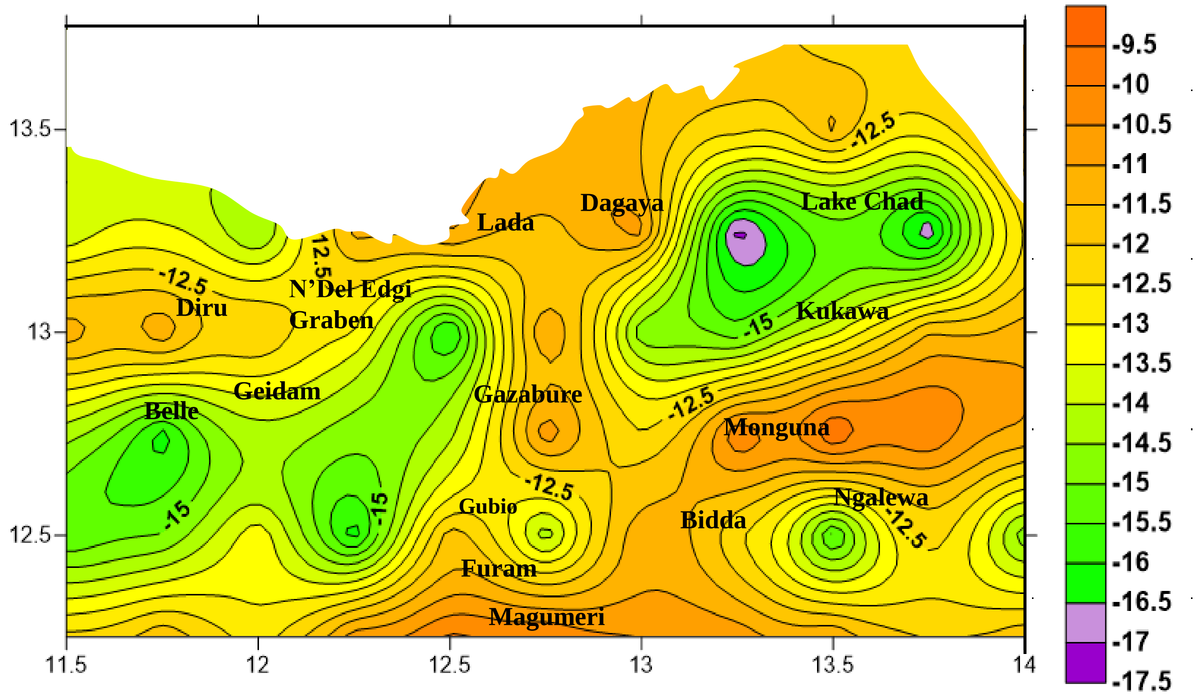

Figure 6: Curie point depth (km)

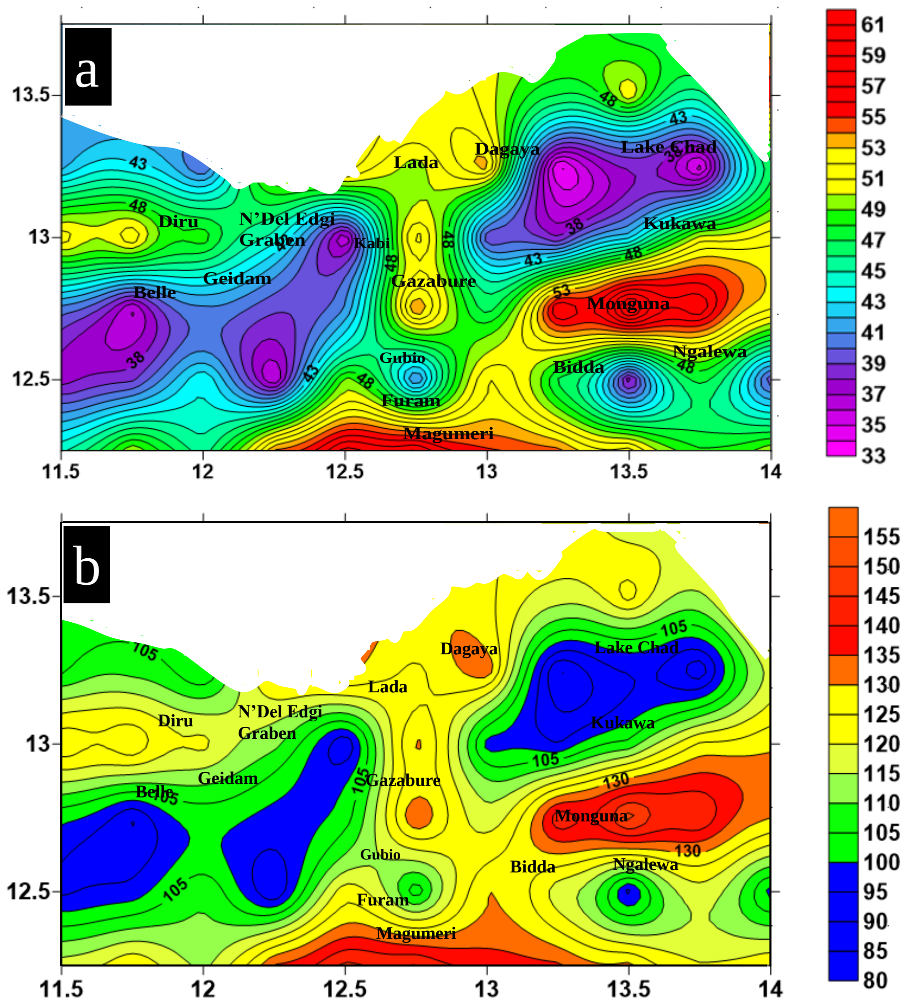

Figure 7. (a) Geothermal gradient, and (b) heat flow contour maps

Magnetic technique is a potential tool that can be applied in the evaluation of the lateral extent of several high temperature geothermal sources in young volcanic rocks (Ben *et al.,* 2022a; 2022b). To ensure various geothermal anomalies are well mapped, the magnetic data of investigated area were sectioned into 61 spectral blocks with 50% overlay of each block. For each spectral block, a power spectrum plot was created, and related parameters such as Z_c, Z_t, CPD or Z_b, GG, and HF were calculated (Table 1).

The centroid depths were estimated to vary from 6.83-10.92 km (with a mean depth of 8.60 km) while the top depth ranges between 2.92 and 6.55 km, with a mean of 4.52 km. The Z_t (2.92-6.55 km) which is like depth to basement (Lawal and Nwankwo, 2017) falls in the range of depth solutions obtained in the Benue Trough (Ekwok *et al.,* 2021b; 2021c). CPD of the investigated location ranged from 2.92-6.55 km, and mean value of 4.52 km, and the gridded result (Figure 6) shows shallow CPD dominance (red colour) in the northern and southeastern areas. The GG results range from 33.64-61.05 °C/km, and mean of 46.80 °C/km. Furthermore, heat-flow observations vary between 84.11 and 152.63 mW/m^2 (average heat flow rate of 117.01 mW/m^2). Semi-oval structures in the south and southeast (Figure 7) of the investigated area reveal zones of high GG and heat-flow. Previous studies have generally stated that CPD and other related parameters are dependent on tectonic events (Ejiga et al., 2022; Lawal and Nwankwo, 2017).

DISCUSSION OF RESULTS.

The Bornu Basin which is described as an interior-sag basin is genetically related to the CARS and WARS (Hamza and Hamidu, 2011; Kingston *et al.*, 1983). The discovery of commercial hydrocarbon in adjoining basins in neighbouring Niger and Chad Republics have triggered various geoscience investigations of the basin (Nwankwo *et al.,* 2012; Obaje *et al.,* 2004a; 2004b; Petters and Ekweozor, 1982). The synclinal structure at the northwestern flank of the study that coincide with N'del Edgi graben that extends into Nigeria from the Niger Republic was revealed by the upward continued map (Figure 4b). This area is characterized by intermediate sedimentation (Figure 5).Furthermore, some pockets in the central and extensive occurrence of deeply buried intrusions in the southern portions of the study location that were previously reported by Nwankwo *et al.* (2012), Genik (1993), Fairhead and Green (1989) were delineated. These intrusions are covered by the Tertiary-Cretaceous sedimentary series (Olugbemiro *et al.*, 1997) with estimated thickness that ranged 130.2 to 5974.7 m (Figure 5).

Furthermore, vital geothermal parameters were evaluated from the magnetic data. The Z_t (2.92-6.55 km) which is somewhat depth to magnetic basement (Lawal and Nwankwo, 2017) agrees relatively well with the SPI and SED result (Figure 5).These depth results correlate strongly with the depth assessment results in the Bornu Basin by Ola *et al*. (2017), Nwankwo *et al.* (2012) and Genik (1993). However, estimated sediment thickness of over 10 km reported by Avbovbo *et al.* (1986) is not supported by the findings of this study. The CPD (2.92-6.55 km) (Table 1) values were observed to be lower than previous results (Abraham et al., 2019). However, the GG (33.64-61.05 °C/km) and HF (84.11-152.63 mW/m^{-2}) values (Table 1) are to some extent higher than results of preceding investigations (Abraham et al., 2019; Onuoha and Ekine, 1999). The western and mid-eastern regions of the study location are dominated by relatively lower GG and HF values, while the portions with very high GG and HF values falls within the area of deeply buried intrusions delineated by upward continuation (Figure 4b). The low magnetisation zone that is sandwiched by Lake Chad and Kukara (Figure 4b) is dominated by low CPD, GG and HF (Figs. 6 and 7) Generally, HF values >80 mW/m^{-2} show anomalous geothermal anomaly in the sub-surface (Abraham et al., 2015; Sharma, 2004). The mapped semi-oval structures (Figure 7) which coincide with the location of shallow CPD (Figure 6), show high GG (>55 °C/km) and HF (>130 mW/m^{-2}) region (red colour, Figure 7) described prospective geothermal regions (Bansal et al., 2011). Within the study location, the southern portions with high sediments thickness (Figure 5) and deeply buried intrusions (Figure 4a), is characterised by high GG and HF values (Figure 7). The exploratory wells sited within this region (Gubio, Furam, Bidda and environs) of anomalous sediment thickness and Lake Chad displayed evidence of gas accumulation (Moumouni *et al.,* 2007) caused by enhanced GG from underlying intrusions (Petters and Ekweozor, 1982). The region with thick sedimentation (Figure 5) is adjoined by high GG and HF anomalies (Figure 7). The northern and northwestern portions of the study location are characterised by low to intermediate sedimentation, GG and HF. Such portions should be investigated further for hydrocarbon involving seismic reflection method and drilling of exploratory wells. The proliferation of igneous intrusions in the southern and central sections are understood to have originated the severe fracturing and faulting of the basement and overlying sedimentary series. Lineaments caused by tectonic events in rift environments like the Bornu Basin, function as probable passageway for hydrothermal fluid movement and mineralization (Mineral Resources of the Western US, 2017).

CONCLUSION

Based on the results and interpretations of the ASIG, we conclude that widespread geologic structures resulting from activities of intrusive rocks coexisting with the horst/graben structures are dominant in the middle and southern areas of Bornu Basin. The underlying volcanics (in the southern and central parts) and synclinal structure (northwestern flank) that coincide with the location of N'del Edgi graben were revealed by the TMI upward continued to 5000 m. Depth ranges of ~130.2 to ~5974.7 m, ~286.1 to ~5885.3 m and ~2920 to ~6550 m were obtained from SED, SPI and Z_t, respectively. The relatively correlated depth results revealed maximum sedimentary series that sits on extensive intrusions at the southern portion of the investigated area. The prospective geothermal regions characterised by high GG (>55 °C/km) and HF (>130 mW/m-^{2}) anomalies coincide with the locations of shallow CPD dominated by igneous intrusions.

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