

New insights into Subsurface Architecture of Gongola Basin: it's Implication for Exploration Failure and Future successes in part of Gongola Basin, Upper Benue Trough, NE Nigeria

I. Yusuf

ishaq.yusuff@gmail.com

Ibrahim Badamasi Babangida University

TU Yusuf

Ibrahim Badamasi Babangida University

JA Adeoye

Ibrahim Badamasi Babangida University

B. Jubrin

Lekoil E & P

AM Ali

Bayero University Kano

OB Balogun

Mountain Top University

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Abstract

Globally, more than 50% exploration failure are attributed to subsurface structural architecture and the recent exploration success in the Kolmani river-2 well validates the presences of favorable stratigraphic framework (petroleum system elements) for hydrocarbon discovery in the Gongola basin. However, no study has attempted to relate subsurface structural architectures to over 2 decades marginal success of the Kolmani River-1 Well and the absence of hydrocarbon (failure) in the Nasara-1 or Kuzari-1 wells in this basin. Therefore, this research evaluates the role of subsurface architectural disposition on the marginal hydrocarbon discovery (gas) and failure (dry well), and attempts to identify potential prospects for more detailed studies through the integration of gravity, radiometric, remote sensing data and high resolution aeromagnetic data over parts of the basin. Surface remote sensing digital elevation model reveals the study area is a highly undulating terrain that exhibits a generally elongated structure trending mostly in the NE-SW and closely E-W direction. The basin has a basement depth of about 8.9 km with a major bedrock depression (a half basin). The Kolmani-1 and Nasara-1 wells are located at the border and outside this depression, respectively. The lineaments exhibit a zero (0°) degree tilt angles to form close to the edges of bodies, and define source structural discontinuities such as faults and geologic contacts that can serve as potential spill points for the migration of hydrocarbon out of a trap or reservoir or into adjacent formations. The distribution of radiometric elements supports the assertion of hydrocarbon generation, and the presence of structural control features such as faults, fractures and folds that can act as pathways for the migration and accumulation of hydrocarbon within the Gongola Basin. The mapped magnetic aureoles at the basement topography indicate that the petroleum system in the area is chiefly controlled by the major depression observed at the central western part of the basin. This implies that the greatest potential hydrocarbon prospects lie within that depression. Based on this premise, the positioning of the Kolmani-1 Well on a magnetic aureole at the margin of the depression accounts for its marginal success of 33 Bcf of gas, while the location of Nasara-1 Well outside the depression may explain why it is a dry hole. Future hydrocarbon prospects within the Gongola Basin are recommended to be targeted at Aureoles A5, A6, A7, A11, A14 and A15, subject to further confirmation through 2D and 3D seismic surveys

1. Introduction

The Gongola sub basin is N-S trending arm of the Yola Basin, both within the Upper Benue Trough (Fig. 1). The entire Benue Trough is a linear depression extending to about 1000 km, and filled with 6000 m thick Cretaceous sediments that have experienced folding due to compressional forces during a non-orogenic event 1985 [2, 3]. The hydrocarbon production potential of the basin was explored in three exploratory wells; namely the Kolmani River-1, Nasara-1, and Kuzari-1. It was reported that the Kolmani River-1 revealed 33 billion cubic feet of gas, while the other two wells turned up dry (no hydrocarbon encountered therein) [4]. Furthermore, the recent exploration success in Kolmani river-2 well validated the presences of favorable stratigraphic framework (petroleum system elements) for hydrocarbon discovery. To confirm hydrocarbon potentiality, several structural and stratigraphic investigations have

been conducted to elucidate the framework and geometries of the basin. There are notable hydrocarbon and basin structures related researches on the basin [3, 5–13]. The most recent studies hydrocarbon exploration within the basin [14, 15] and its hydrocarbon potential [16]. A few studies had reported potential presence of hydrocarbon in the Gongola sub-basin. Hydrocarbon potential of Kanawa Member of Pindiga Formation in Gongola sub-basin was interpreted to be gas prone, although minor oil were expected [17]. [5] analyzed the clastic materials of Cenomanian-Turonian Yolde Formation as consisting of dense uniform marine shales and sandstones with effective permeability of 21mD, effective porosity of 20% and effective water saturation of 12%. Based on aeromagnetic data acquired over Ibi area within the Middle Benue Trough,[18] discovered that the sedimentary formation is sufficiently thick for fossil maturation, thus confirming the plausibility of hydrocarbon exploration within the region.

However, literature shows that more than 50% of the exploration failures worldwide are attributed to poor delineation of subsurface structures (AAPG, 2024). Despite this, no recent study has attempted to relate subsurface structural frameworks of the basin to the marginal success of the Kolmani River-1 Well and the absence of hydrocarbon in the Nasara-1 and Kuzari-1 wells. Therefore, this research evaluates role of subsurface architectural disposition to the modest hydrocarbon discovery (gas) and failure (dry) of the frontier wells (Fig. 1), through the integration of remote sensing data, gravity data, an indirect radiometric data, and high resolution aeromagnetic (HRA) data over parts of the basin. This will further de-risk and narrow exploration search for hydrocarbon prospects in the basin. The data were acquired by Fugro Airborne Geophysical surveys over four decades ago for Nigeria Geological Survey Agency (NGSA). The higher resolution acquisition was carried out at 400 m flight path spacing and 2 kilometer path spacing. This acquired data will enable high visual resolution of the subsurface structures, structural trends, geometry and hydrocarbon accumulation potential of the basin. This will ensure accurate assessment of depth to basement, accumulation and trapping mechanisms in relation to the structural dispositions and positions of the drilled wells in the basin.

This study focuses on the aforementioned exploratory wells, which are located in parts of Gongola basin of the Upper Benue Trough in north-eastern Nigeria, bounded between longitude 10°30' to 11°30' E and latitude 9°30' N to 10°30' N. Among the four (4) exploratory wells, only Kolmani-1 (10°07'03.9"N, 10°42'43.8'E) drilled to a depth 2773 m is marginally successful with about 33 Bcf of gas. Both Nasara-1 (9°50'N, 10°54'E) at total depth 1,700 m and Kuzari-1 at depth 1,666 m are dry. Kolmani River-2, which penetrates the entire Cretaceous sedimentary succession, encountered a hydrocarbon discovery with undisclosed reserve estimates.

2. Geology and Tectonic evolution of Benue Trough

The Benue Trough of Nigeria in central West Africa is a rift basin that extends NNE–SSW with over 780 km in length and less than 160 km in breadth. It is randomly subdivided into Upper, Middle and Lower sections (Fig. 1). However, no physical line can be adopted to discriminate the individual segments, but towns and settlements that made up the depositional-bay of the different segments have been well recorded [19] [20]. The depositional-bay of the Lower Benue Trough constitutes the areas around

Nkalagu, Abakaliki and surrounding environs of the Anambra Basin that include towns such as Enugu, Awka and Okigwe. On the other hand, towns like Makurdi via Yandev, Lafia, Obi, Jangwa to Wukari make up the part of the Middle Benue Trough depositional-bay [21]

The Upper Benue Trough is subdivided into the Yola and Gongola-arms (Fig. 1). The depositional-bay township include the Bambam, Tula, Jessu, Lakun, and Numan, while Pindiga, Gombe, Nafada, Ashaka are towns within the Gongola Arm of the basin.

The entire trough contains more than 5,500 m piles of Cretaceous to Tertiary sediments predating the intense tectonic era of mid-Santonian that resulted in compressional faults, uplifts and folds, which produced more than 100 anticlines and synclines (Benkhelil, 1989) in several places across the three sub-basins. Furthermore, the main deformational structures produced include the Giza anticline, Obi syncline in the Middle Benue, the Abakaliki anticlinorium and the Afikpo syncline in the Lower part of the Benue trough, the Lamurde anticline and the Dadiya syncline in the Upper region of Benue Trough. Proceeding the mid-Santonian tectonic event and magmatism, crustal block axis was downthrown westward leading into subsidence of the Anambra Basin (Fig. 1), which formed as a part of the Lower Benue Trough characterized by post-deformational sediments of Campanian to Maastrichtian-Eocene periods (Fig. 2). It was assumed rational to incorporate the Anambra Basin into the Benue Trough, since they share interrelated structures that resulted from the compressional tectonic era (Akande et al., 2012).

Figure 2 Stratigraphic successions of Gongola sub basin in the Upper Benue Trough (after Obaje, 2009).

The sedimentary stratigraphic sequence shows that the Bima Formation was deposited conformably on the basement rock, making it the oldest sediments. The Bima Formation is overlain by the marine/transition Yolde, Pindiga (marine), the continental Gombe, and then Kerri-Kerri Formations (Fig. 2). Detailed documentation of the geology, stratigraphy and tectonic evolution of the Gongola arm of the Upper Benue Trough in northeastern Nigeria has been recorded [22, 23][20] among other investigators.

3. Materials and Methods

The study utilized topographic maps, gravity data and remote sensed datasets for surface lineaments extraction. Radiometric and high resolution aeromagnetic (HRA) data were extracted from the Nigeria Geological Survey Agency (NGSA) 1:2,000,000 Geologic map of Nigeria. The data cover the index sheet numbers: 130 (Dukku), 131 (Bajoga), 151 (Ako), 152 (Gombe), 172 (Futuk) and 173 (Kaltungo) on the 2018-index map of Nigeria, which traverse Bauchi and Gombe States. The study area is bounded between longitude 10°30' to 11°30' E and latitude 9°30' N to 10°30' N, covering more than 60% of the entire basin.

3.1. Topographic maps and remote sensed data

The topographic maps entail Landsat 8 Operational Land Imager (OLI) and Shuttle Radar Topographic Mission Digital Elevation Model (SRTM DEM) from the United States Geological Survey (USGS).

The SRTM Digital Elevation Model (DEM) was employed to generate shaded relief maps. In pursuit of delineating automatically digitized lineaments that manifest in various orientations, a series of sun azimuth values and elevation angles were systematically applied to the shaded relief images.

Specifically, a sun elevation angle of 45° was chosen, coupled with azimuth values of 0°, 135°, 225°, and 315°. The synthesis of these four shaded relief images was accomplished using the Geographic Information System (GIS) overlay technique, facilitating the creation of a composite image. Subsequently, the combined image served as the basis for automated lineament extraction across the study area. The lineament extraction algorithm, integrated within the PCI Geomatica software suite, encompasses essential steps, including edge detection, thresholding, and curve extraction.

3.2. High resolution aeromagnetic (HRA) data

The aeromagnetic survey parameters included flight line spacing of 500 m, tie line spacing of 2 km, terrain clearance of 80 m, flight direction NW-SE, and tie line direction NE-SW. The Total Magnetic Intensity (TMI) field was corrected for the International Geomagnetic Reference Field (IGRF), and a super-regional field of 32000nT was subtracted from the raw data. The magnetic data was further analyzed to identify buried structures and lineaments relevant to the hydrocarbon exploration project development. To reduce ambiguity in interpretation, the data was reduced to the magnetic equator (RTE) as the study area is very close to the magnetic equator; the RTE data appears very similar to the TMI.

3.3. Gravity data

The Global Gravity Model plus (GGMplus) data was accessed via the GGMplus download page <http://ddfe.curtin.edu.au/gravitymodels/GGMplus/>. The corrections used are: Latitude correction, Tide correction, Drift correction, Free air correction, Bouguer Correction and Terrain Correction . Eq (1) for the derivation of Bouguer anomaly is expressed below:

$$\text{Bouguer Anomaly: } BA = g_{obs} + g_{\phi} + FAC - BC \dots\dots\dots (1)$$

Where,

g_{obs} = observed gravity (mgal)

$g_{\phi} = 978031.85(1 + k_1 \sin^2 \phi + k_2 \sin^2 2\phi)$; gravity variation by latitude

$FAC = 0.3086 h$; Free air correction (mgal)

$BC = 0.04191 \rho h$; Bouguer correction (mgal); h =elevation, ρ =density (Mkg/m^3)

The equation (Eq. 2) for calculating the complete bouguer anomaly is presented as:

Complete Bouguer Anomaly, $CBA = g_{obs} + g_{\phi} + FAC - BC + TC$ (2)

Where,

TC=Terrain correction

3.4. Radiometric data

Saunders, Burson [24], introduced a model for detecting radiometric anomalies related to hydrocarbon occurrences. The model has been exceedingly successful and outstanding. The principal assumption is that alterations in the concentration of one radioactive isotope will likewise affect the concentrations of the other two isotopes (within the analyzed elements) in the presence of hydrocarbons. As outlined in their research, in the absence of hydrocarbons, uranium (eU), potassium (K), and thorium (eTh) should preserve natural and regular proportions. The challenges posed by lithological and environmental variables were addressed through the Thorium Normalization process, which corrected K and eU readings (Saunders et al., 1993). They recognized a correlation among eU, K, and eTh data through detailed studies of aerial radiometric measurements in oilfields designed at identifying hydrocarbon anomalies. Thorium, being highly "retained" in rocks and local soils, remained unaffected by hydrocarbon seepage. (Saunders et al., 1993) defined the "ideal" K and eU as follows (Eq. 3):

$$\begin{aligned} K_i &= (K_{av} * Th_{av}^{-1}) * Th_s \\ U_i &= (U_{av} * Th_{av}^{-1}) * Th_s \end{aligned} \dots\dots\dots (3)$$

where, the subscript "s" denotes the measured or sampled value, "i" represents the ideal value, and "av" is the mean value of the studied area, typically at least 5 times greater than the predicted anomaly. The difference between measured and ideal values (expressed as KD % and UD%, representing relative deviations as a fraction of the measured values) is then calculated (Eq. 4) (Saunders et al., 1993)

$$\begin{aligned} KD &= (K_s - K_i) * K_s^{-1} \\ UD &= (U_s - U_i) * U_s^{-1} \end{aligned} \dots\dots\dots (4)$$

In the presence of hydrocarbons, the KD value is expected to decrease, and the UD value should increase. To leverage these parameters, the authors introduced a new parameter termed DRAD (DRAD =

UD – KD). Positive values of DRAD and negative values of KD and UD (sometimes positive values) typically characterize a hydrocarbon anomaly (Saunders et al., 1993). This methodological approach culminates in the robust identification and characterization of geological lineaments, thus contributing to a comprehensive analysis of the study region.

4. Results and Discussion

Here, we present and discuss the results of integrating surface (remote sensing and radiometric data) and subsurface (gravity and aeromagnetic) datasets used in this paper.

4.1. The Digital Elevation Model (DEM) of the Area

The digital elevation model and 3D map present the study area as a highly undulating terrain (Fig. 4). The area consists of elevated regions in the central, north-central and southeastern parts; and lowlands “B” and “C” flanking the north-south trending elevated structure, A, occurring from the north-central to the middle of the central area (Fig. 4). Kolmani-1 well is located within lowland B.

There is also a suspected rifted structural depression (labeled D) trending NE-SE at the southwestern end. Nasara-1 well is located at the flank of this depression. Elevation within the area ranges from 177 m in the southeastern end to 590 m in the central part to give a relief of 413 m. This indicate that the basin have experienced significant tectonic activity and deformation, thus typify by multiple sub-basins (depressions) in the form of valley and ridges of variable depths.

4.2. Total Magnetic Intensity (TMI) Map

The TMI map shows series of magnetic highs and lows (Fig. 5). These intensities are generally elongated and trend mostly in the NE-SW and approximate E-W direction. A few of these anomalies trend in the NW-SE direction. The northern and south-eastern regions have relative magnetic low signatures. The central region is dominated by relative magnetic-high signatures. A conspicuous NE-SW trending magnetic low was observed to run from the central part down to the SW region. The position of this anomaly coincides with the southern and eastern margins of the lowland “B” (Fig. 1). The “Kolmani river-1 well” drilled by Nigerian National Petroleum Corporation (NNPC) is located close to the southern end of this NE-SW trending magnetic low signature. Thus, this can be attributed to disruption of basement magnetic rocks by faults or fractures or hydrothermal alteration. Nasara-1 Well is located southeast of this anomaly and falls on a similarly trending, but less conspicuously-defined magnetic high signature that is sandwiched between magnetic lows. It should be noted that due to the fact that the study area is located in a magnetic low latitude region, the magnetic highs indicate low magnetic susceptibility, while the magnetic lows indicate high magnetic susceptibility. However, this generally indicates that the basin is significantly faulted and rifted resulting from the tectonic activities of the Santonian era.

4.3. Depth to Magnetic Basement from the Topography

The depth to the magnetic basement was estimated from the magnetic data using the spectral analysis approach. This method of depth involves the determination of the slope of the corresponding ensemble on the plot of the radially averaged power spectrum and dividing it by 4π (for maps). The plot of the radially averaged power spectrum itself is generated from the graph of the natural logarithms (ln) of the Power Spectrum against the Wave number. In spectral decomposition of magnetic signals, the depth to magnetic basement is usually taken to be the depth to the fresh basement rock. This is because, the sediments that overlie the fresh basement are believed to have negligible magnetic susceptibility compared to the magnetic susceptibility of fresh basement. Under an ideal situation, the estimated depth to magnetic basement will coincide with the depth at which the basement rock will be encountered if one were to drill to the basement due to the marked difference in magnetic susceptibility between the fresh basement rock and the overlying sediments. The study area was divided into 15 overlapping spectral blocks of 60 x 60 km (Fig 7). The dimensions of the spectral blocks were such that it can allow for the accurate estimation of spectrum as deep as 9.55 km.

To give an accurate image of the basement topography, the absolute depth to basement evaluated from the magnetic data (Fig.5) was corrected with respect to the Digital Elevation Model (DEM) (Fig. 8b). It should be noted that the absolute depth to the basement (Figure 6a) is the thickness of sediments within the basin. The basement rock topography is relatively flat in the southern and eastern areas. Located to the west is a major bedrock depression (a half basin) where the Kolmani-1 and Nasara-1 wells are oppositely at the border and outside the depressions. Depth to the basement in this basin approached 8.9 km. To the north and northeast are other basement depressions that are less conspicuous (Figs. 8a and 8b). Absolute depth to the basement in this part ranged between 3180 m and 8890 m (Fig. 8a). The northern end is a basement high underneath the sediments. For the accuracy of depth estimates in spectral analysis of potential field data, focus is placed mostly on the relationship between grid size and the maximum depth recoverable based on the grid size [25]. This depth is still between the numerical values of $L_x/2\pi$ and $L_x/2$. Therefore, the Percentage Absolute Error does not exceed 15% (i.e. $(PAE) \leq 15\%$).

4. 4 Total Horizontal Derivative (THD) and Tilt Derivative (TDR) Map

Tilt Derivative (TDR) was adopted because of its ability to precisely map boundaries of both dipping and vertical geological structures to a very reasonable degree of accuracy, while the Euler deconvolution was implemented to generate good edge solutions with limited prior information and to give depth estimates of geologic structures.

The THD and TDR maps are shown in Fig. 9. The peak derivative values (denoted with pink colouration) indicate areas of linear structural discontinuity. Linear structural discontinuities in the geological sense usually indicate fractures (which could either be fault, lithological contact or rock joint) or edges of folds (Gannon, 2023; Gay Jr, 1995). Two distinct types of structural discontinuities were delineated in the study area. They include the relatively broad but still elongated, regional scaled structures (lineaments) trending in the NE-SW and approximate E-W directions, covering most of the northern, central and south

western parts where exploratory Nasara-1 and Kolmani-1 wells are drilled. The region covered by these structures is designated “A” on the THD map (Fig. 9a).

Based on the location and trends of these structures (lineaments), they appear to have controlled the rifting that resulted in the subsidence, and eventual formation of the basins earlier mapped within the study area as supported in Fig 4. Also observable are the sub-regional scaled, densely-packed lineament observable in the north-western tip (labeled B) and south-eastern part (labeled C) of the area. These classes of lineaments appear to be highly superficial. Based on the supposed genetically relation with the mapped basement depressions and its relatively deeper depth, the first class of lineaments that have been mapped to occur within “Region A” are most likely to be associated with the petroleum system of the study area.

For the TDR map presented in Fig 9b, zero (0°) degree tilt angles are believed to form close to edges of bodies, and define source edges, contacts and regions of structural discontinuities such as faults and geologic contacts, which can all be classified as potential hydrocarbon migration spill points, where hydrocarbon can migrate out of a trap or reservoir and into adjacent formations (Harding & Tuminas, 1989; Luo, Zhang, Lei, & Yang, 2023).

The derivative calculation highlights areas where the gradient of the data is zero, indicating a change in direction of the maximum gradient associate with faults, fractures where hydrocarbon can move out of a trap or reservoir. The Nasara-1 and Kolnami-1 well are located close to the zero (0°) degree values (Fig.10), which may potentially explain the exploration challenges recorded in the Gongola basin.

4.5. Euler Deconvolution of the Full Spectrum Data

The original resolution of the TMI data is 100 x 100 m. As established from simulations and empirical testing, minimum depths obtainable are usually about the same as the grid interval while maximum depths are usually about twice the window size (FitzGerald, Thurston, & Biegert, 2023). To enhance the maximum depth resolvable, the data was re-gridded to 400 x 400 m and a window size of 6000 m (i.e. 15×400 m) was adopted. This gave the least and maximum depth resolvable by the Euler deconvolution operation as 400 m and 12000 m respectively. The Euler deconvolution solution map is shown in Fig 11. In addition to defining the outline of the lineaments as done by the THD operation, the Euler deconvolution solutions estimated the depths of the lineaments. The lineaments were classified as mostly within the sediments (i. e. < 6000 m), approaching the basement (6000 m to 9000 m), and entirely within the basement (> 9000 m). Being directly overlying the basement, majority of the observed lineaments are believed to have been imprinted on the highly compacted sediments, possibly Bima Sandstone, by the highly deformed basement.

The variable depths variations that have range between 400 m and 12000 m suggest occurrence of sub basins within the Gongola basin. This also confirms significant occurrence of tectonic activities resulting in fractures and faults as in aforementioned in above subsections. The classified lineaments by the THD

operation within the sediments, reveals to be deep down to the basement surface. This generally will support development of subsurface structural traps and migration pathways within the basin.

4.6. Integration of subsurface structural orientation and structural trap potentials

The integration of surface and subsurface lineaments is an approach to understand geological structures that control the migration and accumulation of hydrocarbon in an area [26]. The surface lineaments are extracted from Digital Elevation Models (DEMs), while the shallow and deep lineaments of the area are derived through lineament edges identified from horizontal derivative, analytic signal, tilt, and Euler deconvolution analyses. Furthermore, a strike orientation rose diagram over the area was plotted with data generated from gravity datasets. As observed in Fig. 12, there are four principal lineament trends: N-S, NE-SW, ENE-WSW, and NW-SE orientations.

Furthermore, surface and magnetic lineaments trend majorly in the NE-SW direction (Fig. 12), the lineament alignments are distributed across the central, eastern, southern, NE, SE, and SW parts of the study area.

This validates classified lineaments by the THD operation within the sediments, and further confirms possibility of subsurface structural traps, such as the fault-bend fold or a fracture-controlled trap, which are capable of accumulating hydrocarbons within the Gongola basin. Thus, these fault and fracture-controlled hydrocarbon migration pathways will also enhance the migration and accumulation of hydrocarbons, as shown in Fig. 12.

4.7. Radiometric element distribution

The radiometric assessment of in situ isotopes (U^{238} , Th^{232} and K^{40}) was used to create maps of standardized values, highlighting both positive and negative radiometric anomalies for each element. These anomalies can be linked to the migration and accumulation of hydrocarbons due to uranium biophile tendency [27]. Furthermore, the vertical migration of hydrocarbon, water or other gases can be inferred by analyzing different isotope anomalies [28] as presented.

An assessment of the equivalent thorium distribution within the Gongola basin was undertaken. Fig. 13a illustrates the spatial distribution of equivalent thorium concentrations, with the southern and eastern parts of the study area exhibiting elevated values, ranging from 11.88 to 22.89 ppm. Thorium naturally occurs in small amounts and is associated with uranium and other radioactive elements in the earth [27]. The overall range for equivalent thorium concentrations extended from - 0.23 to 22.89 ppm across the study area. The elevated values in the NE-SW approximately E-W sectors are consistent with the lineaments alignments (Fig.12), which signifies the region is rich in organic matter, exhibit high thermal maturity, and possible migration and accumulation of hydrocarbon (Mukherjee et al., 2023) in the study area.

Further examination of the data yielded significant findings. Across the entire study area, uranium concentrations range from 0.37 to 5.09 ppm. As illustrated in Figure 13b, uranium concentrations are

prevalent within the southern and eastern sectors of the study area, ranging from 2.77 to 5.09 ppm. These concentration patterns suggests localized structural complexities such as fracture, folds, faults (see Fig. 12) that control the migration and accumulation of hydrocarbon as organic matter is linked with uranium (U) due to their biophile tendency [27]. The concentration of potassium (%K) varied from -1.26% to 2.53% across the study area. It was observed in Figure 12c that the southeastern segment of the study area exhibits the highest values of %K, ranging from 1.11% to 2.53%. The elevated concentration of %K values in the southeastern region can be involved in diagenetic reaction that effect organic matter potentially influencing hydrocarbon generation or migration. Also, presence of structural features such as faults, fractures [29, 30] and folds control the migration and accumulation of hydrocarbon within the Gongola Basin. These correspond to the zero (0°) degree values where the Nasara-1 and Kolnami-1 wells, indicating a change in direction of the maximum gradient associate with faults, fractures where hydrocarbon can move out of a trap or reservoir (Fig 10). Thus, the THD and TDR maps, supports also by observable densely-packed lineament in the north-western tip (labeled B) and as the "Region A" are most likely to be associated with the petroleum system of the study area (Fig.9).

It is also indicated by high and low magnetic susceptibility (Fig 5 & 6) shown on the TMI map. The radiometric data confirms integrated datasets clearly with the measure of decrease in radioactive elements the migration pattern and distribution of hydrocarbon which also coincides with presences of subsurface structures such fractures, faults, fault-bend fold or a fracture-controlled traps or as pathways for hydrocarbon to move out of the reservoirs within the Gongola basin.

4.8. Isolation of sediment column from the full spectrum data and Mapping of Micro-seepages of Hydrocarbon

The basin subsurface architecture was also investigated in relation to the dry wells drilled in parts of the basin. The spectrum corresponding to the sediment column was filtered in order to identify magnetic signatures that occur entirely within the sediments. Based on the termination depth of the "Kolmani-1 Well" at 13,701 ft (i.e. 4,176 m), a band-pass filtered spectrum range corresponding to the spectrum with depth range of between 500 and 5000 m was filtered out using the Butterworth Band-pass filter (Fig 14). This filtered spectrum was searched for evidences of hydrocarbon micro-seepages (magnetic aureoles). Magnetic aureoles are often associated with hydrocarbon micro-seepages [31] identified as circular magnetic lows surrounding magnetic highs from all sides.

The lower band of 500 m was chosen because at sediment thickness of < 500 m, the temperature, pressure and anoxic conditions necessary for the formation of hydrocarbon are unmet. An upper band of 5000 m was chosen based on the prior knowledge of the depth at which the successful Kolmani-2 well was terminated (i. e. 4176 m). The band pass filtered magnetic data showing the aureoles is displayed in Fig 14a and b.

Magnetic aureoles manifest as roughly circular or elliptical signature of magnetic high (low susceptibility) completely or almost completely enclosing a magnetic low (high susceptibility). Fig 14b shows the magnetic aureoles A1-A16 identified on the spectrum. The delineated regional scaled linear

structure identified in the study area was superimposed on the magnetic aureole map (Fig 14b). All the 16 magnetic aureoles fell on or very close to a linear structure.

This is expected because magnetic aureoles are created as a result of the migration of hydrocarbon from reservoir towards the surface through faults and micro-fractures. However, this also agrees discussion in the subsection 4.7.

Migrating hydrocarbon, which is been driven by temperature gradients, compaction and changes in atmospheric pressure, sometimes react with the surrounding strata to create alteration features rich in diagenetic magnetite that in turn creates magnetic aureoles [31, 32] These findings are consistent with the abovementioned results.

A superposition of the mapped aureoles on the basement topography map gives an impression that the petroleum system in the area is mainly controlled by the major basin depression observed at the central western part of the study area (Fig.15).

While a fairly even distribution of the aureoles suggest that hydrocarbons may have been formed in most parts of the study area, it appears that the positions of Kolmani-1 (located on a magnetic aureole at the margin of the depression); and Nasara-1 (located on a magnetic aureole outside the basin depression) wells relative to the basin depression influenced the productivity of the wells, especially the Kolmani-1 Well that has a marginal gas success. This could be that the edge of the basin depression can create structural traps, such as faults as shown in subsection 4.7. However, hydrocarbon might migrate towards the edge of the basin, responsible for discovery of the 33 million cubic feet of gas in the well. In spite being positioned on a mapped magnetic aureole and its proximity to a lineament, the Nasara-1 Well (located outside the major basin depression) was found to be dry. On the other hand, the Kolmani-1 Well, which is also located on an aureole and proximate to a lineament, at the margin of the depression, was fairly successful ascribed probable hydrocarbon migration through structural fault trap at the edge of the depression within the Gongola basin. This indicates that the trapping mechanism of the petroleum system in the study area could be located within the major depression. This further implies that the hydrocarbon prospect lies within this depression. Based on this premise, the locations of aureoles A5, A6, A7, A11, A14 and A15 whose coordinates are given in Table 1, are promising locations recommended for detailed studies to attain exploration successes in the Gongola Basin.

Table 1: Coordinates of the Mapped Magnetic Aureoles*

X	Y	Z	Location with Respect to the Basin	Prospect (High/Low)
689366.3	1184675	A1	Outside	Low
708037.8	1181380	A2	Outside	Low
743184	1187970	A3	Outside	Low
760208	1194560	A4	Outside	Low
716824.3	1155021	A5	Inside	High
719570.1	1142939	A6	Inside	High
689366.3	1122620	A7	Inside	High
684973	1109440	A8	Margin	Moderate (Kolmani-1 Well)
707488.6	1086925	A9	Outside	Low (Nasara-1 Well)
684423.9	1063860	A10	Outside	Low
671793.2	1106695	A11	Margin	Moderate
707488.6	1106695	A12	Outside Margin	Low
733468.3	1156048	A13	Outside	Low
677991.1	1137883	A14	Inside	High
671117.8	1135428	A15	Inside	High
745742.1	1144265	A16	Outside	Low

5. Conclusion

This study focuses on parts of Gongola basin of the Upper Benue Trough in north-eastern Nigeria, bounded between longitude 10°30' to 11°30 E and latitude 9°30 N to 10°30 N, and covering more than 60% of the entire basin. The aim of the research is to achieve new insights into subsurface architecture of the Gongola Basin in relation to the failed (dry) well(s) drilled in parts of the basin. This was achieved through the integration of both surface and subsurface datasets that include satellite remote sensing, radiometric, high resolution aeromagnetic and gravity datasets.

The study area reveals a complex subsurface architecture comprising highly undulating terrain and structural trends. A significant bedrock depression was identified in the western segment of the study area, which was considered the potential site for hydrocarbon generation and accumulation. This was confirmed by distribution of thorium, potassium and uranium in the depression, indicating the presence of structural control features that can facilitate hydrocarbon generation and accumulation.

Furthermore, the trapping mechanism within in the basin is mainly controlled by a major basin depression, which offers a novel insight into the modest success of the Kolmani – 1 Well that yielded 33 Billion cubic feet of gas. In contrast, the location of Nasara-1 well is outside the depression probably explains why it resulted a dry hole. The study also identifies new exploration targets at the aureoles A5, A6, A7, A11 and A15 which can be potential sites for future hydrocarbon discoveries in the basin

Declarations

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Data availability: The research data is available on request from the corresponding author (Dr. Ishaq YUSUF).

Code availability: Not applicable

Declaration on clinical trial: Not Applicable in the manuscript

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Ethics approval and consent to participate: This study adheres to the ethical standards required by the journal.

Consent to publication: Not applicable

Competing interests: The authors declare no competing interests

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Figures

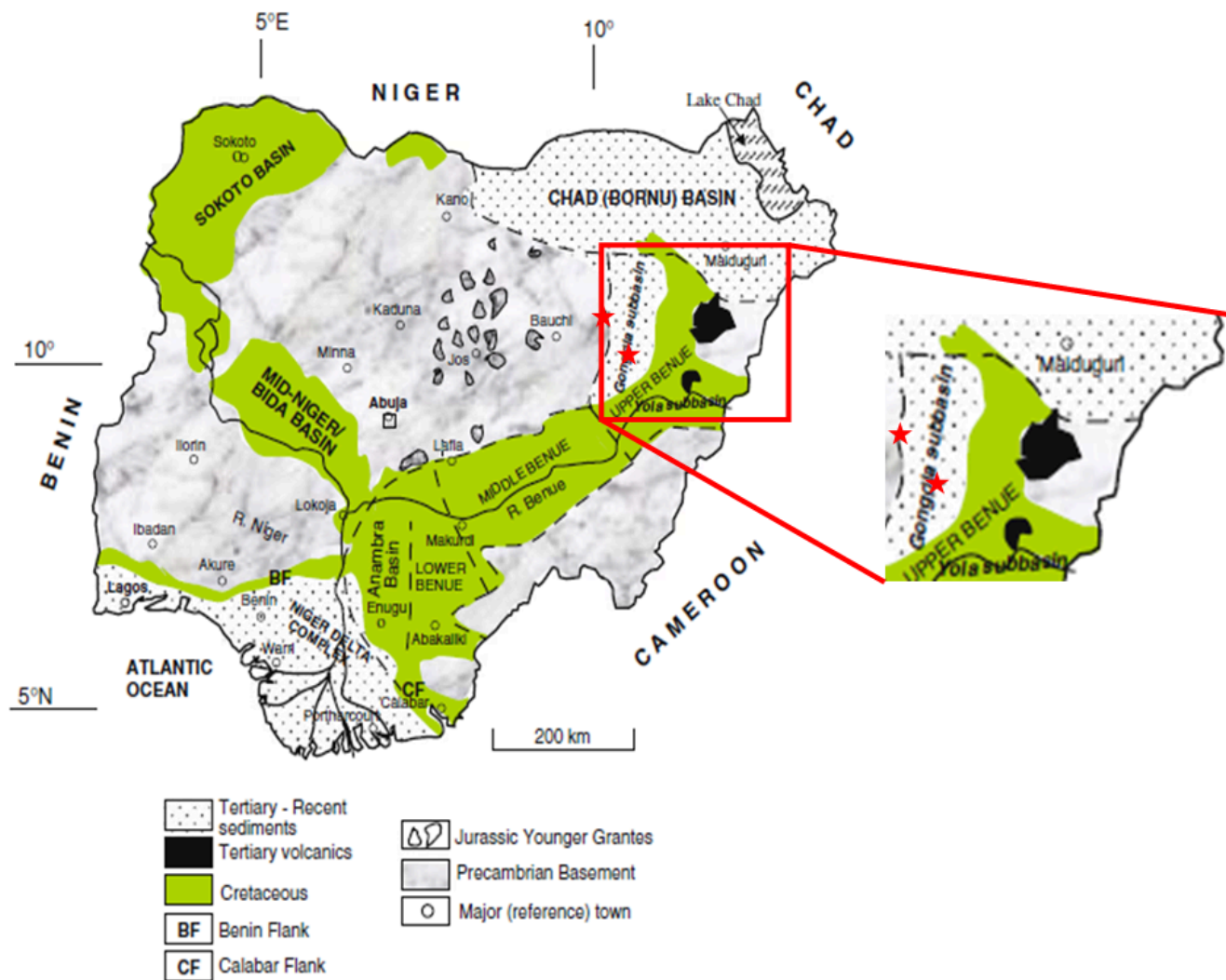


Figure 1

The Gongola sub basin: showing study well positions in red square and other Nigeria inland basins (after Obaje, 2009)

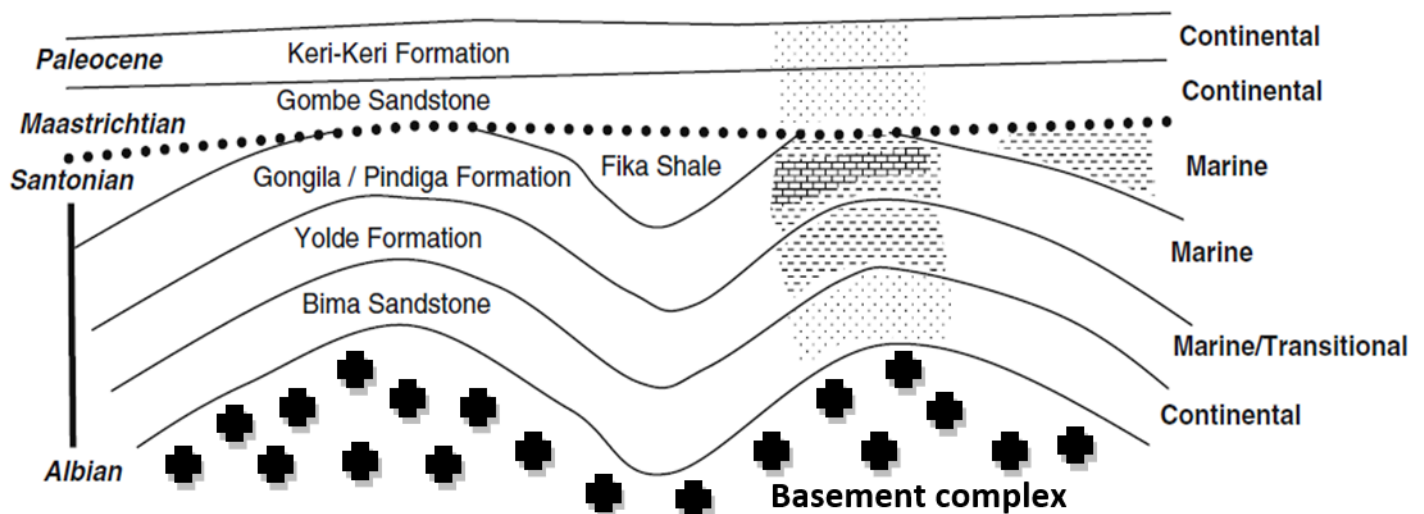


Figure 2

Stratigraphic successions of Gongola sub basin in the Upper Benue Trough (after Obaje, 2009).

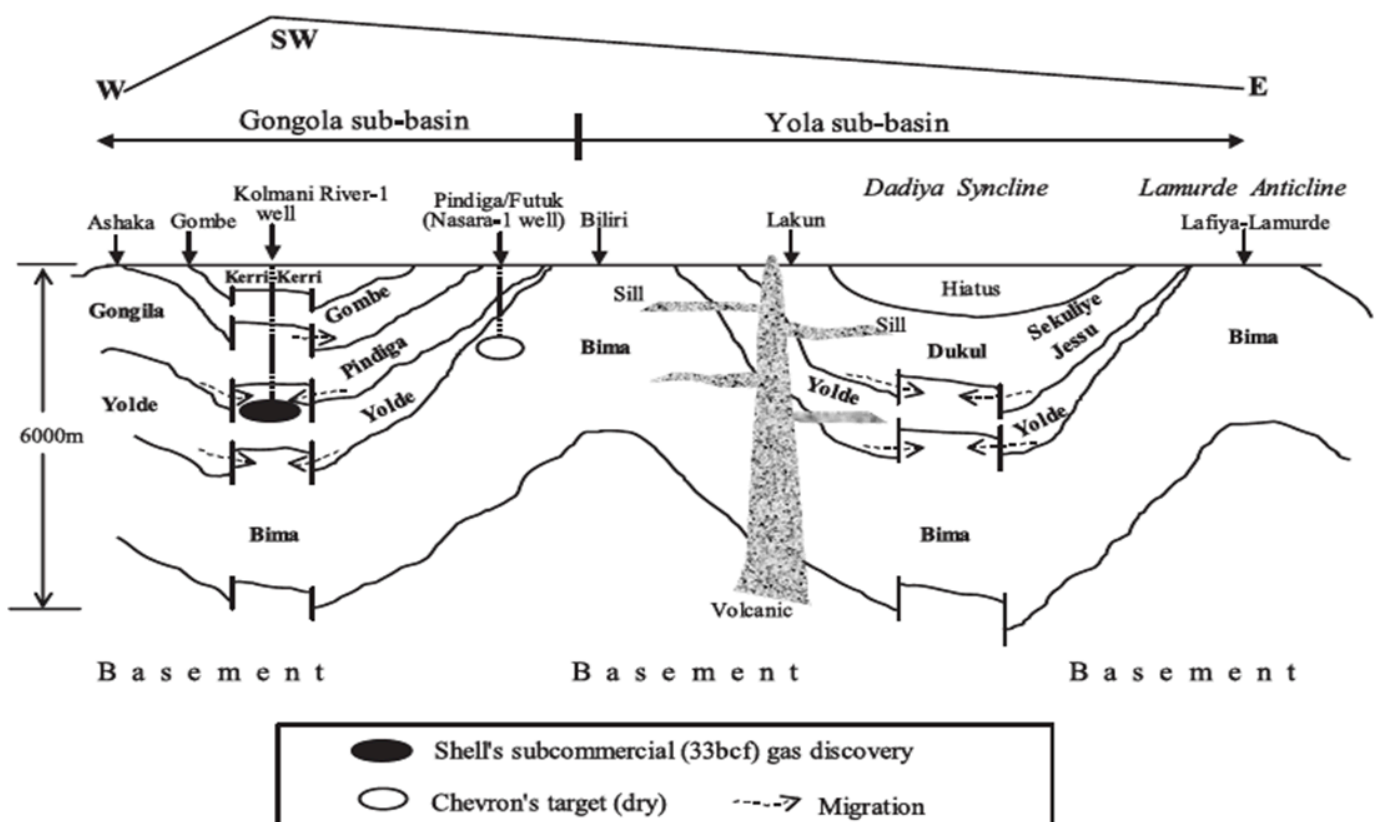


Figure 3

A cross-section of the Upper Benue Trough (West-East) depicting locations of the wells; Kolmani-River-1, Nasara-1, and probable the Kuzari-1 southwest of the cross-section (modified after [1])

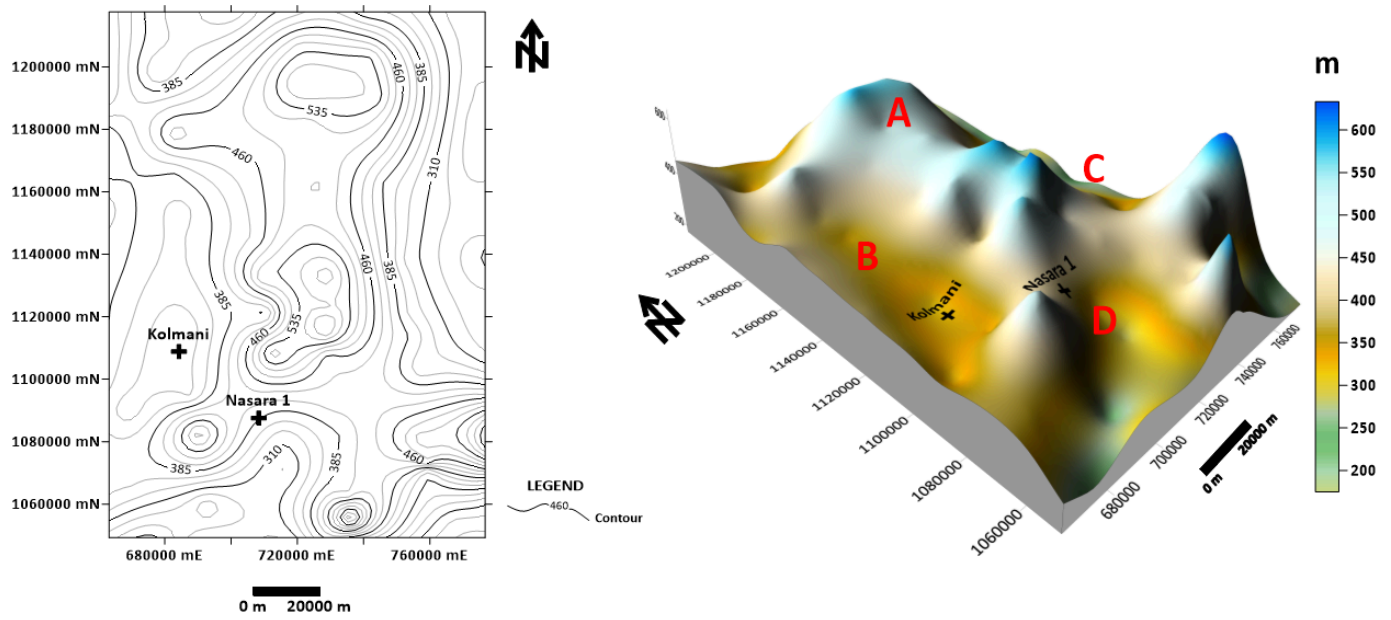


Figure 4

The digital elevation model and 3D map of the study area

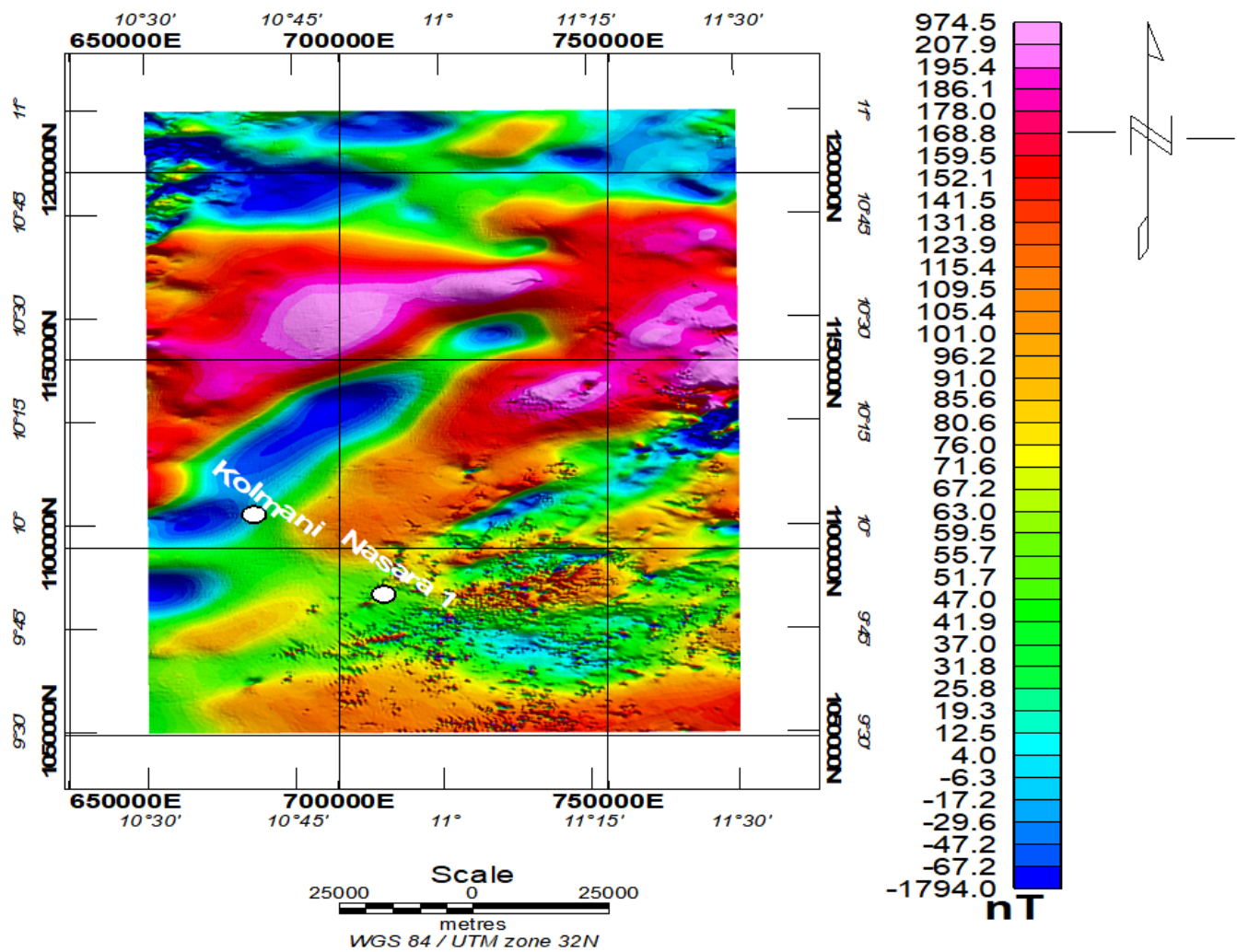


Figure 5

The TMI map of the study area

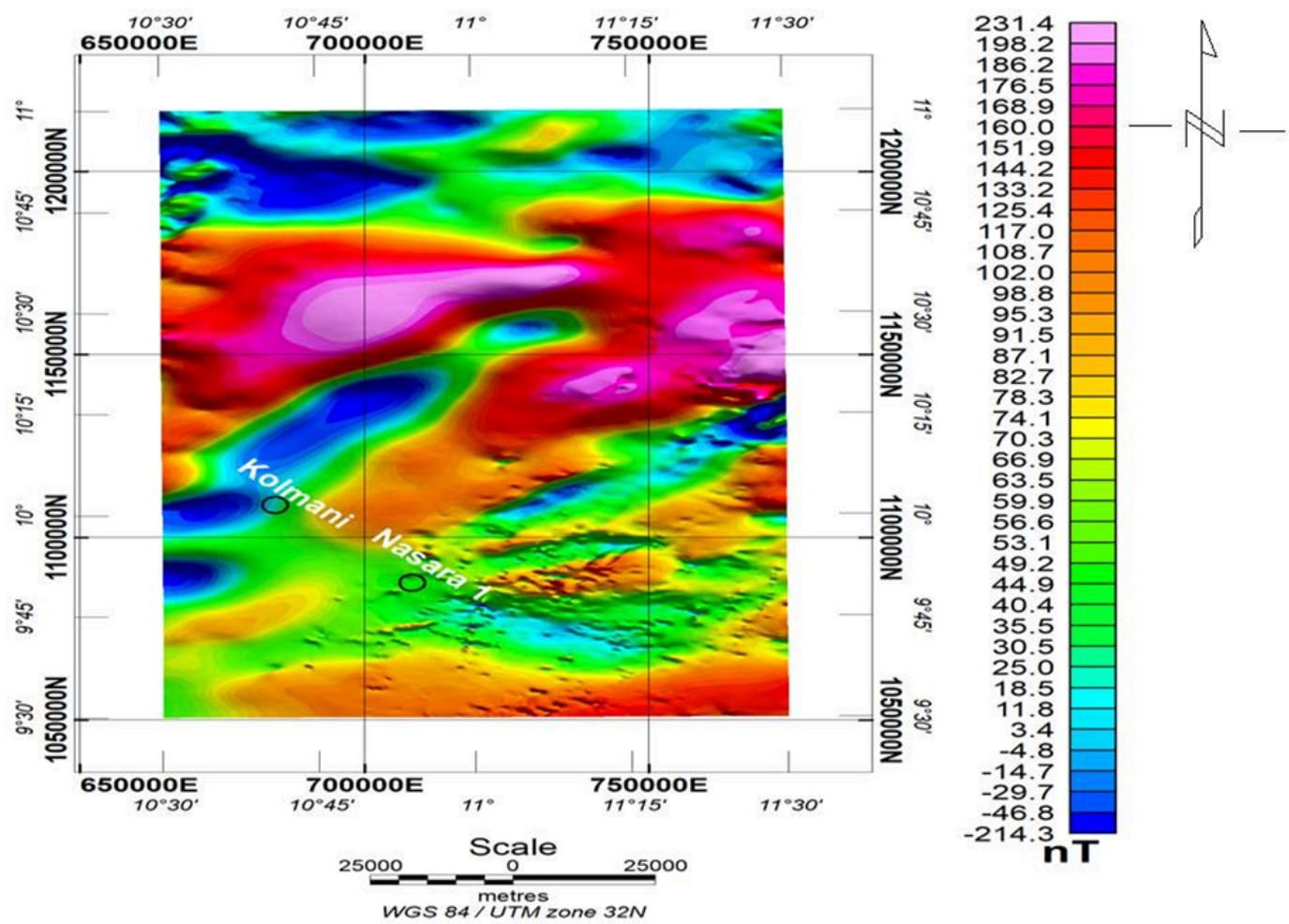


Figure 6

The Reduced to the Equator (RTE) Map of the study area

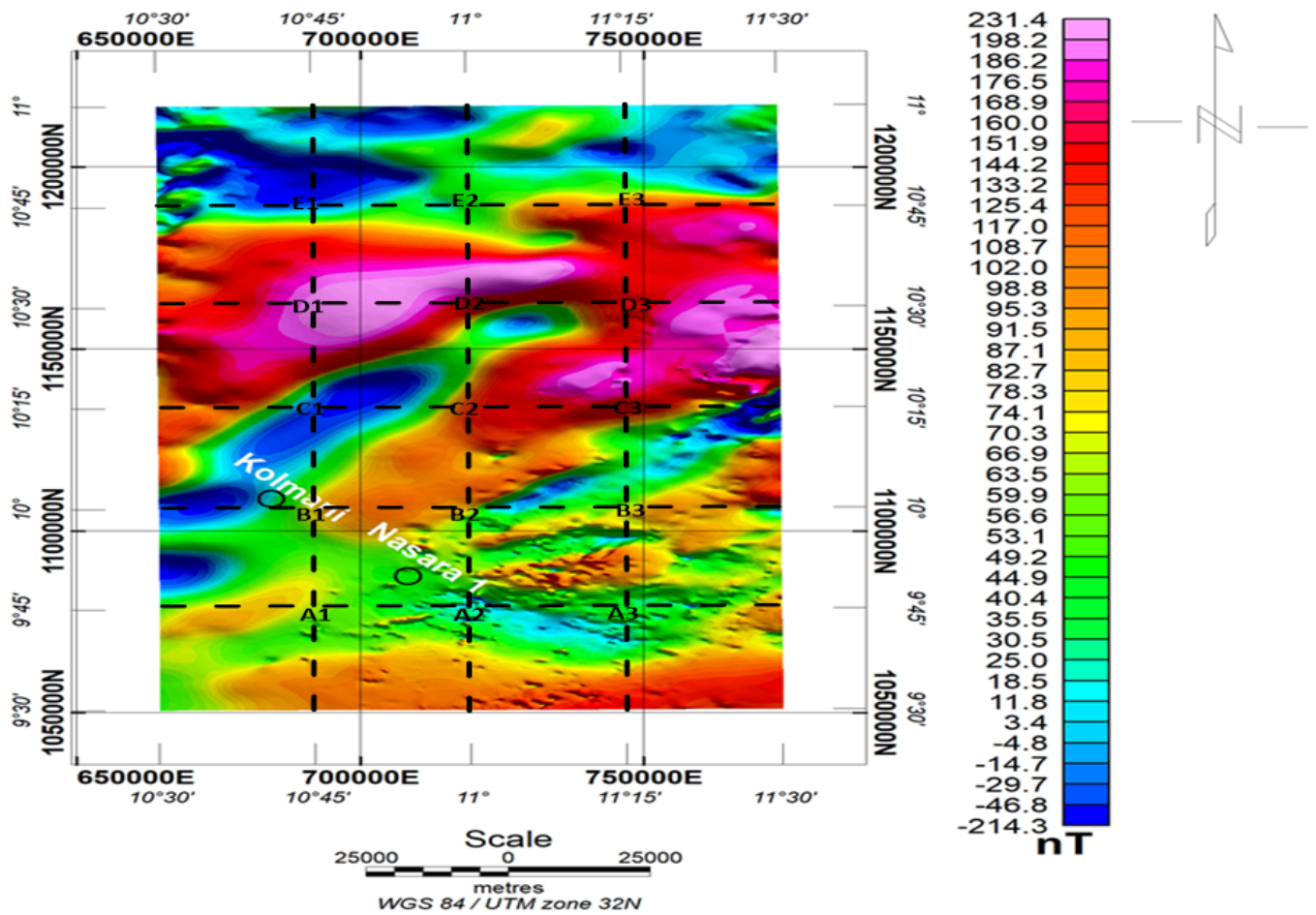


Figure 7

A layout showing partitioning of the area into blocks for spectral analysis. A1, A2,...E3 represents the centre of a 55,000 m × 55,000 m overlapping sub-grids.

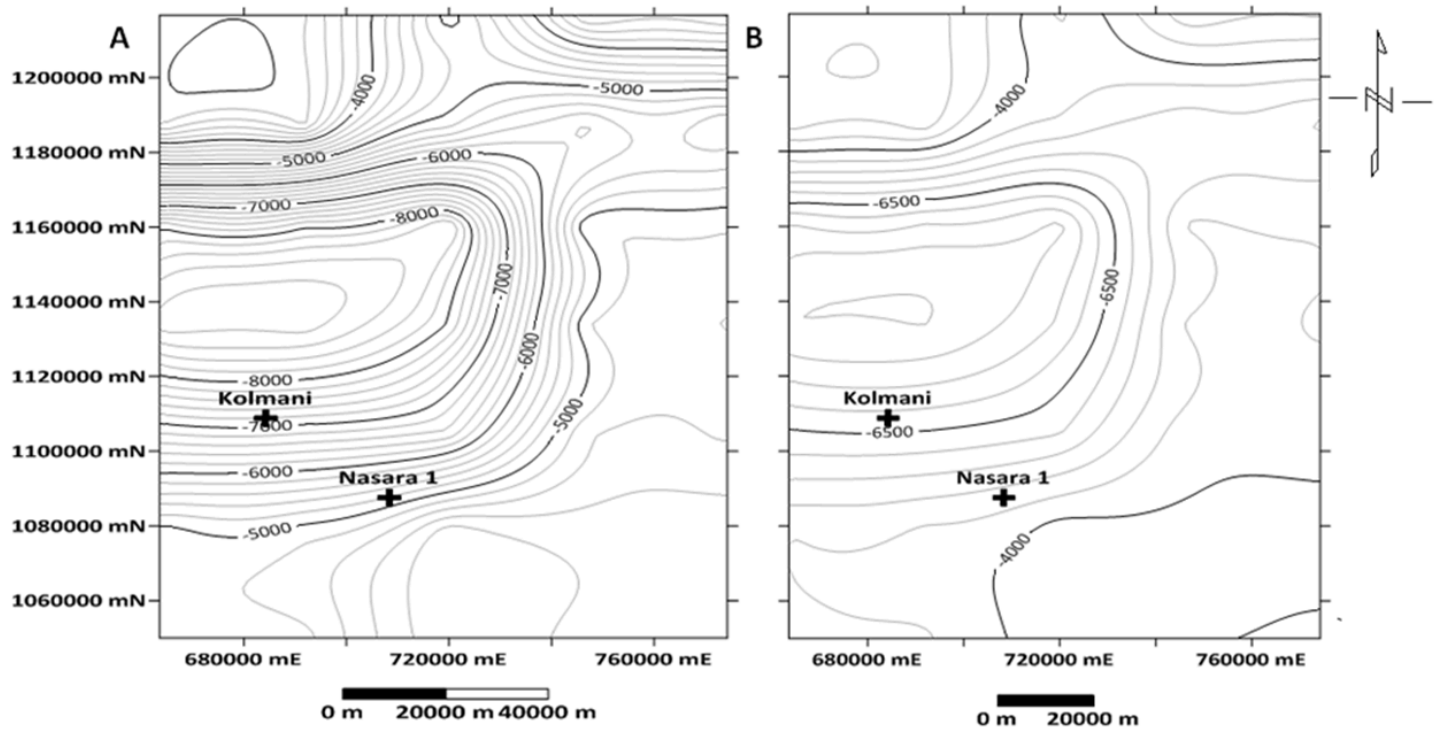


Figure 8

(a) Absolute Depth to Basement area, (b) Depth to Basement Corrected with respect to the Topography area

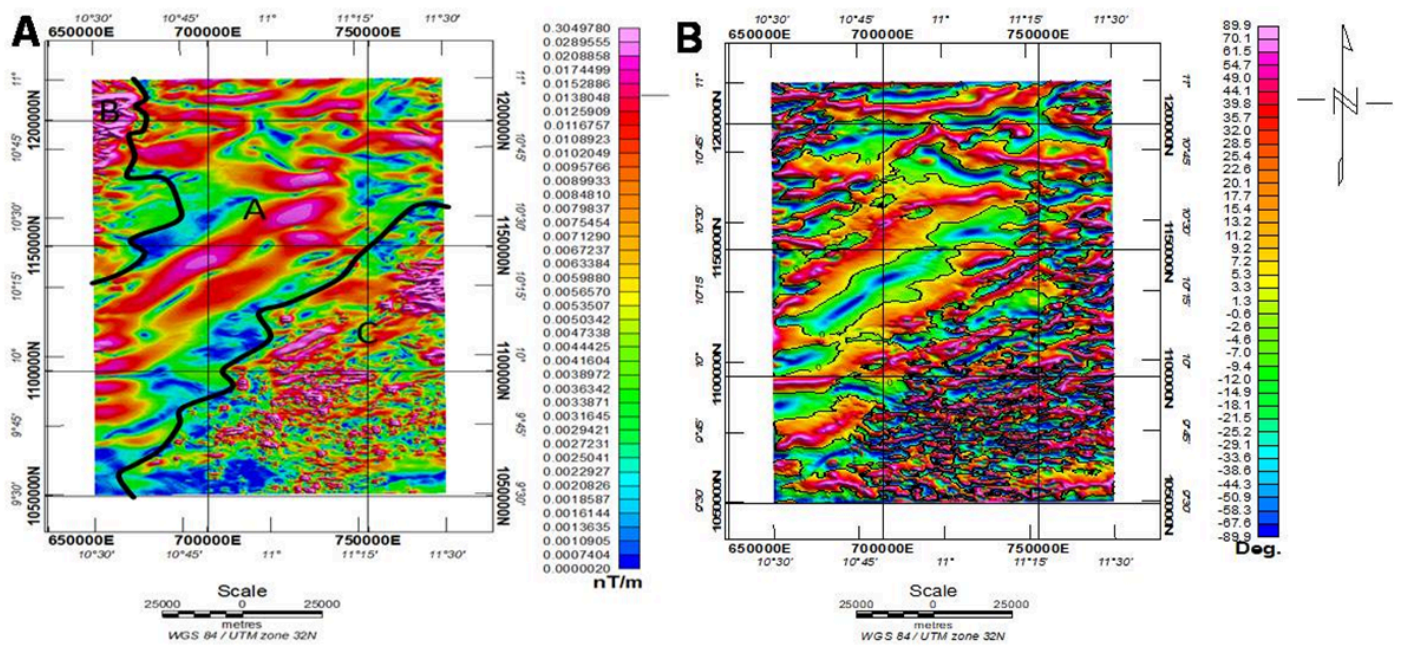


Figure 9

(a) Total Horizontal Derivative Map of the Study Area, (b) Tilt Derivative Map of the Study Area

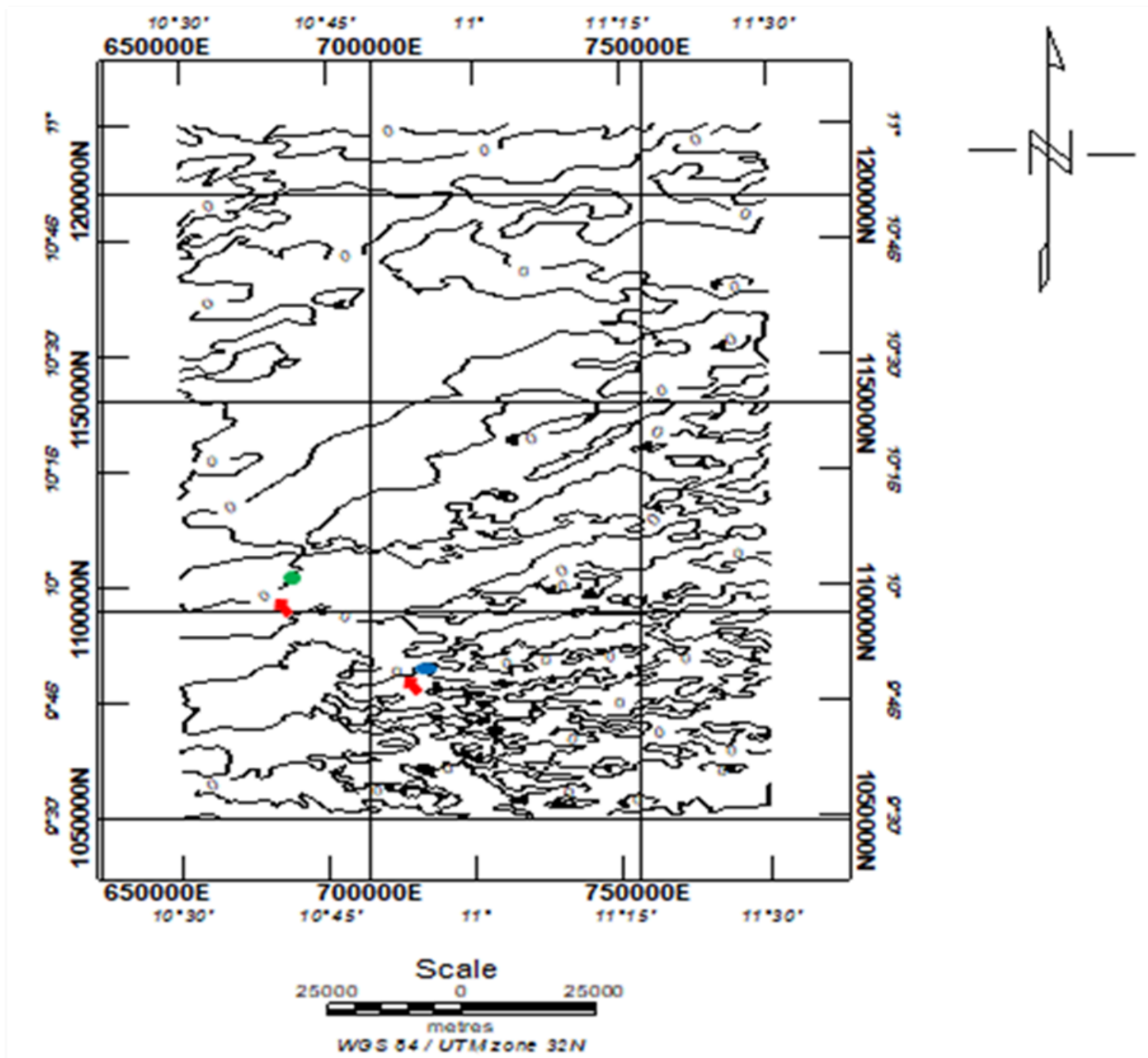


Figure 10

The delineated areas of zero degree values for Nasara-1 and Kolmani-1 wells

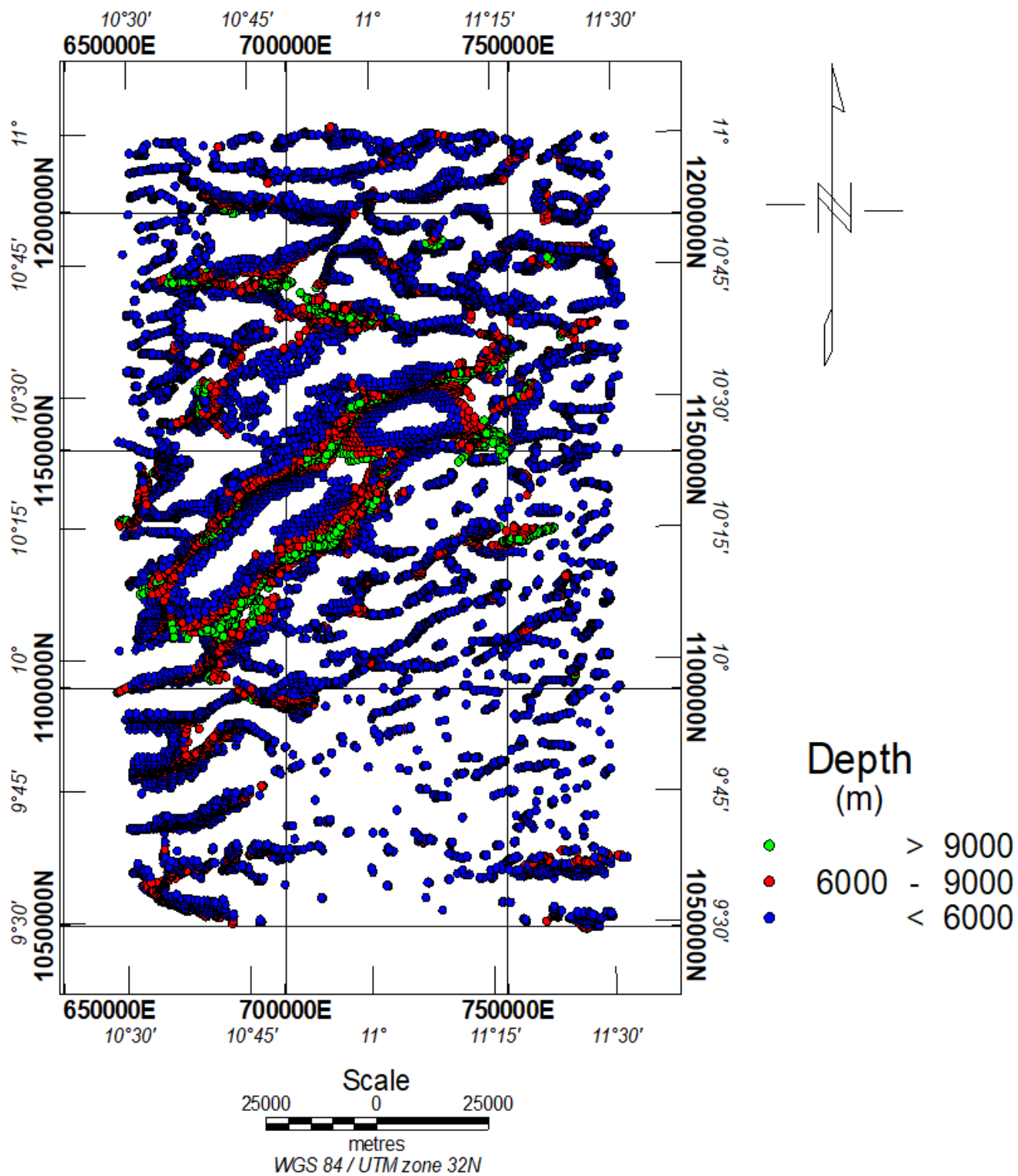


Figure 11

Euler Deconvolution map of the study area

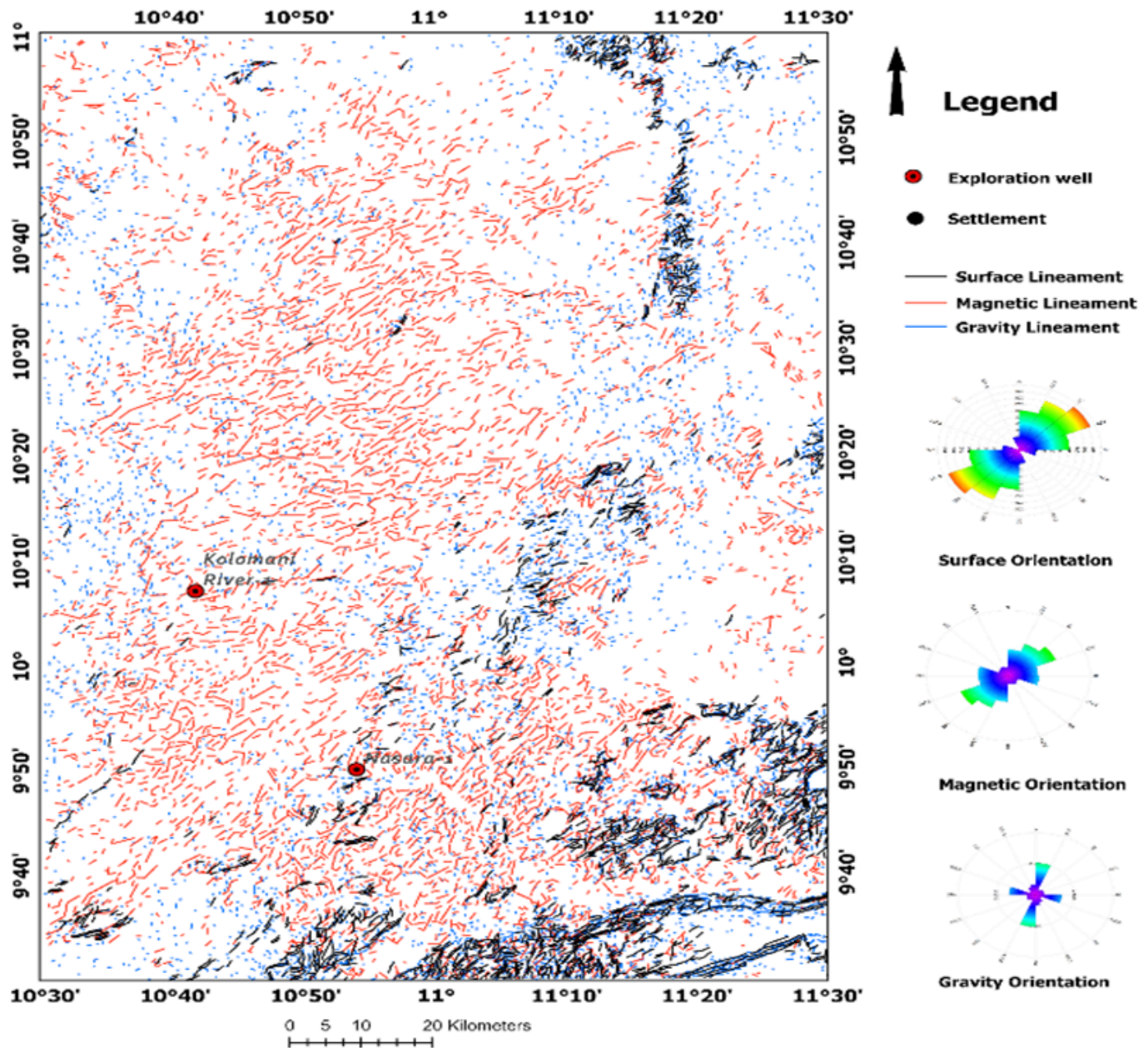


Figure 12

integrated structural analysis (remote sensing, magnetic and gravity datasets of dominant trend directions of surface and subsurface lineaments.

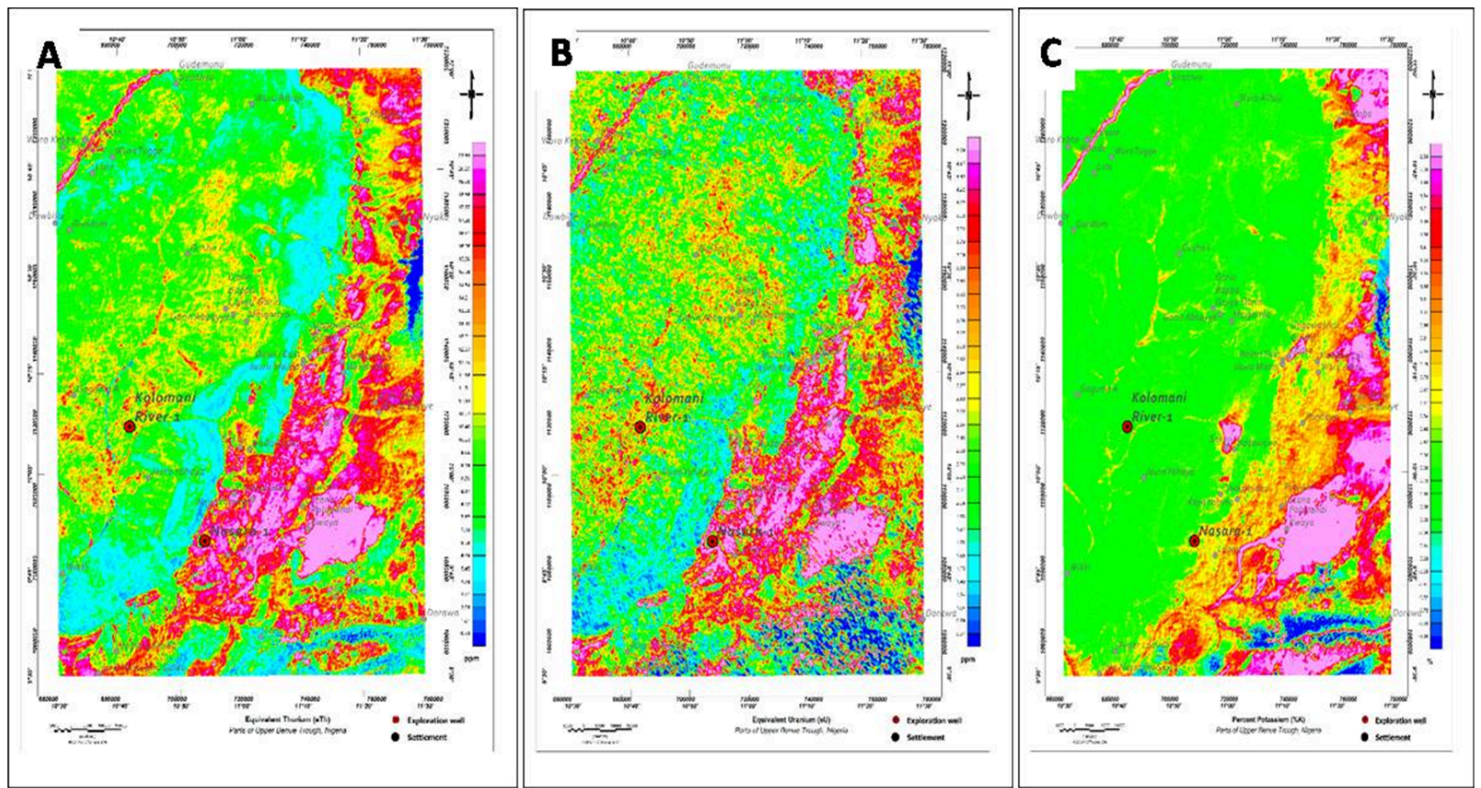


Figure 13

Radiometric elements of (a) high Thorium (b) high Uranium (c) low Potassium distributions

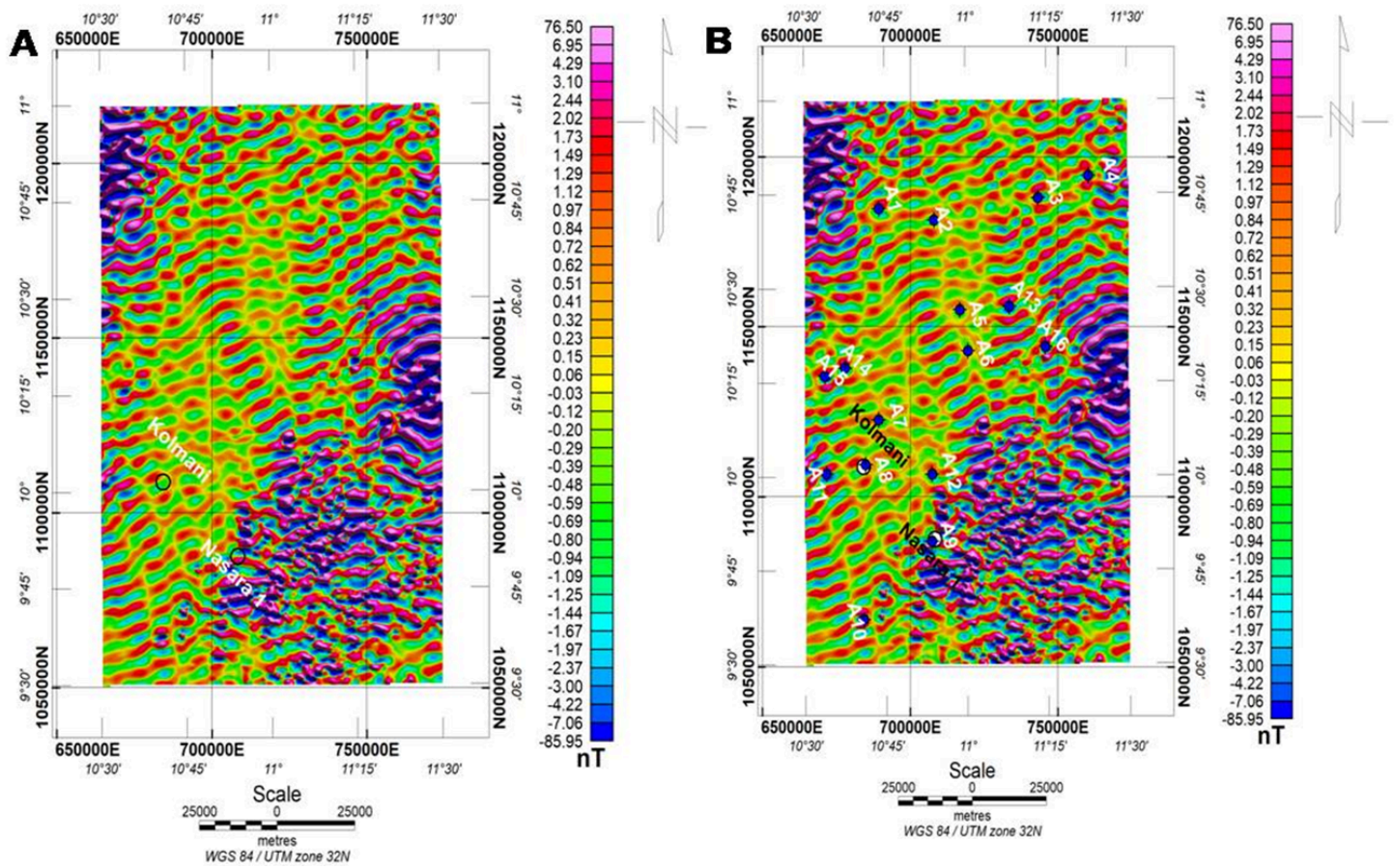


Figure 14

(A) Total Magnetic Intensity (TMI) field spectrum corresponding to depth range between 1000 m and 5000 m, (B) Total Magnetic Intensity (TMI) field spectrum corresponding to depth range between 1000 m and 5000 m with magnetic aureoles A1-A13 indicated on it.

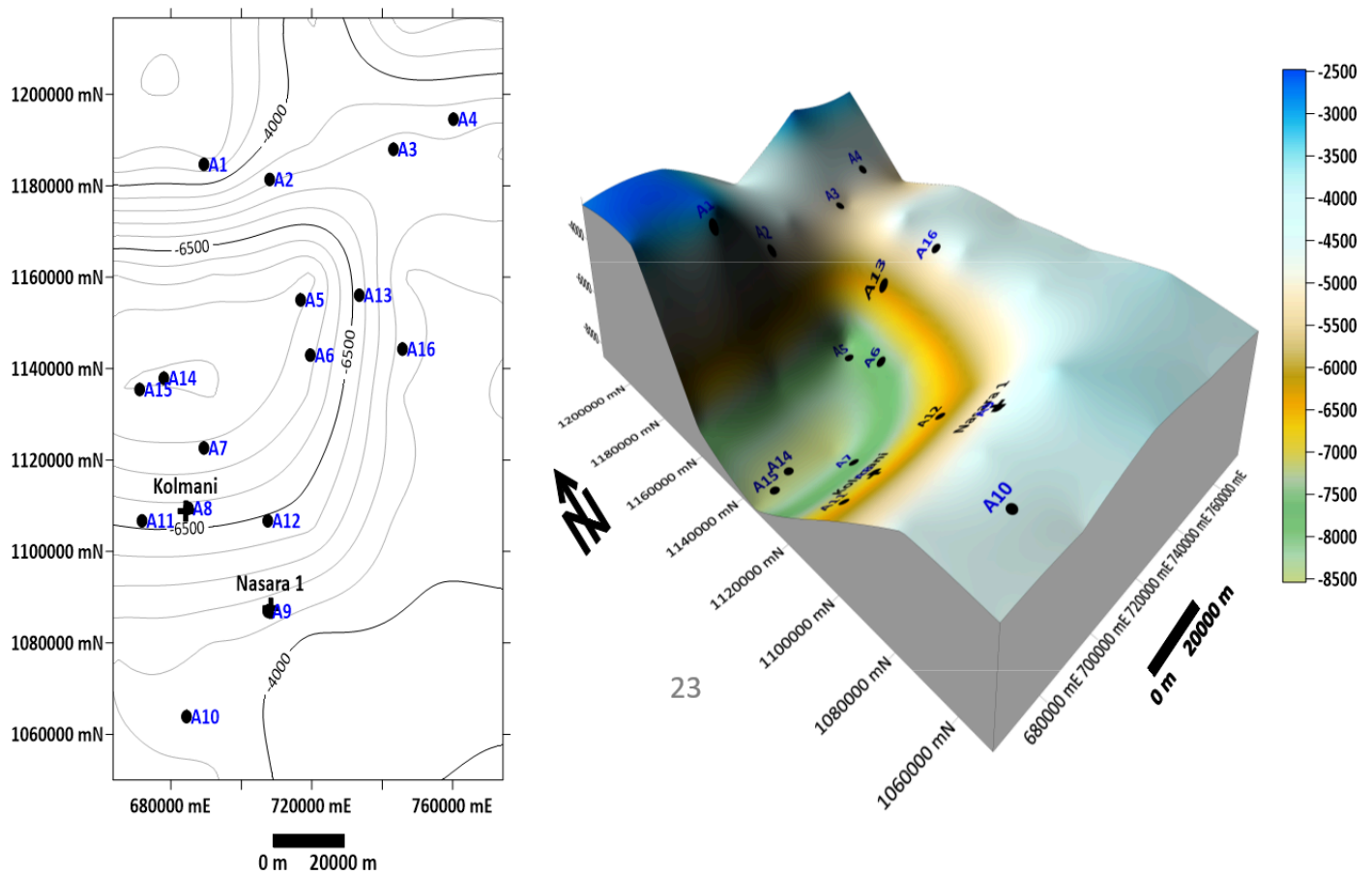


Figure 15

Superposition of the Mapped Aureoles on the Basement Topography

Supplementary Files

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