



# Mapping of mineral deposits within granitic rocks by aeromagnetic data—a case study from Northern Nigeria

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## Abstract

Evaluations of subsurface mineralized structures within the crystalline basement complex of northern Nigeria have been performed. The complex is notable for hosting vast accumulation of economic minerals including Tin (Sn), Niobium (Nb), Tantalum (Ta), Beryllium (Be), Zircon (Zr), Kaolin/Kaolinitic clay (Ka), Tourmaline (Tm), and Molybdenite (Mb). Geophysical processing techniques of Euler deconvolution, analytic signal (AS) evaluation, source parameter imaging (SPI), and 3D inversion of magnetic anomalies were adopted to delineate the various subsurface mineralized structures in the region. Locations with notable mineral presence have been confirmed with additional information provided on the trends and depth extents of the mineralized structures. Structures of greater significance have been delineated at Tudun Wada-Kabong, Jos Jawara, Gyer, Kuru, Marit/Maza, and Karshi regions with average depths ranging between 60 and 1700 m. Some subsurface host structures appear as dykes and sills within the basement complex and younger granite of the study area. Results would guide industrialized exploitation of the various minerals and also provide ample resources for further exploration of the vast mineral deposits at northern Nigeria.

**Keywords** Mineral · Aeromagnetic data · Depths · Geologic structures · Nigeria

## Introduction

Abundant mineral resources abound in Nigeria. There is no urbanization or industrialization without the use of mineral resources and the economic growth of some countries depends largely upon their available natural resources. Northern Nigeria bears enormous solid mineral resources and a part of this region is considered for this study. This study encloses the Naraguta and Kurra regions in northern Nigeria and lies between Longitudes 8°30' and 9°00' E and Latitudes 9°00' and 10°00' N (Fig. 1). The region covers an area of about 6112 km<sup>2</sup> and comprises of major settlements engaging in diverse forms of mineral mining activities.

Some prevalent minerals documented within northern Nigeria includes cassiterite, xenotime, Niobium, bismuthinite, columbite, gemstone, pyrochlore, wolframite, gelana, fergusonite, thorite, arsenopyrite, molybdenite, monazite, beryllium, zircon, cryolite, and other minor minerals such as topaz, pyrite, and chalcopyrite. Although local mining activities have been on-going in this region for some time, there are no formal evaluations of their subsurface host structures, neither has there been adequate assessment of existing deposits in terms of location and quantity. Such information becomes necessary to allow for an informed economic evaluation of the deposits and also encourage large-scale industrial investments in this regard. Right from the 1920s, tin mining has been taking place at the region even as more cassiterite (tin ore) disclosures have been recently made. Also, recent global demand for tin increased significantly as this mineral extends its applications into circuit-boards production for electronic gadgets, computers, and microwave ovens due to its low melting point. It therefore becomes pertinent to direct attention toward formally assessing subsurface geologic structures hosting these mineral deposits. This study conducts geophysical assessment of subsurface geologic structures in the study area with the ultimate aim of

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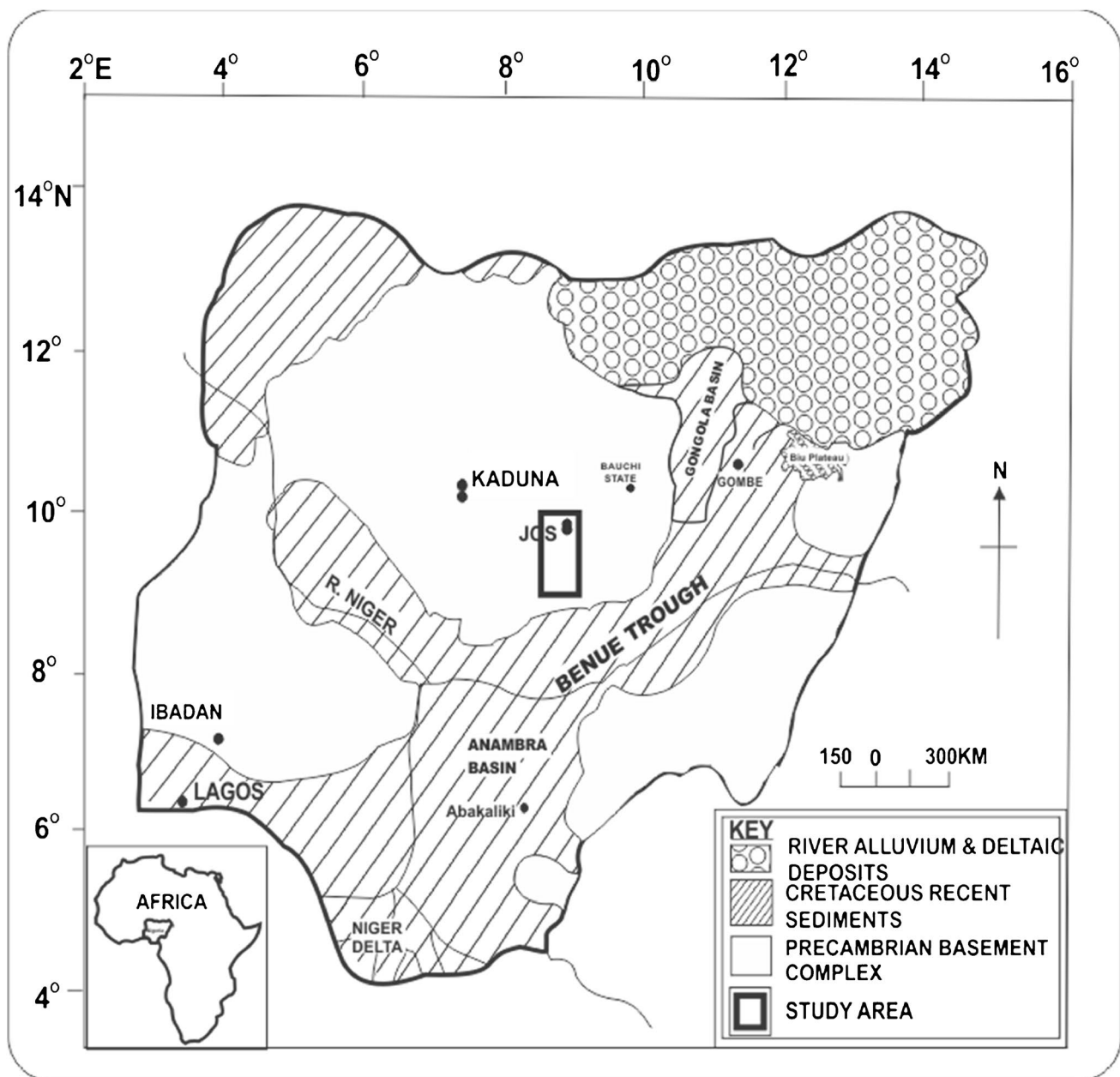


Fig. 1 Map of Nigeria showing the study area. The main geology of the country and locations are also shown

delineating those structures directly hosting these minerals and also present reliable location information for effective, sustainable, and efficient exploration and exploitation of these mineral resources. Some mining activities carried out over the years in the area were done by trial and error means, e.g., (lotto mining). Therefore, the full potential and availability of minerals in the region may not have been exploited. The non-directional mining in the region may have also adversely affected the environment resulting in environmental degradation and avoidable health hazards. Locating novel sources of minerals toward meeting the technological

and industrial needs of a country is cardinal in any mining exploration (Idowu 2013). Nigeria is endowed with abundant mineral resources, particularly energy fuels (petroleum, coal, and bitumen), and extensive deposits of industrial minerals, gemstones, and metallic minerals. Prior to the discovery of petroleum, Nigeria was a prominent mining nation and one of the world's leading producers of cassiterite (tin ore) and columbite (niobium ore). Mineral production in the country has declined substantially over the age due to neglect by polity and the increased focus of both private and public investments in the petroleum sector. The solid

minerals industry has been very much underdeveloped, contributing only 0.3% to the gross domestic product, despite the considerable mineral resource potential of the country (Olade 2020). In recent years, with the declining revenue from crude oil, the Government of Nigeria has embarked on a path of diversification of its economy through priority development of the solid minerals and mining sector. The objectives of this study therefore supports the current efforts by the Nigerian government toward proper mineral resources evaluation and exploration, and includes provision of credible geosciences information on industrial minerals availability in the region of study, proper evaluation of these mineral resources, their locations, quantitative awareness, and guidance on extractions. Additional objectives include the generation of credible data on exportable economic minerals resources inherent in the region toward attracting foreign direct investment to the country, and also provide for domestic industry consumption and the export market.

## Geology

Ananaba and Ajakaiye (1989) suggested that the primary ore bodies in Nigeria were probably oriented following lineament trends in the regions. The three main rock groups within the study area include the basalts, younger granite, and basement complex rocks (Kinnaird et al. 1985; Kinnaird 1985). The southeastern and northeastern parts of the area bear the younger granites, whereas the basement rock transpires mainly around the northwestern region. The basalts are dominant in the western and southeastern parts (Fig. 2). Granite gneiss and migmatites constitutes the basement rocks. These rocks have undergone multiple episodes of deformation including the Eburnean ( $2000 \pm 200$  Ma), Kibaran Orogeny ( $1100 \pm 150$  Ma), and Pan-African ( $6000 \pm 1500$  Ma) climaxed in the older granite emplacement (Wright et al. 1985). A clear topographic expression is portrayed by the younger granites in the region (Fig. 2), and forms a high rising plateau of between 300 and 1100 m above the surrounding basement rocks.

Hornblende-Biotite granite (characterized by needles of apatite and mafic dots presence), Hornblende-Pyroxene-Fayalite granite (porphyritic and greenish with feldspars and phenocrysts of quartz), Biotite granite (a granular rock having abundant gabbros, riebeckite, and granite), and dolerites (less prominent nevertheless) constitute the four key lithological ensembles of the younger granites in the region. Deep seated Paleo-lineaments of the Precambrian basement complex controls the younger granites resulting from magmatic fluid emplacement. An early volcanic cycle along with four separate cycles of magmatic activities ensued in the complexes (Rahaman and Lancelot 1984).

The Younger Granite rocks are richly mineralized with cassiterite. Cassiterite connects with other minerals which

include Columbite, monazite, and supplementary parts like topaz and zircon. The primary host of tin mineralization is traced to the biotite granite and is connected with the younger granites. Alluvial deposits of oxides of tantalum-niobium, manganese including iron (columbite ( $\text{Fe,Mn}$ )  $(\text{Ta,Nb})_2\text{O}_6$ ), monazite ( $\text{Ce,La,YtPO}_4$ ), radioactive mineral residues (zircon ( $\text{ZrSiO}_4$ )), and cassiterite (tin oxide,  $\text{SnO}_2$ ) have their origins in the granite among other rock units of the region. Newer and older basalts and lateritized basalts comprises the basalts at the region. The older basalts appear as plugs and dome-like outcrops and partly decomposed basaltic boulders, well preserved southward of Jos (Werram Valley). This extends to Ganawuri, Rukuba, and southwards of Ropp areas. Weathering of the older basalt produced the lateritized basalts (MacLeod et al. 1971). An extensive occurrence in the southern and western regions of Jos Plateau of the newer basalts is seen as lava flows and cones characterized by steep sided craters that aligned in NNW-SSE directions.

## Methodology

High-resolution digital airborne data utilized here was acquired by Fugro Airborne Survey–Limited for the Nigerian Geological Survey Agency (NGSA) amid 2005 and 2009. The entire data consist of approximately 2 km line of magnetic data carried out using 80 m terrain clearance, at 500 m line-spacing. Ambient magnetic field and diurnal magnetic effects were removed from the data. The resulting magnetic data is presented as total field anomaly (TFA) map (Fig. 3). Strong variations in magnetic intensities, suggesting different magnetic properties, could be discerned from the TFA map. The data covers map sheets 168 (Narakuta) and 189 (Kurra).

Notable positive magnetic anomalies ranging from 72 to 100 nT are obtained at various locations on the TFA map (Fig. 3) especially at the northern, central, and southern regions. These anomalies are largely traced to parts of the basement complex (Fig. 2) at the respective locations. The negative magnetic anomalies ( $-8.7$  to  $-130$  nT) locate largely on the granitic rocks of the younger granites. We believed that the negative anomaly signatures emanates from an intruded subsurface geologic structure within the younger granites. At the northeastern region (Jos Jarawa and Gyer 'A' towns), the negatives magnetic anomalies ( $-105$  to  $-130$  nT) are also pointers to subsurface geologic structures of interest in this study. The positive magnetic anomaly located at the central domain of the study area (around Karshi town) is also a pointer to an anomalous geologic structure within the basement complex.

The standard 3D Euler technique is founded on Euler's homogeneity equation—an equation relating the magnetic

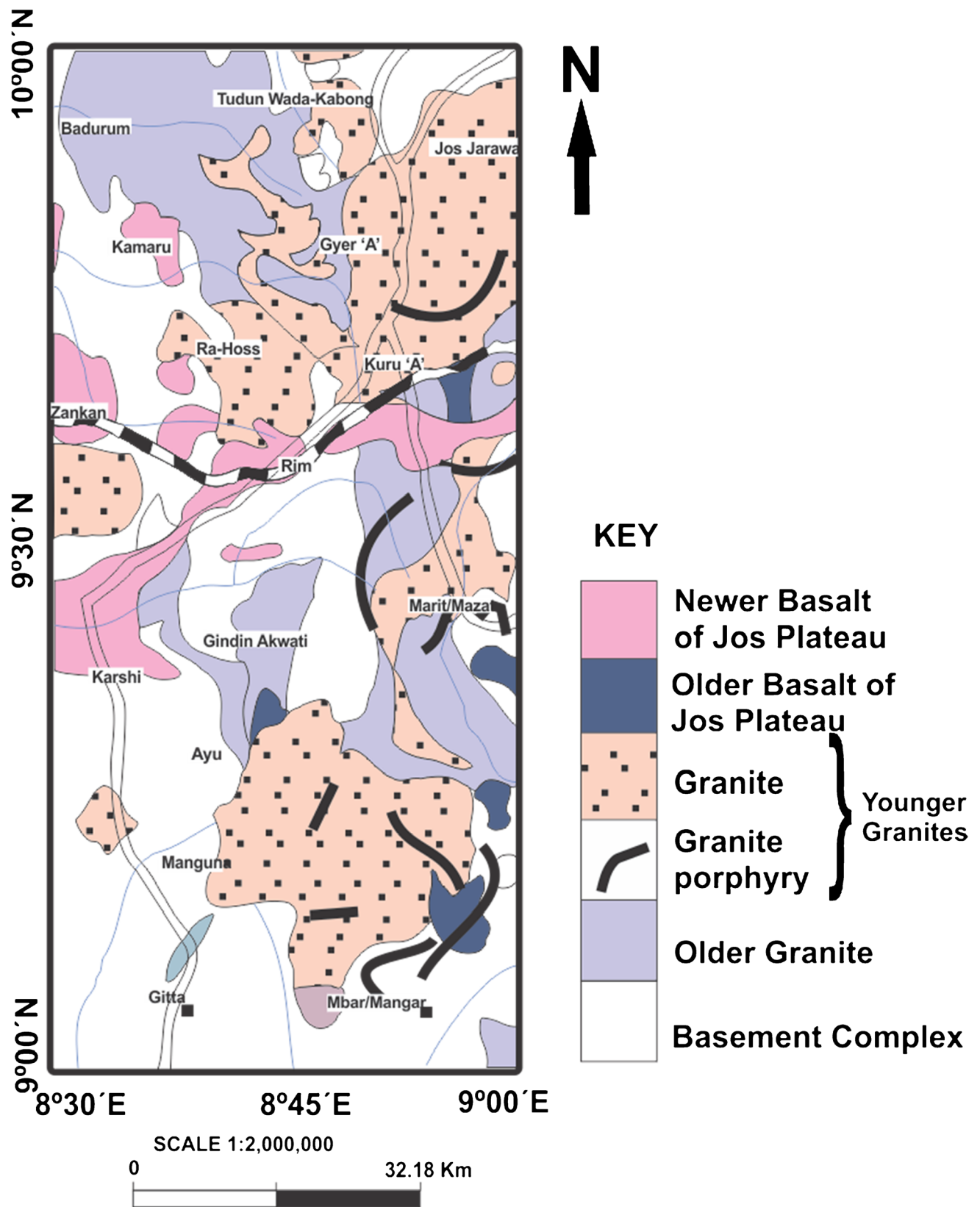
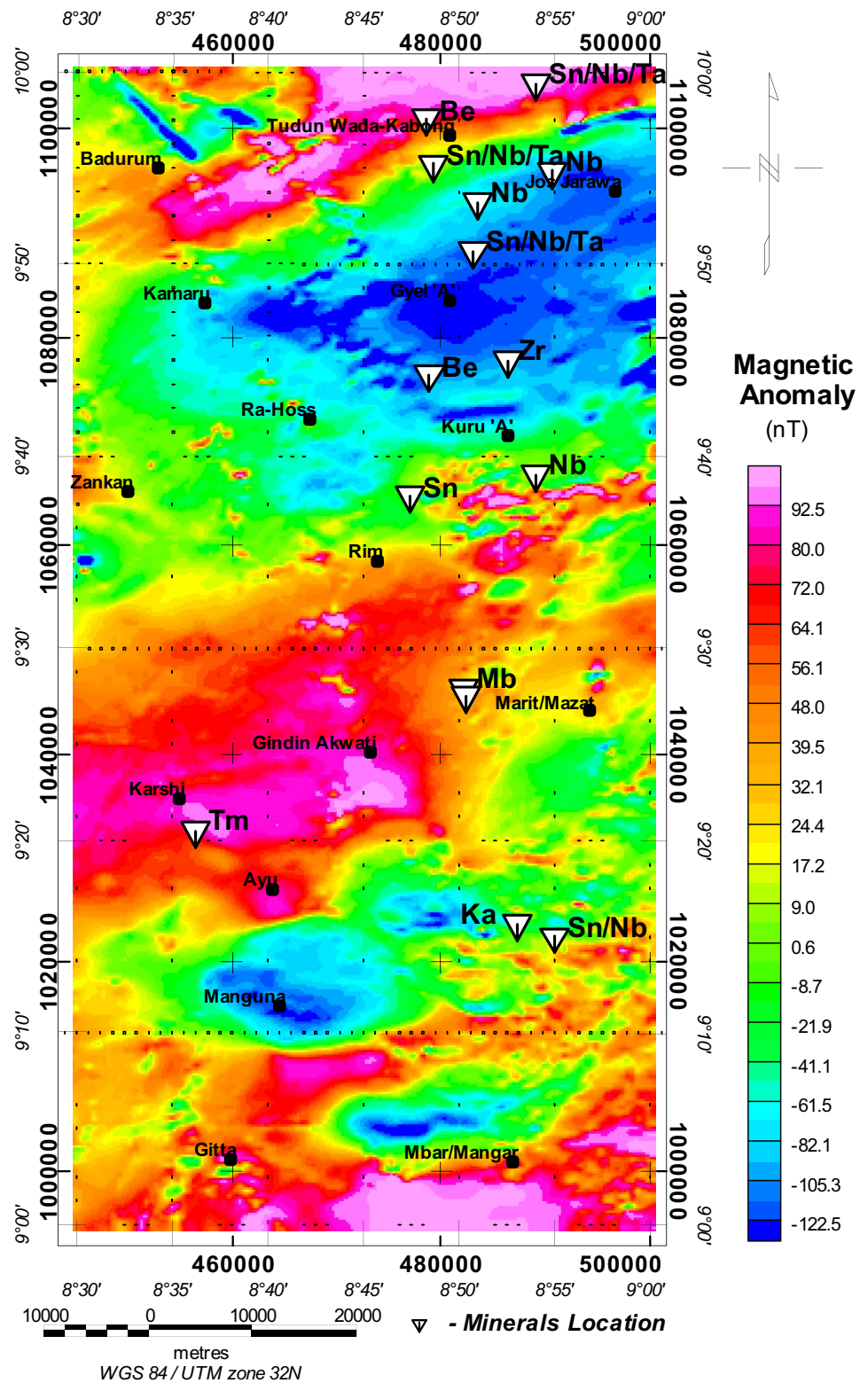


Fig. 2 Map representation of the dominant geology in the region under study. The complexities in geologic structures are seen in the various intercalations and intrusions in the crystalline basement complex, with the older and younger granites and the basaltic rock units

**Fig. 3** Map representation of geomagnetic anomalies within the study area. Inverted white triangles represent locations with confirmed mineral presence. Minerals in the region includes Tin (Sn), Niobium (Nb), Tantalum (Ta), Beryllium (Be), Zircon (Zr), Kaolin/kaolinitic clay (Ka), Tourmaline (Tm), and Molybdenite (Mb)



or gravity field along with its gradient constituents to source position, with structural index, SI (the degree of homogeneity) (Thompson 1982). We used the Oasis Montaj software from Geosoft to implement the standard 3D model of Euler's

equation. The source body type of interest determines the value of Structural index  $\eta$  (Whitehead and Musclemann 2005). As an example, Thompson (1982), Reid et al. (1990) and Abraham and Alile (2019) proposes  $\eta=0$  for a contact,

$\eta=1$  (vertical dyke or the edge of a sill),  $\eta=2$  (centre of a horizontal or vertical cylinder), and  $\eta=3$  (centre of a magnetic orb or dipole). For the present study, we select  $\eta=0$  to achieved possible contact source investigation and an  $\eta=1$  to investigate the existence of dykes or sill structures with attendant information on possible rock minerals hosting within the study area.

Horizontal displacement regarding sources has always complicated the elucidation of observed magnetic anomalies. The non-vertical direction of the induced magnetization and geomagnetic field, results in displacement or skewness of the observed magnetic anomalies. To verify if the geomagnetic anomalies were brought about by intrusions, the total field anomaly data have been subjected to analytic signal computation according to Roest et al. (1992), Li (2006), Riedel (2008), and Obande et al. (2014).

The 3D analytic signal amplitude may complement the horizontal-gradient method for edge detection (Whitehead and Musselman 2005), especially when the remanent magnetization is important, magnetic latitude is low, and sources of interest are very regional or shallow, yet its parameters are unknown (Li 2006).

Source parameter imaging (SPI) method (Nabighian et al. 2001; Thurston and Smith 1997) appraises the depths from the local wavenumber of the analytic signal. Further derivatives on the SPI method were achieved from Reford (1964), Murthy and Mishra (1980), Hsu et al. (1996), and Smith et al. (1998). Our definition of the SPI structural index is such that the numerical values of the Euler structural index are interchangeable with numerical values for the thin sheet and contact models (Ried et al. 1990). For 3D inversion procedures, we inverted the entire dataset to produce a 3D voxel susceptibility model using Pilkington (2009) and Pilkington and Bardossy (2015) as implementation in GEOSOFT program.

## Results and discussion

### Results

We present results from further analysis on the magnetic anomaly data (Fig. 3). Investigation of the source contact using the Euler deconvolution method resulted in Fig. 4. Figure 5 display Euler depth solutions investigating possible presence of a sill or vertical dyke structures within the subsurface.

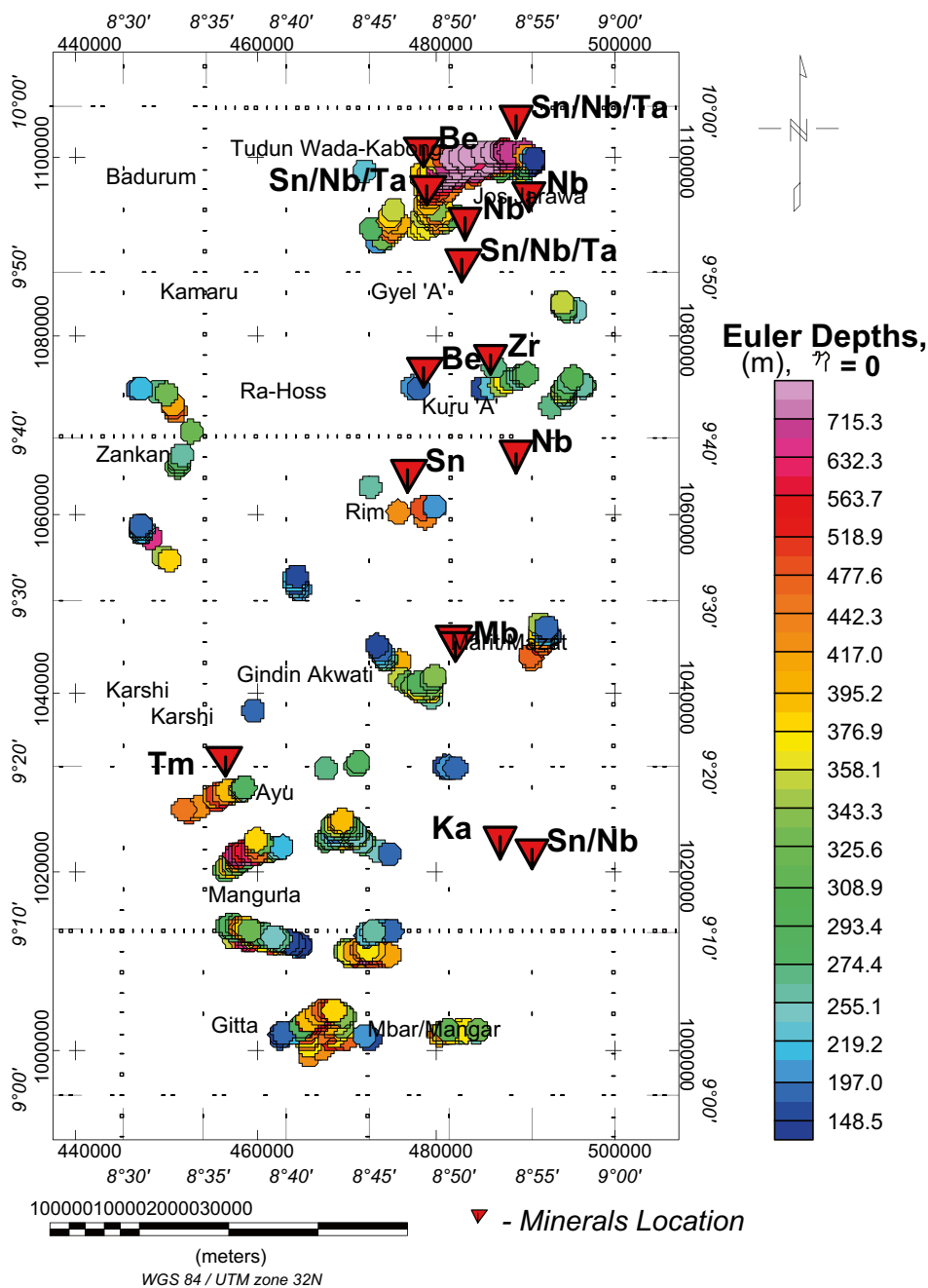
The analytic signal solution is presented in Fig. 6. SPI results are presented on Fig. 7. Windows A, B, and C were selected on strategic magnetic anomaly regions in order to model its 3D subsurface structures. Results of the 3D susceptibility structures with respect to the various windows are presented in Fig. 8a, b, and c respectively.

### Discussion

Understanding the general structure of non-exposed mineral deposits at the Naraguta and Kurra regions of northern Nigeria is one of the pressing challenges currently militating against the smooth exploration and exploitation of inherent minerals in the region. Previous information on the mineralization was derived from ground investigations and surface analysis of sparsely sampled geological units. Rugged surface topography and dense vegetation in the region are contributory to the sparse sampling, leading to insufficient information on the mineral deposits in the region. Current interests in the extensive exploration of notable minerals in the region have raised the need for prospecting the deeper concealed deposits within the region. In the present study, we successfully applied a cost-effective and high-resolution aeromagnetic data analysis to examine the subsurface host structures for possible mineral deposit prevalence in the study area. At initial observation, majority of the sites with notable mineral presence locates at regions with negative magnetic anomalies (Fig. 3). Dominant Tin (Sn), Niobium (Nb), and Tantalum (Ta) mineral structures locates on geologic structures within the northern and central regions. Positive anomalies at Karshi and Ayu regions could represent subsurface structures bearing useful economic minerals. Notable quantities of Tourmaline (Tm) have been recorded at this location and results from this study could provide information on structures bearing other economic minerals that are yet to be discovered in the region.

Figure 4 display results from Euler deconvolution investigation for contact sources. Good clustering of solutions was achieved at the northeastern and southern regions of the area under consideration. The contact sources identified from this computation indicates that most contact sources trends in the E–W directions especially at regions with notable minerals (Sn, Nb, Ta, Be) presence. These trending contact sources could be subsurface faults or fracture network with links to mineralized formation and host structures in the study area. Contact sources at the Jos Jawara and Gyer 'A' regions, with depths ranging 100–650 m are traced to the Younger Granite formation in the region and could indicate existence of intruded contact sources or fractures within the region. Similar observation is seen at the Manguna region with controlling trends in the E–W and NE–SW directions. Abundant minerals of the type Tm, Ka, and Mb have been noted at these regions. An evaluation to examine possible existence of subsurface mineralized structures as vertical dykes or sills was made (Fig. 5). Possible subsurface dykes are deduced from the good clustering of solutions, especially at notable locations of existing minerals. Particular reference is drawn here to the northeastern region of the study area, at Tudun Wada-Kabong and Jos Jawara regions. Similar deduction is made at Kuru region where notable Be and Zr minerals have

**Fig. 4** Euler depth results for contact sources within the study area. Good clustering of solutions is seen in the area especially at notable regions of identified mineral presence

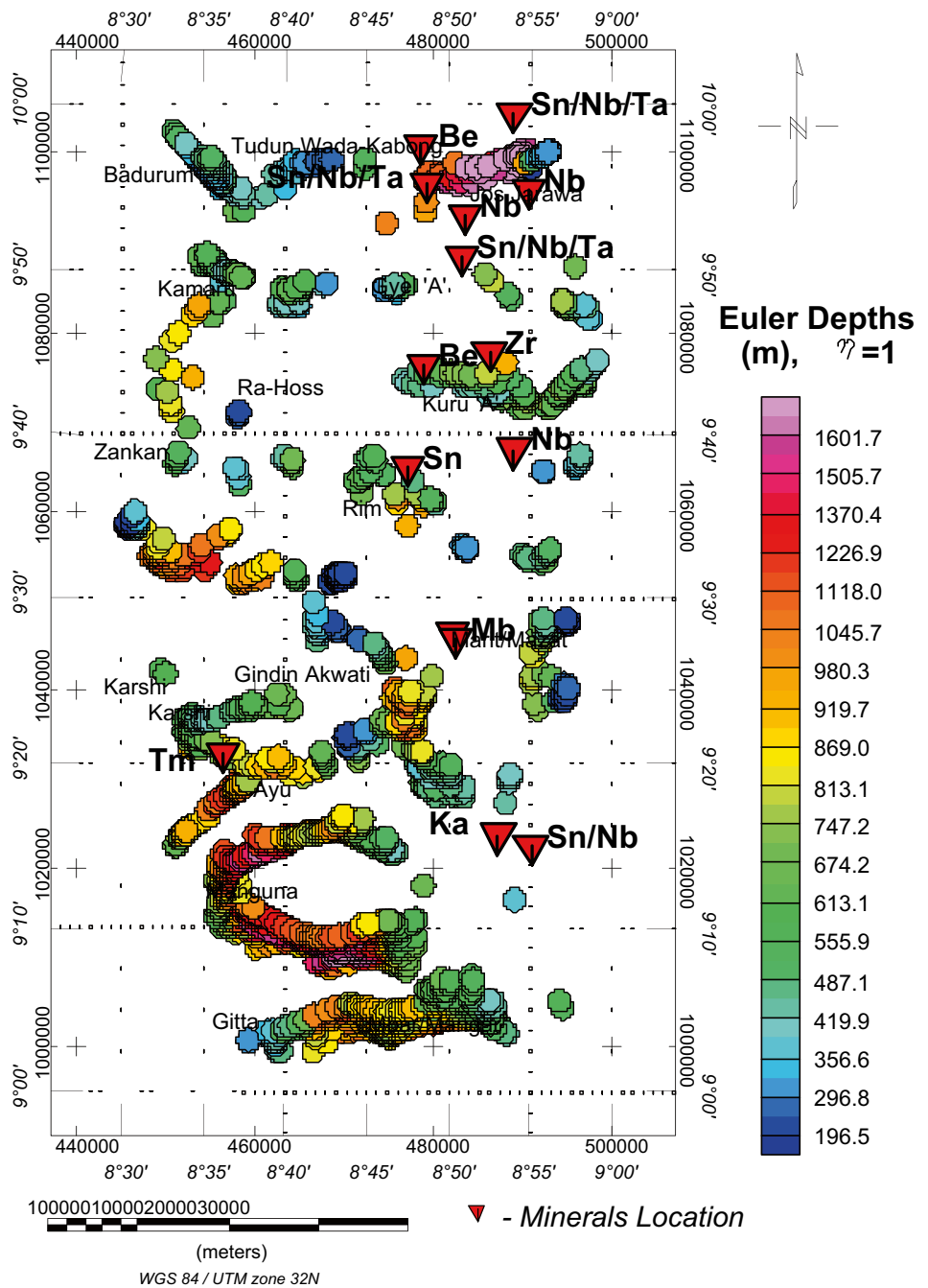


been recorded. A suspected dyke structure is traced at Rim region (Fig. 5). This could provide hints on the subsurface structural arrangements bearing the Sn mineral at that location, with its attendant depths extents of 480–680 m. Suspected edge of Sill structure (depths ranging 180–1500 m) is notable at the Manguna region. This structure is outstanding given its unique curve and trends that could possibly encircled the suspected sill structure within the basement complex and granitic rock of the region. A subsurface geologic structure at Karshi–Ayu towns, within the basement complex formation is interpreted as possible dyke structure bearing mineral (Tm) within the region. This structure is quite

extensive with depths ranging between 100 and 850 m. The NE–SW trending structure at depths 100–900 m, at Gitta region, could also present possible mineral bearing sill structures within the basement complex. Further examination of this structure is recommended.

The need to confirm if the magnetic anomalies within the region were caused by crustal thinning or intrusions inspired the application of the analytic signal technique to the magnetic anomalies (Fig. 6). Locations of the analytic signal (AS) maxima determine the outlines of magnetic sources (Roest et al. 1992; Obande et al. 2014). Examination of Fig. 6 enabled identification of mineralized

**Fig. 5** Euler depth results for edge of sills or vertical dyke structures within the study area. Good clustering of solutions is also seen in the area and at regions of identified minerals

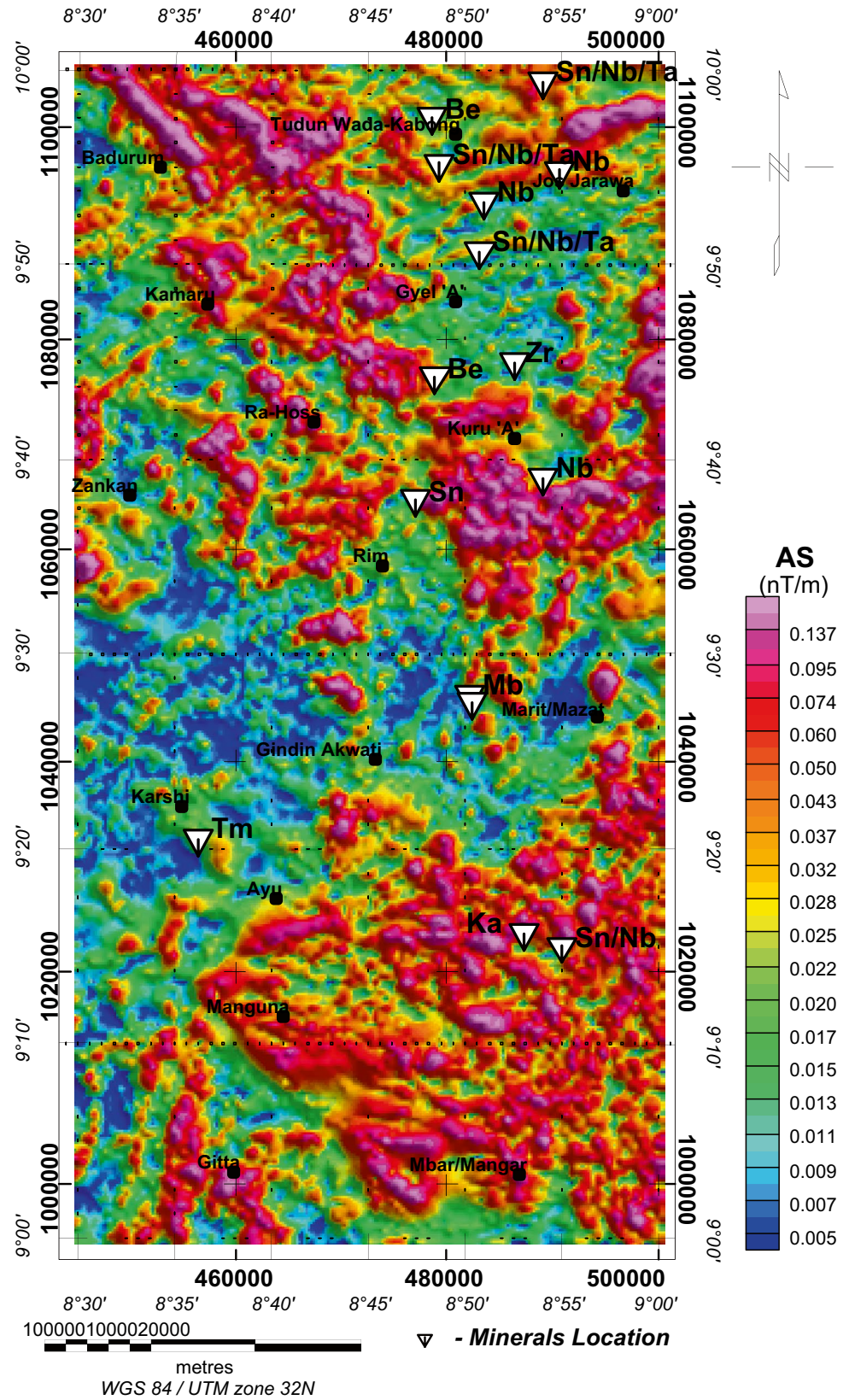


structures within the study area with possible origins attributed to subsurface intrusions. At locations with notable minerals (Tudun Wada-Kabong, Jos Jawara and Gyer regions) like Be, Sn, Nb, and Ta, high AS values are obtained reaching 0.10–0.2 nT/m. these values mostly contrast with the surrounding information and could point to some isolated subsurface structures that might have intruded the location. Similar observation is deduced mostly at sites with recorded mineral presence (Kuru ‘A’ and Mbar/Mangar). Generally, regions with higher AS hosts subsurface structures bearing most of the minerals

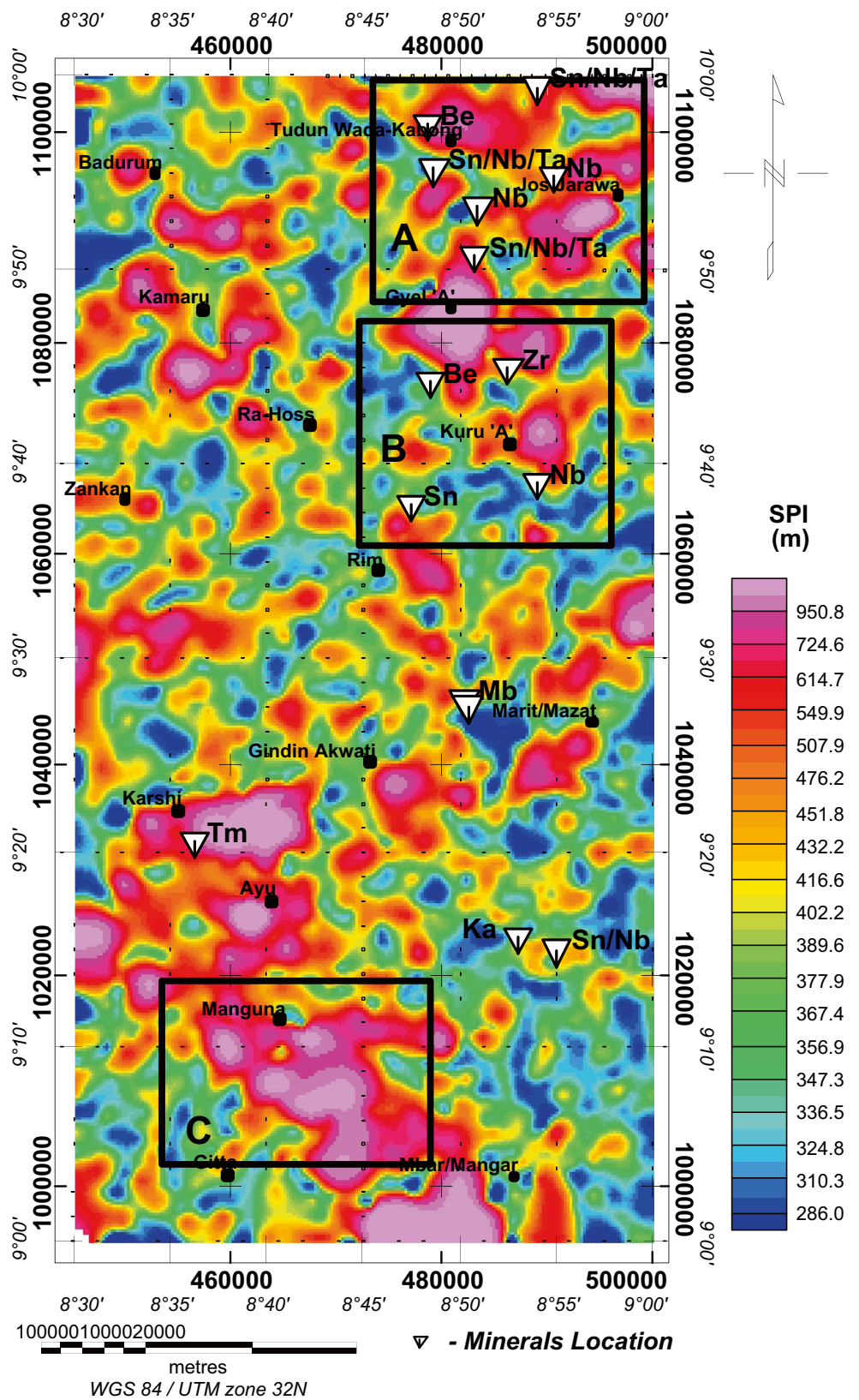
in the study area and these includes Ka, Sn, Nb, Be, and Tm. Further examination of depth to the subsurface structures is performed in the SPI evaluation (Fig. 7). The general depth range from SPI stands at 60–1150 m. This depth range agrees for the most part, with depths obtained from the Euler depths estimates especially at locations with identified mineral presence. An example is seen at the Tudun Wada-Kabong, Jos Jawara and Gyer regions with attendant depth to sources ranging between 100 and 1100 m. Recall that this region has been noted for the presence of Be, Sn, Nb, and Ta minerals (Fig. 7). Similar

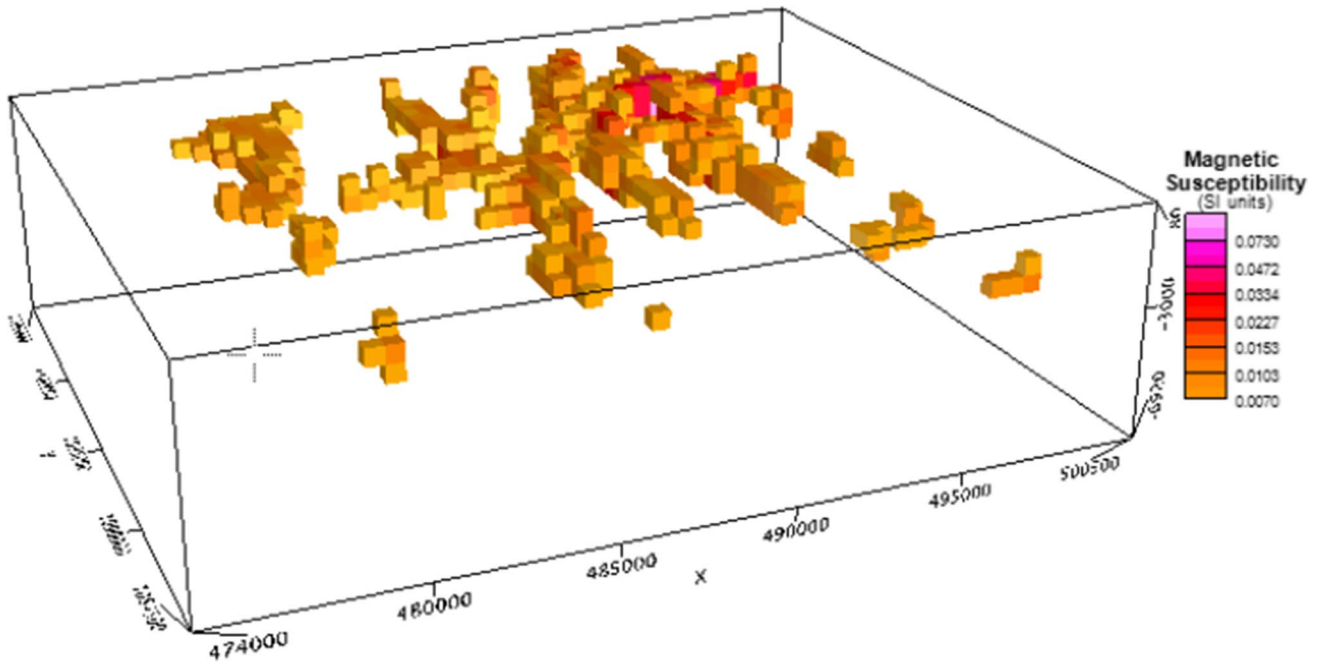


Fig. 6 Analytic Signal Map of the study area



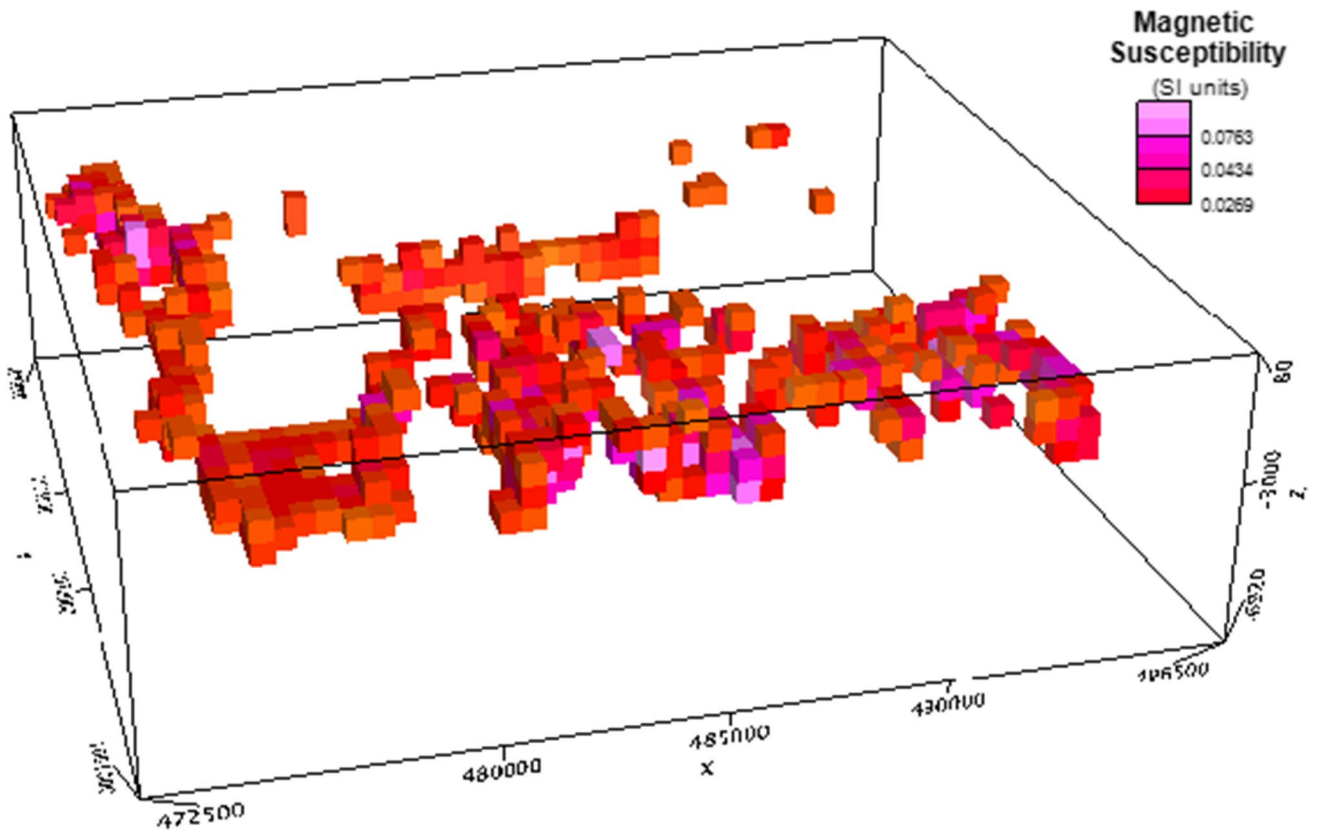
**Fig. 7** SPI results for the study area. Selected windows (A, B, and C) were considered for 3D Magnetic inversion investigation of subsurface structures





**Fig. 8 a** 3D inversion result for window A with r.m.s. error of 0.10. Model result was achieved by clipping susceptibilities lower than 0.006 SI and depths greater than 1600 m. **b** 3D inversion result for window B with r.m.s. error of 0.10. Model result was achieved by

clipping susceptibilities lower than 0.014 SI and depths greater than 1620 m. **c** 3D inversion result for window C with r.m.s. error of 0.10. Model result was achieved by clipping susceptibilities lower than 0.0078 SI and depths greater than 2400 m



**Fig. 8 (continued)**

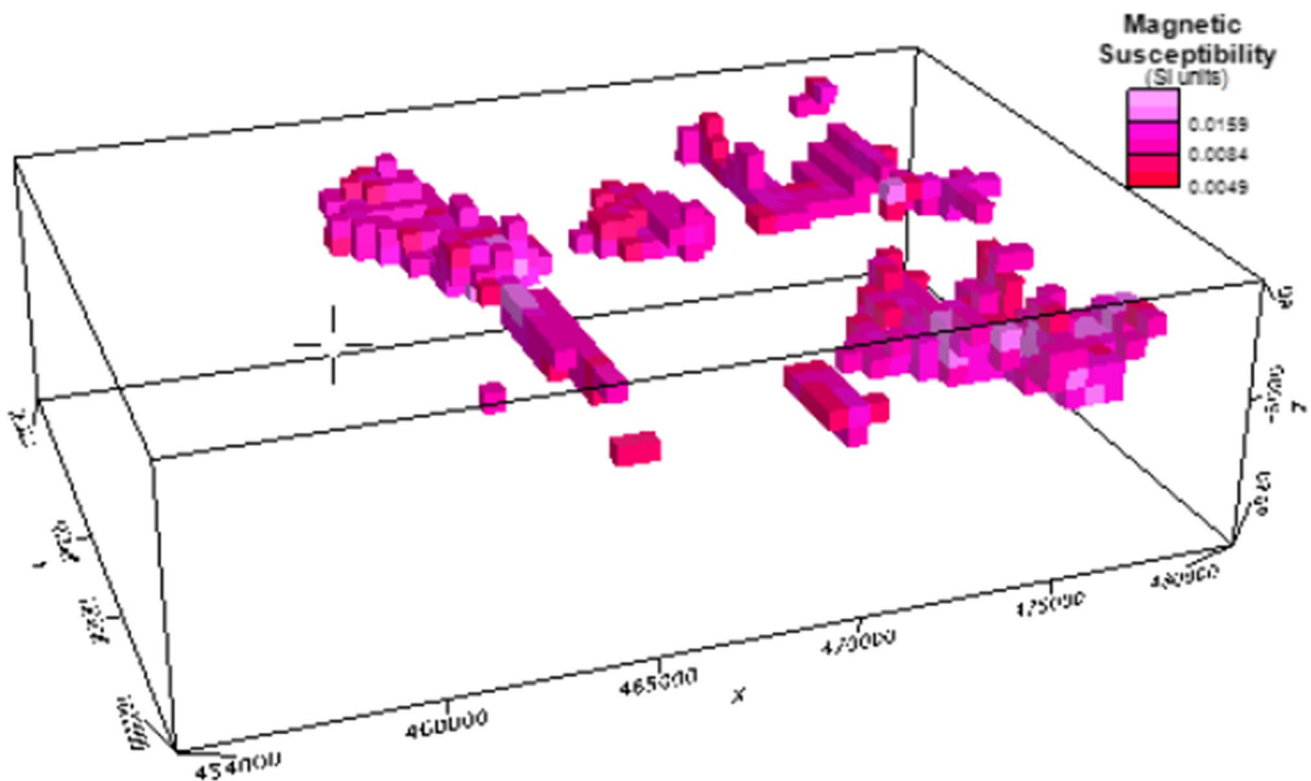


Fig. 8 (continued)

observations are also noticed at Kuru, Karshi, and Marit/Maza regions with Mb, Tm, and Be minerals present.

Figure 8 presents inversion results calculated from magnetic anomalies from selected windows in Fig. 7. Selection of the various windows was guided by notable locations of mineral presence with comparable Euler deconvolution, AS and SPI results. Figure 8a (window A) display possible isolated subsurface structures which could represent mineral structures within the window. Results from window's A identifies isolated and contrasting magnetic susceptibility structures within the respective window. These structures bear possible ties to already identified mineralized structures from earlier evaluations. The susceptibility structures as modeled from window's A could represent the subsurface geologic structure bearing the identified minerals (Sn, Nb, Ta, Be) at the location. The Be, Zr, Sn, and Nb minerals notable at the Kuru 'A' region on the Younger granites are represented by the symbolized subsurface structural setup (Fig. 8b) for window B. Further analyses on window C also expose possible subsurface geologic structures at the location, with possible hosting characteristics of the known and yet-to-be-discovered minerals in the study area.

## Conclusion

The Naraguta and Kurra regions of Northern Nigeria have been noted for hosting various economic minerals including Sn, Nb, Ta, Be, Zr, Ka, Tm, and Mb. However, no regional information on the trends, extents, and depths of the subsurface mineral host structures has been acquired before now. Earlier information on the presence of some minerals in the region has been grossly shallow and insufficient for an economic scale exploitation decision. A cost-effective, broader coverage, and faster geophysical technique of analyzing aeromagnetic data has been applied to investigate the subsurface structures with possible connection to mineralization in the region. This study has successfully delineated host geologic structures bearing these minerals along with their possible depths extent. While a confirmation of appreciable mineralized subsurface structures have been achieved at locations with notable mineral presence, suspected mineral-bearing structures have also been delineated at unexplored regions as well. Mineral-bearing geologic structures delineated in this study (depths ranging between 10 and 1300 m) are found

to exists majorly as dykes and sills within the region. Successful analyses of depths at varying locations of potential mineralized structures have been achieved and construction is made of the accompanying 3D magnetic susceptibility models representing the major isolated anomalies. The crystalline basement complex of which the various conglomerates of mineralized structures are hosted is marked by various faults and fracture units especially at sites with notable minerals. This observation could have been contributory toward influencing mineralization at these locations. This study has successfully delineated the various mineral hosting structures along with their attendant depths, toward providing informational guidance as well as direction for further research and exploitation of these minerals at the study area. Additional geophysical and geological data from the area is recommended for further studies to gain additional understanding of the mineral deposits in the region.

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## Declarations

**Conflict of interest** The authors declare no conflict of interest.

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