ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug055

Geophysical Assessment of Curie Point Depth and Thermal Structure Over the Pb-Zn Bearing Region in the Lower Benue Trough, Nigeria Using Aeromagnetic Data

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Publication Date: 2025/08/12

Abstract: The Pb-Zn mineralization in the lower Benue Trough (LBT) is associated with the continental rifting which accompanies very high geothermal gradients. The origins of Pb-Zn deposits are often linked with intrusions and its ore formation has been related to regional processes having a temperature range of 90 – 200^{0}C. An essential parameter to understand the thermal history of a region is the Curie point depth (CPD). Several studies have been done in LBT, but none, as far as we know, has used CPD to delineate thermal characteristics of the Pb-Zn bearing regions despite geochemical reports on the thermal attributes of the mineralization zones. In this work, the CPD, geothermal gradient, and heat flow of the LBT were determined. It was noted that while the area of greater depth to the top has a higher surface elevation. The CPD value in the area where currently Pb-Zn deposits are being mined in the LBT region shows that the ore is generated in a low shrinking encased high-temperature region that extends beyond the active mining regions. This implies a possibility of occurrence of Pb-Zn in the extension. The zone trends in the NE direction and goes as far as Abakaliki which is a low thermal area. The outcomes show that such mining locations also experience considerable geothermal gradients and heat flow.

Keywords: *Curie Point Depth, Geothermal Gradient, Heat Flow, Lower Benue Trough, Pb-Zn.*

How to Cite: Abubakar Shuaibu; Owen Monday Alile; Osariere John Airen; Yusuf Ayoola Bello (2025) Geophysical Assessment of Curie Point Depth and Thermal Structure Over the Pb-Zn Bearing Region in the Lower Benue Trough, Nigeria Using Aeromagnetic Data. *International Journal of Innovative Science and Research Technology*, 10(8), 134-141. https://doi.org/10.38124/ijisrt/25aug055

I. INTRODUCTION

Alongside the continental rifting process, a high geothermal gradient initiates the Pb-Zn mineralization in the lower Benue Trough, LBT (Eze and Adaora 2018).). Ores of these Pb-Zn deposits have been found to be intimately linked with intrusions and its ore formation has been related to regional processes having a temperature range of 90 – 200 ^{0}C (Ezeh *et al.* 2022) with a low-temperature mineralizing fluid (Oha *et al.*, 2017). The deposition of the mineral is principally caused by rapid cooling (Ezeh *et al.*, 2022).

Curie point depth (CPD) refers to a temperature extent below which a magnetic material retains its magnetism (~580 ^{0} for magnetite), is a crucial characteristic for comprehending a region's thermal history. A low CPD region would suggest a thermal anomaly. Several authors with an interest in identifying regions with prospects for geothermal energy (e.g. Omokpariola and Anakwuba 2021) and hydrocarbon (e.g. Onuba *et* al., 2013) have utilized CPD to achieve their aims. The CPD within the middle-lower Benue Trough range from 11 – 21 km with the Abakaliki region having the shallowest depth of 11 km (Yakubu *et al*., 2020). The average CPD for a part of the LBT was reported to be 8.1 km and the high geothermal gradient around Abakaliki has been attributed to the presence of intrusive rock (Anyadiegwu and Aigbogun, 2021). A region within the eastern section of the LBT where a low CPD value of 9 km has been linked with a noticeably high potassium and thorium concentration (Akinnubi and Adetona, 2018). The Calabar flank of the LBT has an average

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug055

CPD of 9.5 km (Omokpariola and Anakwuba, 2021). Bello *et al.* (2017) reported a "true" depth range of 4.1 – 6.1 Km and a relative sedimentary thickness of 5.7 km within a part of the LBT whereas Ezeh *et al.* (2022) reported a sedimentary thickness range of 0.23 – 3.5 km. Onuba *et al.* (2013) identified a zone within the LBT that falls within the oil-generating window based on the value of its geothermal gradient. As far as we know, no studies have been carried out on CPD to delineate thermal characteristics of the Pb-Zn bearing regions despite geochemical reports (Oha *et al*., 2017) on the thermal attributes of the mineralization zones.

Based on the operations of miners in some recognized places holding Pb-Zn mineralization, the CPD, geothermal gradient, and heat flow of the LBT were calculated, and the nature of these thermal parameters was observed. Additionally, the study area's digital elevation map was compared to the depth to the top, which is indicative of the sedimentary thickness of the region.

II. GEOLOGY OF THE STUDY AREA

Detailed information on the geology of the LBT has been provided by Oha *et al*. (2017). The South Atlantic Ocean opened as a result of post-tectonic processes that separated the African and South American plates, creating the sedimentary basin known as the LBT (Weber and Daukoru, 2020). The LBT emerged as a result of the marine transgression that originates from the Gulf of Guinea's opening (Adebiyi *et al*., 2020). Deposition of the Asu River Group, the Eze-Aku Group, which covers the Asu River Group, and the Awgu Group (Figure 1), which is composed of Agwu-Ndeaboh shale and Agbani sandstone, regulated the emergence (Umeji, 2020). A compressional force turned the Basin into an anticlinorium with some faults and folds and volcanic activity (Mukaili *et al*., 2018).

III. MATERIALS AND METHODS

The Nigerian Geological Survey Agency (NGSA) provided the high-resolution aircraft magnetic data. In the investigation, aeromagnetic data from latitudes 5ºN to 8ºN and longitudes 7ºE to 9.5ºE were employed.

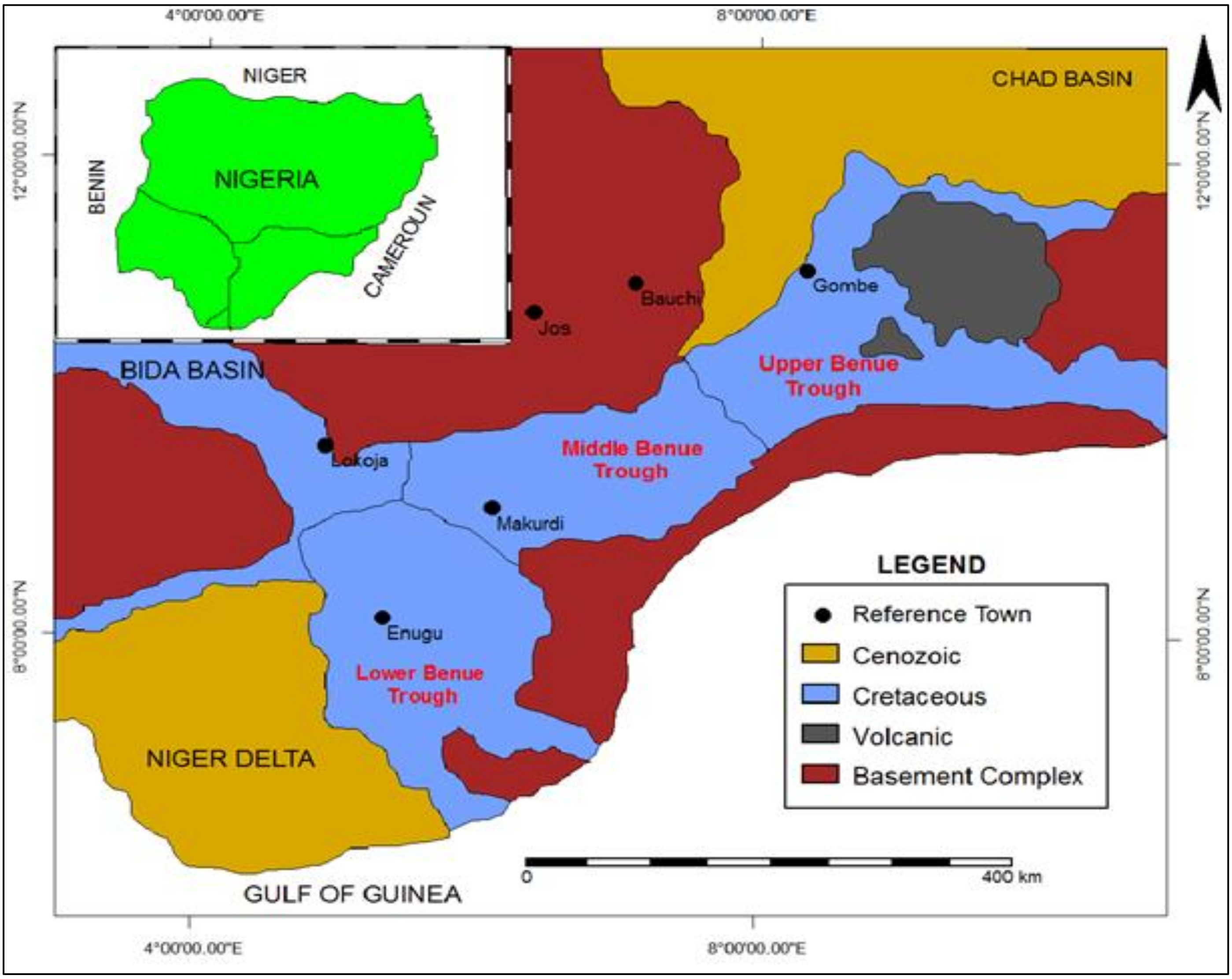

Fig 1 Geology Map of the Study Area (Fatoye and Gideon, 2013)

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug055

After obtaining data from the NGSA, each value in column Z was added 33,000 nT, which was then regarded as the overall magnetic intensity (in nT). This was done because the overall magnetic field strength (Z) of 33,000 nT was omitted from the NGSA database for convenience.

Prior to being designated as the preferred columns, the X and Y columns were georeferenced using the Universal Transverse Mercator (UTM) projection scheme. Finally, gridding the data yields a total magnetic intensity (TMI) grid map, as illustrated in Figure 2.

Before applying the Centroid method of Curie depth estimate, the aeromagnetic data grid underwent many data processing techniques, including block division, regional-residual separation (using the least squared regression method), and others.

To extract 25 blocks, each measuring 55 × 55 km, the remaining magnetic data was windowed (Figure 3). All blocks were then transformed using the Fast Fourier transform after zero padding and tapering, to reduce the edge effects.

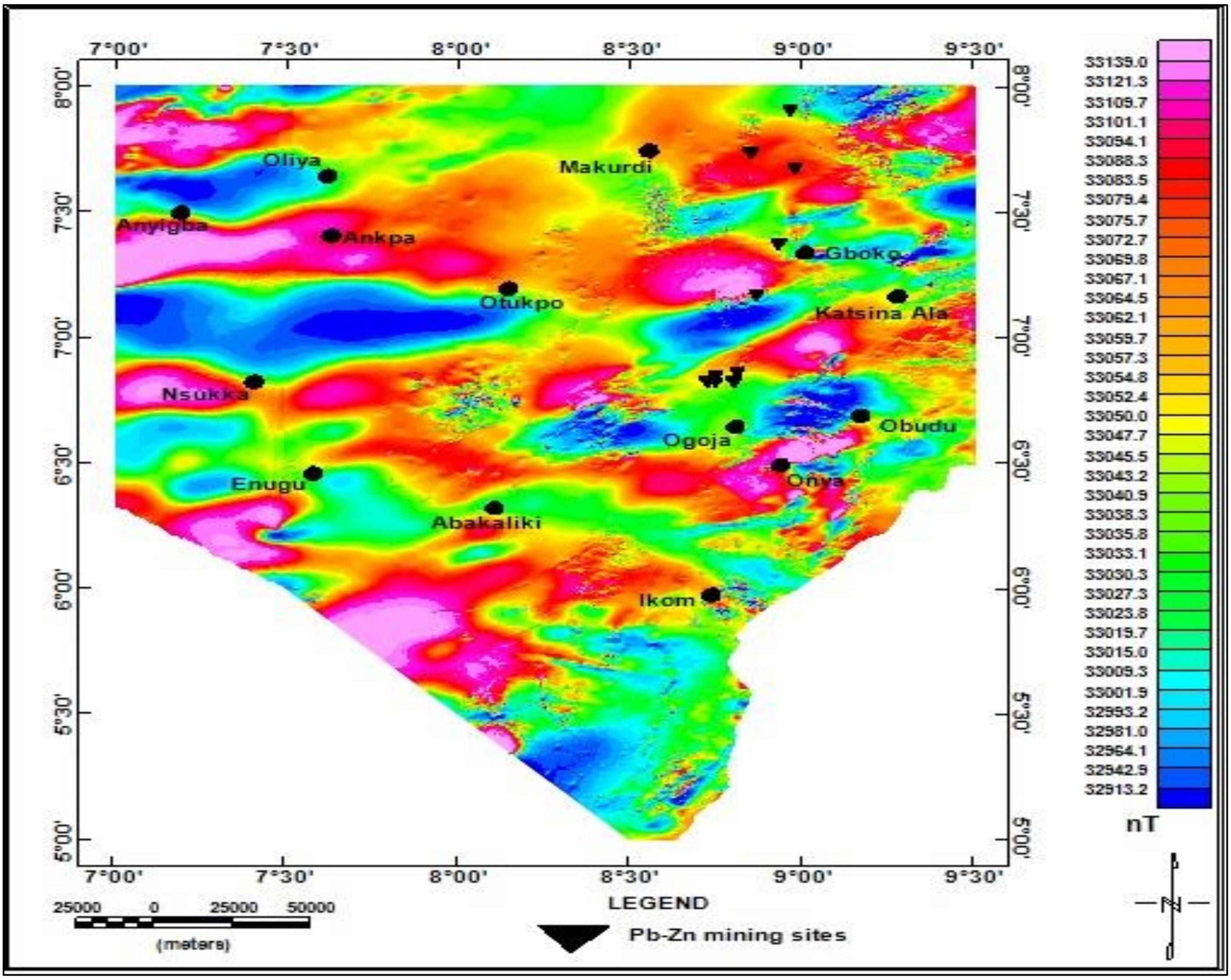

Fig 2 Total Magnetic Intensity Map of the Study Area

The Curie point depth estimate of each block is determined by analyzing the spectra of the magnetic data from the research region. One of the most prominent ways is the centroid method, which produces better estimates with less depth errors than other methods (Ravat et al, 2007).

The mathematical models for the centroid approach employed in this study are based on Spector and Grant's (1970) research of the statistical properties of magnetic ensembles, as well as Bhattacharyya and Leu's (1977) investigation of the shape of single magnetic anomalies.

After Blakely (1995) introduced the power spectral density of the total magnetic field, Tanaka et al. (1999) showed that the power spectrum of magnetic anomalies can be used to determine the top bound and centroid of magnetic sources, which can then be used to estimate the magnetic source's basal depth. The low wavenumber portion of the wave number-scaled power spectrum is used in practice to determine the centroid depth as:

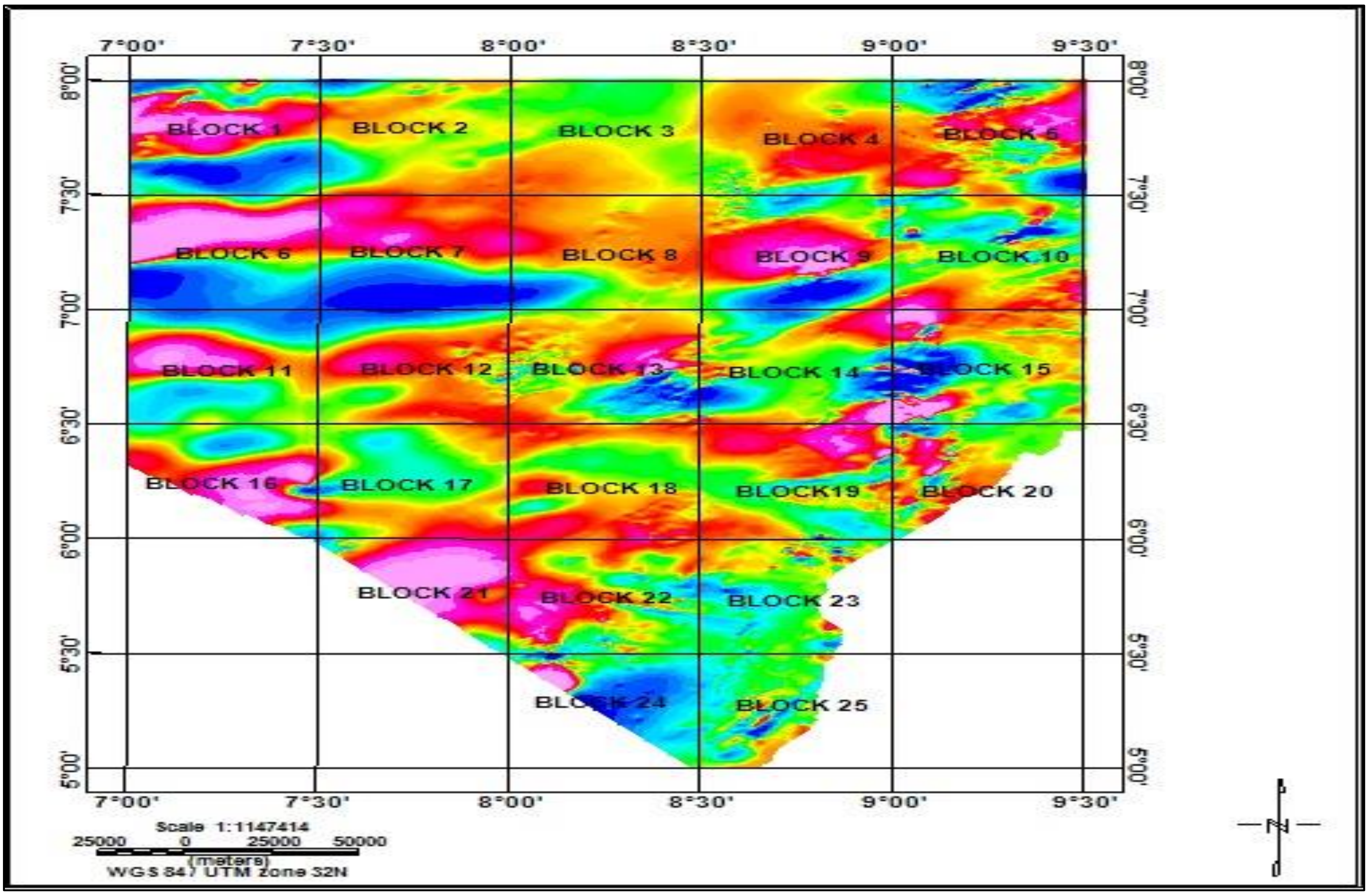

Fig 3 Map Showing the Block Divisions in the Study Area

$$\ln(P(k)^{\frac{1}{2}}/k) = A - |k|Z_0 \quad (1)$$

where Zo is the centroid depth, A is a constant, k is the wave thermal condutivity, and P(k) is the azimuthally averaged power spectrum. The slope of the medium—to the high-wavenumber region of the power spectrum—is also used to determine the depth to the top of the magnetic source:

$$\ln(P(k)^{\frac{1}{2}}) = B - |k|Z_t \quad (2)$$

where B is a constant and Zt is the depth to the top.

The linearized equation for the depth to the top is applicable for wavelengths greater than the layer thickness, according to Tanaka et al. (1999), who supported fitting the slope to a higher wavenumber portion of the spectrum. According to Tanaka et al. (1999), fitting the slope to a higher wavenumber portion of the spectrum results in deeper magnetic bottom estimations, which occasionally seem preferable (Ravat et al, 2007). Lastly, the relation is used to determine the magnetic source's depth to the bottom (Zb) (Okubo et al., 1985):

$$Z_b = 2Z_0 - Z_t \quad (3)$$

The geothermal parameters are computed after the basal depth has been established. The geothermal gradient (dT/dZ) can be calculated using the basal depth (Zb) data as follows (Tanaka et al, 1999):

$$\frac{dT}{dz} = \frac{\theta_c}{Z_b} \quad (4)$$

where θc stands for the Curie temperature. Magnetite (Fe_3O_4), the most common magnetic mineral in igneous rock, having a Curie temperature of about 580 ^{0}C. Nonetheless, the magnetic components found in the granite determine the Curie temperature.
Again, using Zb, the heat flow (q_z) can also be estimated as (Okubo *et al*, 1985):

$$q_z = -k\frac{\theta_c}{Z_b} = -k\frac{dT}{dZ} \quad (5)$$

where thermal conductivity is denoted by k. A Curie-temperature of 580 ºC (Stacey, 1977) and an average thermal conductivity of 2.5 W/mºC for igneous rocks was employed in this study.

IV. RESULT

The Curie point depth was determined by performing a spectrum analysis of the two-dimensional Fourier transform of the aeromagnetic data. The Spector and Grant (1970) method for measuring the depth extent of magnetic sources examines anomaly patterns and provides a link between the spectrum of the magnetic anomalies and the depth of the

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug055

magnetic sources by converting spatial data into the frequency domain.

The spectrum analysis on each block of aeromagnetic data were processed using the magmap extension option in Oasis MontajTM, which enables two-dimensional frequency domain processing of potential field data.The results of the investigation are shown against the radial wave number using a logarithmic scale. In order to determine the depth to the shallow (Zt) and deep (Zo) sources for the 25 blocks, the plot was divided into two or more sections with different slopes. If a set of sources on such a plot have the same depth, they will fall along a line with a constant slope (tangent to the power spectra line). A shallow plutonic formation over a deep basement is an example of a source at a different depth.

Estimating the depths to each block's top (Zt) and the centroid of the magnetic source (Zo) allows one to calculate the research area's Curie point depth. The power spectrum and wavenumber plots for block 1 were used to determine the centroid and top depths (Figures 4a - b). Block 1 has a depth of 1.9 km to the top and 7.5 km to the centroid.

The map of the depth to the top (Figure 5) of the research region was created using the depth to top value that was calculated for each block; this value ranged from 0.8 to 1.9 km.

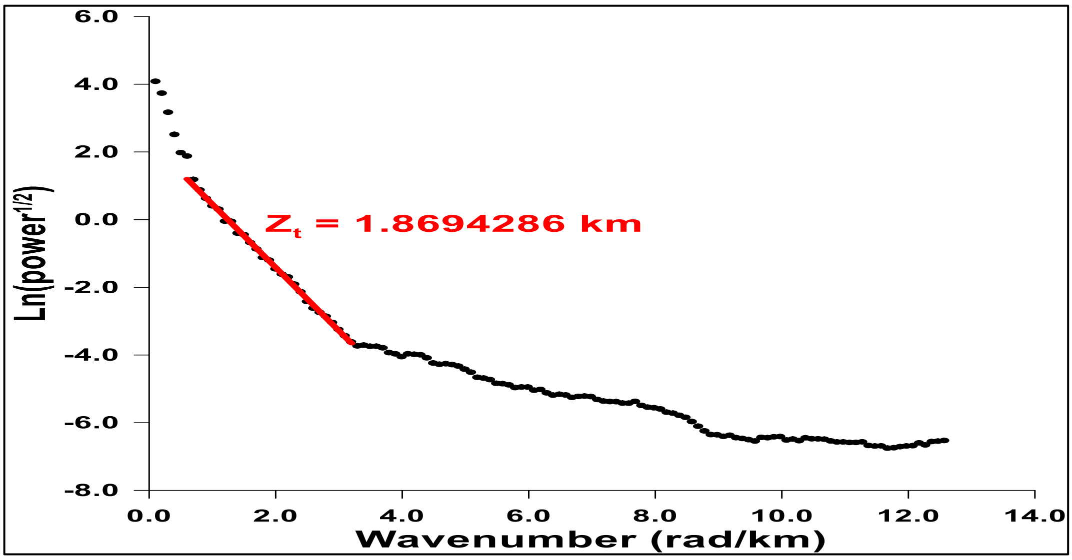

Fig 4(a): Spectral Plot for Block 1 Showing the Depth to the Top of the Source

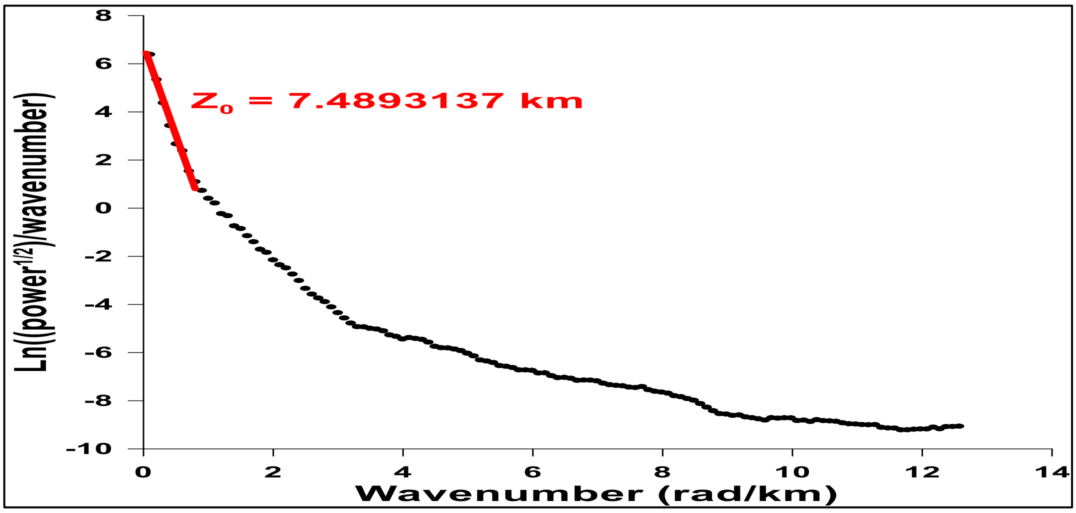

Fig 4(b) Spectral Plot for Block 1 Showing the Depth to the Centroid

The Curie point depth for each block was determined by taking the values of the depth to the top and centroid depth. Figure 5 displays the map of the research area, which has a calculated Curie depth ranging from 10.5 km to 21.4 km. According to calculations, the LBT's geothermal gradient and heat flow range from 23.338 to 81.921 ^{0}C/km and 58.345 to 204.802 W/m^{2}, respectively

V. DISCUSSION

A number of lead-zinc, barite salt, and fluorite deposits found in Cretaceous strata can be found in Nigeria's Benue Trough, an intra-cratonic rift basin that is filled with sediment (Olade 1976). In the early Cretaceous, the Benue Trough began as a "abandoned" rift basin (aulacogen), which sank

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and accumulated roughly 5,000 meters of volcanic and sedimentary rocks (Olade 1975). From previous research it was found that the maximum sediment thickness in this area is 4250 meters (Adighije, 1981). However, the centroid approach was used to determine the depth to the top of the research region, which represents the sedimentary thickness. The findings indicate that the largest silt thickness of 2.0 Km is found in the vicinity of the Oliya and Enugu zones (Figure 5). The Makurdi-Gboko axis's Pb-Zn mining zone has a low.

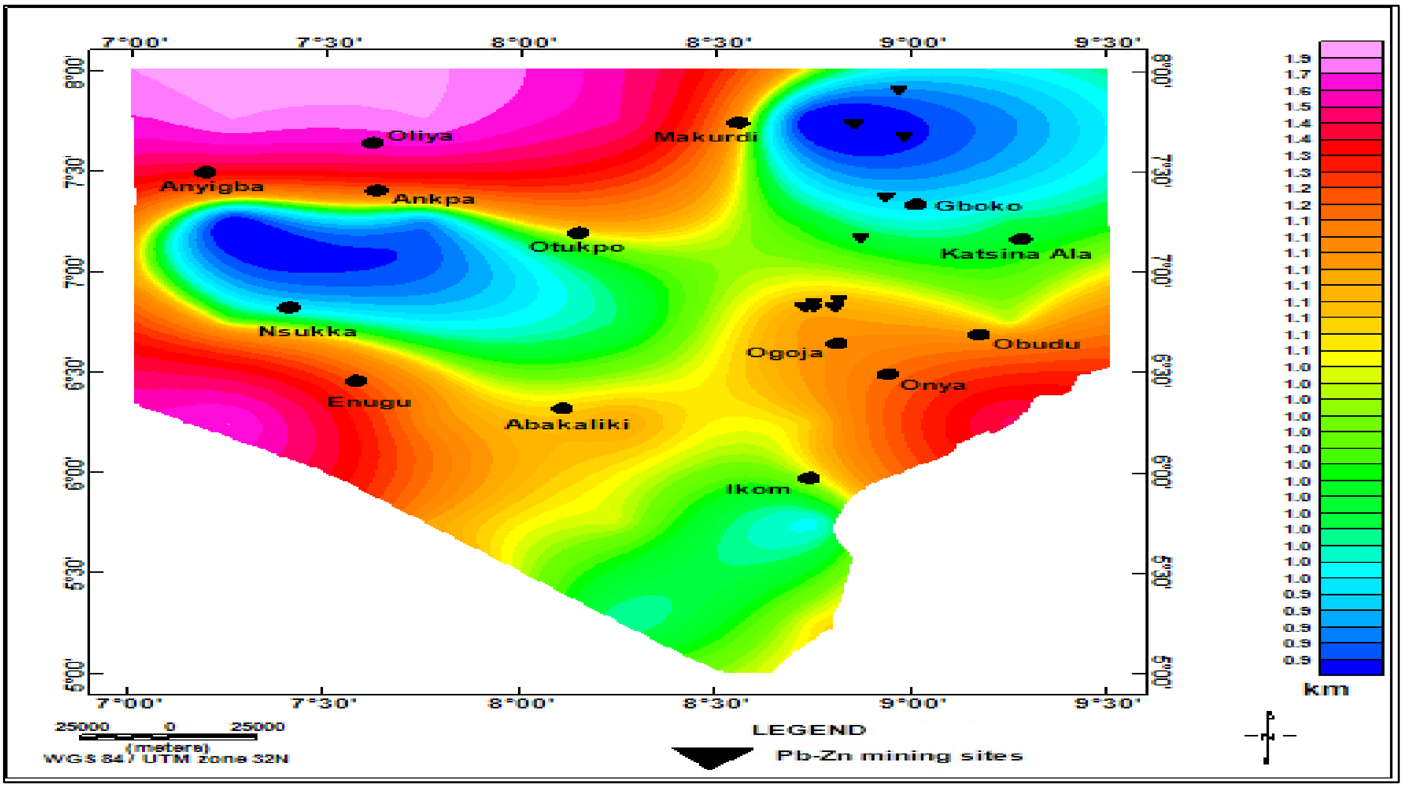

Fig 5 Map of the Depth to the Top of the Study Area.

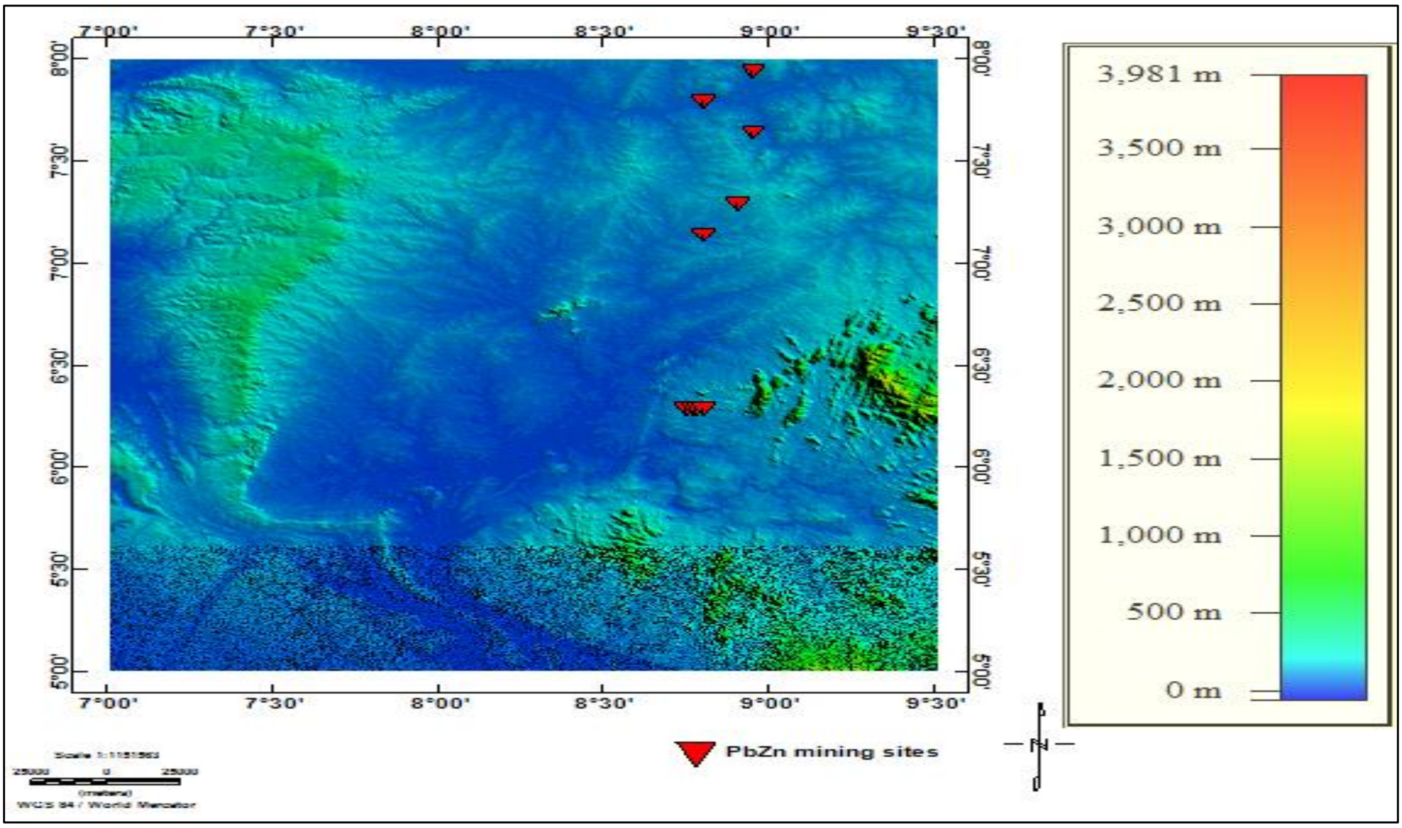

Fig 6 Digital Elevation Map of the Study Area

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Sedimentary thickness of roughly 0.9 km, but the 1.5 km sedimentary thickness of the mining zone surrounding the Ogoja axis is comparable to that of Abakaliki (Workum Hills). A deeper basement is anticipated in an area with a thick sedimentary thickness. There is steep topography at the surface of the NW region with thick sediment (Fig. 5 and 6).

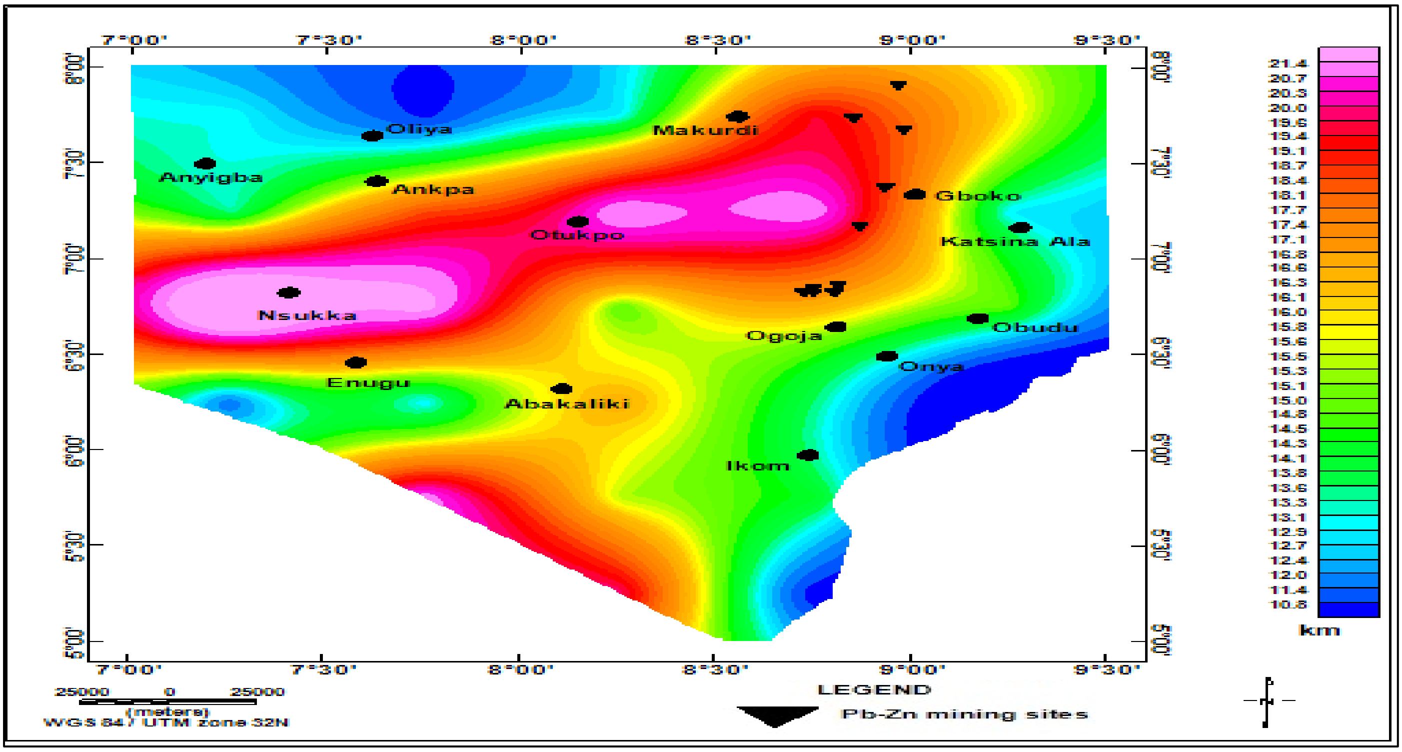

Fig 7 Map of the Curie Point Depth of the Study Area.

The magmatic activity was occurring concurrently with the opening and filling of the Benue Trough. The Abakaliki region has the most remnants of this activity.

Cretaceous magmatism was particularly active in the Abakaliki Trough, which has alkaline affinities, but it was confined to the trough's main fault zones for the most part.. Low-grade metamorphism coexisted with the magmatism in the Abakaliki Trough from the Albian to the Santonian period (Benkhelil, 1989). The Workum Hills in the Lower Benue Trough have been known to have a variety of volcanic eruptions. The Albian strata are primarily characterized by intrusive bodies, dykes, and lava flows that are accompanied by tufts and breccias (Benkhelil, 1989).

The lead-zinc ores were precipitated by low temperature, highly salty, and thick ore fluids, according to the results of fluid inclusion studies of the southern (lower) Benue Valley deposits (Oha et al., 2017). There has been debate on the ore fluids' origins (Oha et al., 2017). The three primary competing theories are as follows: (1) circulating connate waters (Olade 1976); (2) magmatic-hydrothermal (Oha et al., 2017); and (3) mixing of juvenile and connate waters.

High heat flow linked to continental rifting and mantle plume activity most likely improved the ore fluids' leaching qualities and encouraged active circulation through dilated fractures (Oha et al., 2017). Magmatic events are indicated by the depth of the Curie point. In addition to signaling a high Curie temperature event, a shallow Curie point depth may also be indicative of crustal thinning or intrusion. Around Abakaliki, Abdullah and Kumar (2020) reported the shallowest Curie point depth, measuring 11 kilometers. This is in contrast to the study's findings, which place Abakaliki and every Pb-Zn mining site in a deep CPD region. Abakaliki's CPD value is around 16 km deep, whereas the sites are all 18.5 km deep (Fig. 7). This implies that the area is a low-temperature zone, which supports the conclusions that rapid cooling is the primary cause of Pb-Zn deposition (Eze et al., 2022) and that Pb-Zn deposits are associated with a low-temperature mineralizing fluid (Oha et al., 2017). The Pb-Zn mining site also has a low geothermal gradient, with heat flow values of 31.353 0C/m and 78.378 mW, respectively, according to the results.

VI. CONCLUSION

A regional perspective of the geodynamic processes in the region as they affect the emplacement of the Pb-Zn mineralization can be obtained by computing the CPD of the LBT. The mineral is generated in a low-temperature zone, according to the CPD value inside the area of the LBT where Pb-Zn mining is known to occur. Beyond the mining locations, the low-temperature zone expands, indicating the potential occurrence of Pb-Zn inside the extension. The zone trends in the NE direction also reach Abakaliki, which is known to have low temperatures. The findings show substantial geothermal gradients and heat flow in those mining site location.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25aug055

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