Songklanakarin J. Sci. Technol.
46 (4), 390–397, Jul. – Aug. 2024

http://www.sjst.psu.ac.th

Original Article

Topographic and subterranean structural mapping utilizing aerial magnetic and remote sensing data

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Received: 1 May 2024; Revised: 15 June 2024; Accepted: 21 June 2024

Abstract

The current investigation focuses on conducting surface and subsurface structural mapping of Warana River basin's Rafin Rewa's warm spring area and its surroundings utilizing airborne magnetic and topographic datasets. To fulfill this objective, the residual magnetic data underwent reduction to the magnetic pole, and two methods of source edge detection were implemented: the first vertical derivative (FVD) and 3D Euler deconvolution. SRTM data was transformed into hillshade maps employing four distinct solar elevations and a constant azimuth of 450. From the FVD map, discernible structures traversing the study area were delineated, with one significant structure intersecting Rafin Rewa's warm spring. These delineated FVD structures were superimposed on the Euler solution map with a structural index of one for further structural delineation. The Euler solutions unveiled most major structures trending in the NE-SW and NW-SE directions, with Rafin Ruwa Warm Spring located within an Euler solution cluster, suggesting its shallow-seated structural origin at depths ranging from 200 m to 400 m. Moreover, a surface structure trending NW-SE was observed to intersect Rafin Rewa's warm spring, potentially representing a subsurface structure reflection. The magnetic structure intersecting with the topographic structure was hypothesized to be responsible for upward fluid migration, leading to the warm spring's evolution during the Mesozoic era coinciding with the emplacement of Nigeria's younger granite series. Statistical trend analysis revealed that 38.76% of magnetic structures trended in the NE-SW direction, followed by NNW-SSE at 33.72%, NNE-SSW at 18.22%, and NW-SE at 7.75%. Similarly, surface topographic structural trend analysis indicated that the most predominant trend was NNW-SSE at 38.57%, followed by NW-SE at 34.38%, NNE-SSW at 19.71%, WNW-ESE at 6.38%, and NE-SW at 1.05%.

Keywords: fluid migration, warm spring, structural index, warm spring and edge detection

1. Introduction

A spring is delineated as an aquiferous flow that ascends autonomously from the subterranean strata to the terrestrial surface. Thermal springs, alternatively termed warm springs, denote such occurrences as they intermittently discharge water exhibiting temperatures exceeding the norm (Todd & Mays, 1980). The Rafin-Rewa warm spring is positioned within a fluvial conduit within the Lere local government jurisdiction of Kaduna State (Figure 1). Notably, the spring manifests a surface temperature of 42.50 °C, as documented by the groundwater division of the National Water Resources Institute, 2020 Mando, Kaduna, following extensive geophysical, hydrogeological, and hydrogeochemical analyses of the warm spring and its vicinity. Furthermore, a salient attribute of the spring is its adjacency to the Mesozoic younger granites (Figure 1), delineated by the configuration and dimensions of individual complexes, as depicted by the aggregation of contour lines (Figure 1).

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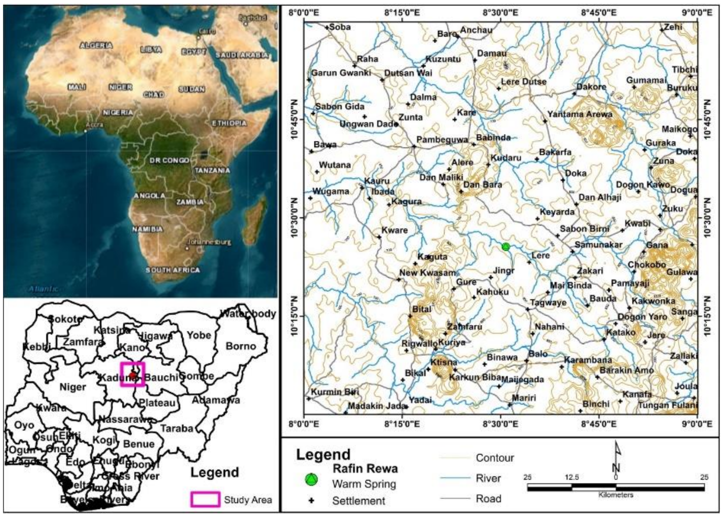

Figure 1. Location map of the study area

The ages of rocks in this area had led to the suggestion that magma that evolved to form these rocks was locally generated from several magma chambers that were linked to highly dissected, fractured, or faulted deeper sources (Ike, 1983; Rahaman, Van, Bowden, & Bennett,1984), and the magnitude of the fracturing within the portion of the basement determined where these ring complexes were emplaced (Rahaman, Van, Bowden, & Bennett, 1984). The geologic structure serves as a pathway when fluid moves upward along the fault plane and can be a hindrance as well pathway when fluid migrates partly across the fault and partly along the structure at the same time (Netshithuthuni & Zvarivadza, 2018; Olivier, Vente, & Jonker, 2011). Carrying out hydrogeological research are few examples of the technical problems that can be tackled using structural studies (Netshithuthuni & Zvarivadza 2018; Sabins, 1997). Magnetic data have long been used for structural studies either for water, mineral, warm spring or dam design studies (Ayuba & Nur, 2018; Faruwa, Qian, Akinsunmade, Akingboye & Dusabemariya, 2021; Halder, Nath, Gogoi, Mahanta, & Thapa, 2021; Netshithuthuni & Zvarivadza, 2018). Likewise, remote sensing data have also been applied for structural studies just like the magnetic data and several works have been published employing the method for lineament delineations (Errami, Algouti, & Farah, 2022; Fajri, Surtiyono, & Nalendra 2019; Kassou, Essahlaoui, & Aissa 2012; Mohammed, Gazali, Odihi, & Daura 2020; Oluwaseun-Loveridge *et al.*, 2022).

In Nigeria, warm springs such as the Wikki and Ikogosi have been the subject of extensive investigations for both geothermal, and structural purposes with physicochemical and microbiological analysis (Abraham & Alile, 2019; Fasesan- Esiobu *et al.*, 2020; Nwankwo, 2014; Obande, Lawal, & Ahmed, 2015; Ojo, Olorunfemi, & Falebita, 2011Olaleye, Ilesanmi, & Oladipo, 2022; Salawu-Dada *et al.*, 2021;), and the Rafin Rewa warm spring, which has not received much attention as other warm springs in Nigeria, served as the inspiration for this paper. One of the foremost published works on Rafin Rewa warm spring was that of Garba, Kurowska, Schoeneich, and Abdullahi (2012) who carried out a hydrogeochemical analysis of the spring water with a focus on the yield, type of aquifer, the presence of cations and anions, and the gas emanating as a bubble from the spring as it migrates to the surface.

Several articles on the structures have been published in north-central Nigeria employing airborne magnetic data (Goki- Adekeye *et al.*, 2011; Ibeneme, Oha, Abdulsalam, & Onuoha, 2018; Ogunmola-Agene *et al.*, 2015; Tawey, Alhassan, Adetona, Salako, Rafiu, & Udesi, 2020a, 2020b). The research area cuts across four Nigerian states (Kaduna, Kano, Plateau, and Bauchi), as displayed in (Figure 1), and is bordered between longitudes 8° E and 9° E and latitudes 10° N and 11° N. The younger granite intrusions surrounding the Rafin Rewa warm spring are 1. Kerku, 2. Rishua, 3. Kudaru, 4. Banke, 5. Liruel, 6. Tibchi, 7. Zuku, 8. Saiyi, 9. Shokobo, 10. Amo, and 11. Buji, (Figure 2).

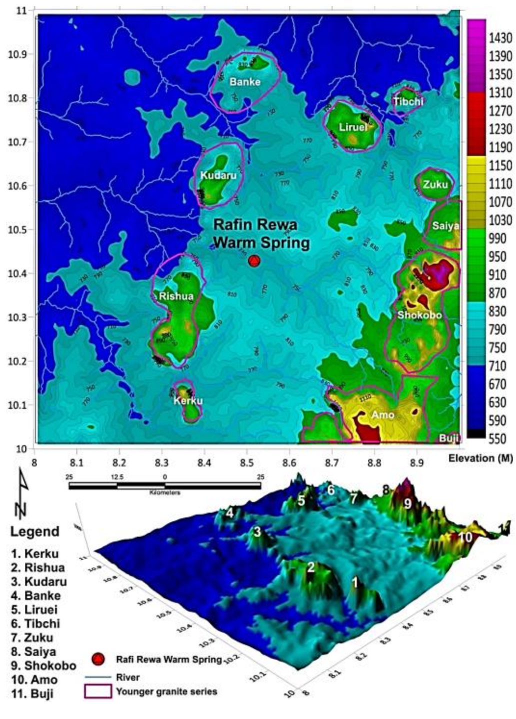

Figure 2. Digital elevation model of study area

2. Tectonic Settings and Geology

The Nigerian younger granite series intruded the basement complex during the Mesozoic (Obaje, 2009). The basement complex that was intruded by the younger granite series is tectonically situated within the Togo-Benin-Nigeria swell (Wright, 1985) and it bordered the southern limit of the Iullemeden basin called the Sokoto basin at the northeastern end of Nigeria. Abba, 1983, put forward that the deformational event (Pan African) occurred within this area that resulted in regional metamorphism and led to the formation of migmatite, Granite and Gneiss (Figure 3). However, airborne magnetic anomalies have suggested several deeply seated northeast-to-southwest (NE-SW), structures as a result of faulting that must have controlled the emplacement of each of the complexes within Nigeria (Ajakaiye, 1983; Ike, 1983; Tawey and Magaji, 2022).

3. Material and Methods

3.1 Source SRTM data

The Shuttle radar topographic mission (SRTM), digital elevation model (DEM) used for this research was downloaded from the United State Geological Survey (USGS) website, (*https://earthexplorer.usgs.gov/*) freely, having a spatial resolution of 30 m.

3.2 Source of aeromagnetic data

The four (4) airborne magnetic data sheets (Dutsin-Wa-125, Ririwai-126, Geshere-146 and Lere-147) that cover the study area were obtained from the Nigerian Geological Survey Agency (NGSA, 2006) Abuja. The survey took place between 2005 and 2009 and was jointly financed by the Nigerian Federal Government and the World Bank.

4. Methodology

Hillshade maps at four distinct Azimuths (0°, 90°, 180°, and 270°) were produced and merged into one composite map from the SRTM digital elevation model of the study area to enhance linear structural features in the area after which, the structures were automatically delineated using Geomatica software (Figure 4). The residual magnetic intensity data was reduced to magnetic pole, after which the first vertical derivative (FVD), and 3D Euler deconvolution filters were applied, and lineament was extracted using Oasis Montaj version 8.3. The magnetic lineaments delineated using FVD were overlayed on the Euler deconvolution map with a structural index of 1 (SI = 1), to compare structural location using the two edge detection techniques (Patil & Bhagwat, 2022). Depth classification using Euler 3D was done by grouping these depths into four groups (depths less than 200 m, depths between 200 m to 400 m, depths between 400 m to 600 m, and depths greater than 600 m). Statistical structural trend analysis was carried out on both surface and subsurface structures delineated and aided by a Rose diagram that was produced from the structures.

5. Theory of the Methods

5.1 Reduction to pole

Baranov (1957) introduced the RTP conversion operation which was later developed by Bhattacharya (1965) for repositioning magnetic anomalies above causative sources. RTP is a fast operation converting total magnetic intensity anomalies into induction-generated anomalies (Gunn & Milligan, 1997; Li, 2008). The RTP operation has been applied to the residual anomaly in the study area and is expressed as

$$M_p(u,v) = \frac{M_c M_p(u,v)}{[\sin(I) + i\cos(I)\ \cos(D-\Theta)]^2} \tag{1}$$

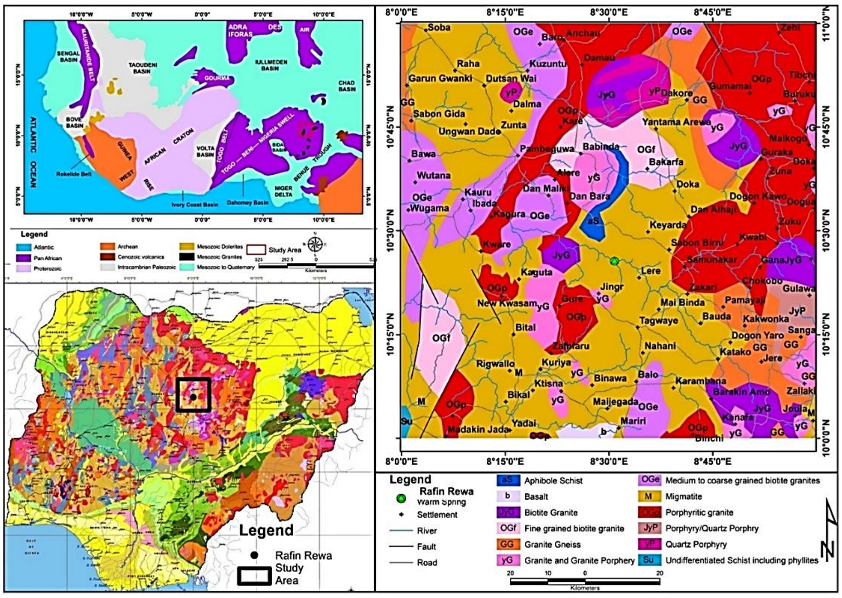

Figure 3. Geologic map of the study area (modified from Wright 1985 and NGSA, 2006)

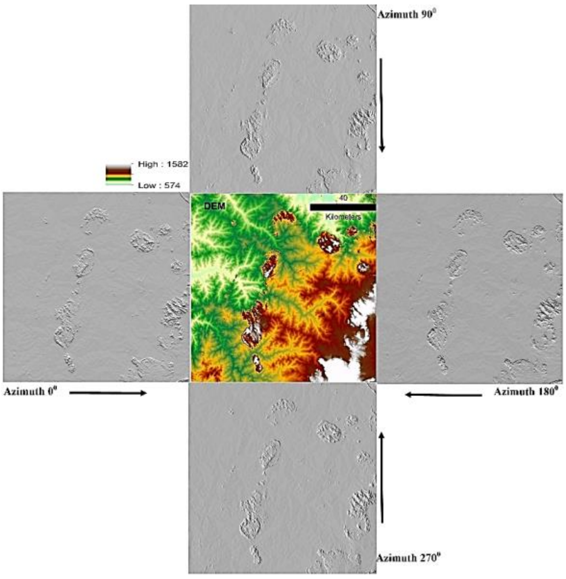

Figure 4. DEM and four Hill shade maps of Azimuths (0°, 90°, 180°, and 270°) at a constant tilt angle of 45°

where:

$M_p(u,v)$ is the Fourier transform of these observed magnetic data, $M_c(u,v)$ is the Fourier transform of the vertical magnetic field, I and D is the inclination and declination of the core field, (u,v) is the wavenumber corresponding to the (x,y) directions respectively and $\theta = arctan\left(\frac{u}{v}\right)$.

5.2 First vertical derivative

Vertical derivative filters generally enhance short-wavelength components in gridded data using FFT filters, at the expense of the longer wavelengths (Foss, 2011). Vertical derivatives of a magnetic field can be estimated by multiplying amplitude spectra by a factor of the form:

$$\frac{1}{n}\left[(U^2+V^2)^{\frac{1}{2}}\right]^n \quad (2)$$

where n is the order of the vertical derivative, and (U, V) is the wavenumber corresponding to the (x, y) directions respectively and this filter was applied to the magnetic data for structural delineation.

5.3 Euler deconvolution

Euler Deconvolution method determined magnetic anomaly source shape and depth (Reid, Allsop, Granser, Millet, & Somerton et *al.*, 1990; Thompson, 1982), using 3D Euler's equation of form,

$$(x-x_0)\frac{\delta T}{\delta x}+(y-y_0)\frac{\delta T}{\delta y}+(z-z_0)\frac{\delta T}{\delta z}=N(B-T) \quad (3)$$

where $(x_0, y_0, z_0)$is the position of a magnetic source whose total field T is observable at (x, y, z). B is the regional field value, and the degree of homogeneity is interpreted as the structural index (SI) represented by N. The present study used only one structural index (S1 = 1) for contacts, faults, and horizontal bodies to delineate structures and their respective depths.

6. Results and Discussion

6.1 Magnetic data interpretation

Figure 5A represents the residual magnetic map of the study area. Magnetic susceptibility within this area varies from -158.046 nT (low) to 113.634 nT (high). High susceptibility values are observed around the southeast, north-central portion and northwest. Settlements around high magnetic susceptibility values are Joula, Kanafa Doka, Bakarfa, Dan Bara, Pambeguwa, Baro, Sabon Gida Zunta Damau and Dogon Kawo. Low magnetic susceptibility values are observed around the central portion of the map to the southwestern end of the map (Figure 4). Towns around areas with low magnetic susceptibility values are Kayarda, Sabon Birni, Saminakar, Lere, Gure, Zamfaru, jingr, Kahuku, Karambana, Barakin Amo, Yadai, Gidan Gajere, Bikai, Ktsina and north of Dakore. There is an observed trench cutting across Bital in the NW-SE direction that is suspected to be a structure or dyke. Figure 5B represents the residual magnetic intensity map reduced to the pole overlayed with the geologic map of the area. Magnetic susceptibility varies from -121.943 nT (low) to 150.549 nT (high). Amphibolite schist (As), biotite granites (JyG), porphyritic granite (OGP), fine-grained biotite granite (OGf), granite gneiss (GG), medium to coarse-grained biotite granite (OGe), migmatite (M), quartz porphyry (yG), porphyry/quartz porphyry (JyP), undifferentiated schists including phyllites (Su) and basalt (b) have been mapped as well as higher susceptibility values are shown (Kayarda, Sabon Birni Saminakar, Lere, Gure, Zamfaru, Jingr, Kahuku, Karambana, Barakin Amo, Yadai, Gidan Gajere, Bikai, Ktsina, and north of Dakore). On this map, anomalies have been centred over the source. The younger granite series are observed to have high magnetic susceptibility values, which is peculiar to them. Areas with lower magnetic susceptibility could be attributed to metasomatic alteration of magnetite within the rock (Isles & Rankin, 2011). The map also reveals the feature observed in the RMI map that was suspected to be dyke or fault trending NW-SE direction and some strands of magnetic anomalies that trend NE-SW around the northeast and southwest part of the map. Higher magnetic susceptibility observed within the migmatite could be attributed to the magmatic intrusion during the emplacement of the younger granite series (Patil & Bhagwat, 2023).

6.2 Structural analysis of the area

Figure 6A represents the first vertical derivative map of the study area while Figure 5 represents the first vertical derivative map with delineated structures. From Figure 5A short wavelength that represents structures such as faults within the study area have been accentuated. The area is observed to be dissected with a series of structures that trend majorly in the NE-SW direction. The Rafin Rewa is observed to be situated within this area that has been dissected with structures. A critical look at the map (Figure 6B) revealed one major fault that was also revealed in the work of Rabiu, Ogwuche, Momoh, & Owolabi (2021), passing through the warm spring which is

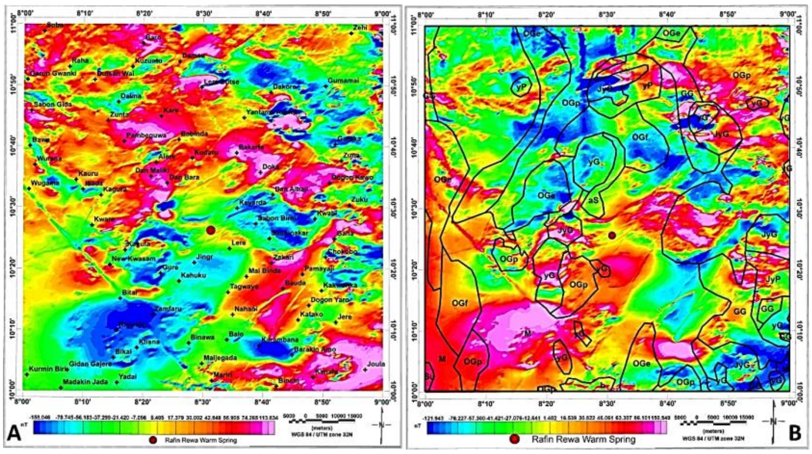

Figure 5. (A) RMI map and (B) RTP map of study area

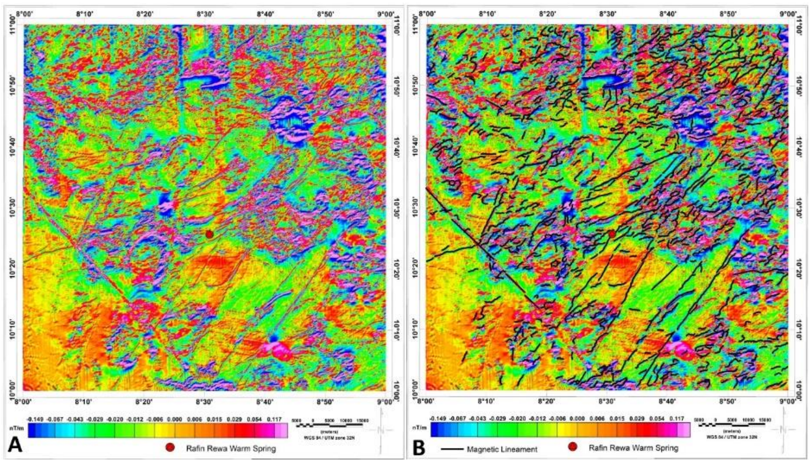

Figure 6. (A) FVD map and (B) FVD map delineated within the study area

suspected to be the structure responsible for the evolution of the Rafin Ruwa warm spring. Figure 7A represents the 3D Euler deconvolution map of the study area with a structural index of one (SI = 1). Figure 7B represents 3D Euler deconvolution with overlayed structures delineated from the FVD. From Figure 7A, Euler solutions are seen to have revealed most of the major structures delineated using the FVD (Figure 6B) that trends in the NE-SW and SW-NE. The Rafin Ruwa warm spring is observed to be situated on an Euler solution cluster which suggests that the structure that brought about its evolution is shallow seated at a depth of range (200 m to 400 m) as displayed in Figures 7a and 7b. This depth range of the structure (200 m to 400 m) that possibly brought about the evolution of the warm spring is contrary to the assertion of Garba *et al.* (2012) who stated that the structure that brought about the evolution of the spring is situated at a depth deeper than 700 m below the subsurface but in support of Rabiu *et al.* (2021) who employed the analysis of an airborne magnetic dataset to delineate geologic structures that could have been responsible for the evolution of the Rafin Rewa warm spring where they gave a possible range of the structure responsible for the evolution of the Rafin Rewa to be between 100 m to 1,500 m. Figure 8A represents the delineated magnetic structural map while Figure 8B represents the structural density map. From Figure 8A Rafin Rewa's warm spring is seen to be situated within a series of neighbouring magnetic structures with one major structure passing through it with all the structures within this location trending NE-SW direction (Figure 8A). Figure 8B reveals structural density that ranges from 0 to 0.15 km/km^2 low to 0.76 km/km^2 high. The Rafin Rewa fall within an area of high magnetic structural density of range 0.46 km/km^2 to 0.61 km/km^2.

6.3 Structural trend analysis

Statistical trend analysis of surface and subsurface structures delineated through the utilization of magnetic and topographic data is illustrated using rose diagrams (Figure 9A and 9B). As shown in Figure 9A, the predominant structural orientation is 38.76% of the magnetic structures aligned in the NE-SW direction, followed by NNW-SSE at 33.72%, NNE-SSW at 18.22%, and a secondary NE-SW trend at 7.75%. Similarly, the surface topographic structural trend analysis (Figure 9B) reveals that the most dominant trend is NNW-SSE at 38.57%, followed by NW-SE at 34.38%, NNE-SSW at 19.71%, WNW-ESE at 6.38%, and a minor NE-SW trend at 1.05%.

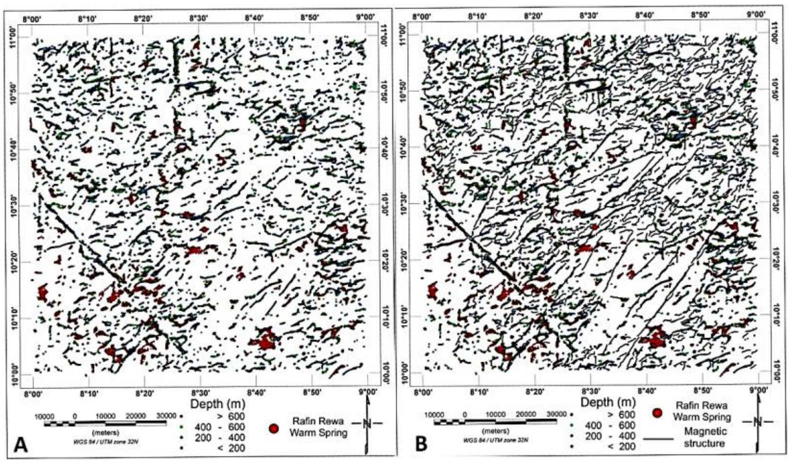

Figure 7. (A) Euler solution map with SI=1, and (B) Euler solution map with SI=1 overlayed with FVD structures source (produced using Oasis)

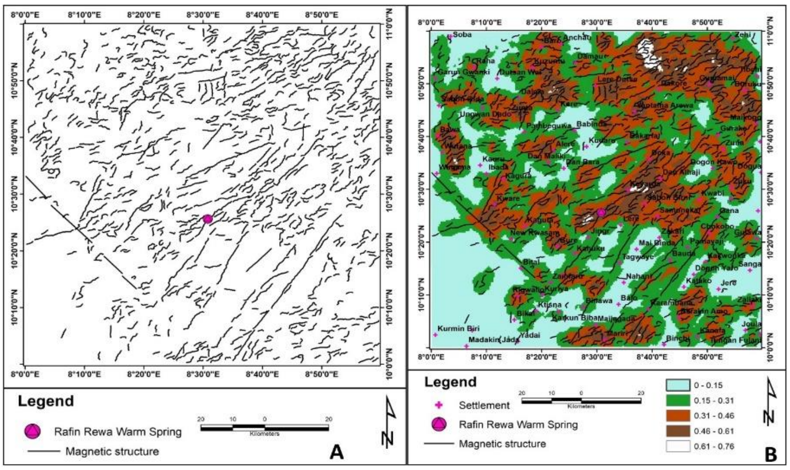

Figure 8. (A) Magnetic structural map of the study area, and (B) magnetic structural density map of study area

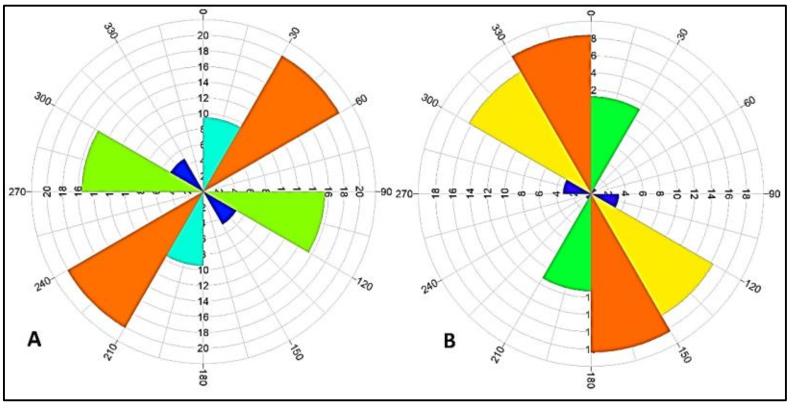

Figure 9. (A) Rose diagram of magnetic structures, and (B) rose diagram of the topographic structures

7. Conclusions

The magnetic susceptibility within the study region spans from -158.046 nT to 113.634 nT, showcasing elevated values in the southeast, north-central, and northwest sectors. Conversely, diminished values prevail from the central to southwestern extents, where a trench-like feature, exhibiting an NW-SE orientation around Bital, suggests a probable structural or dyke presence. The study zone manifests significant faulting and structural fragmentation, with Rafin Rewa positioned amid this terrain, notably intersected by a major fault suspected to underpin its genesis. Confirmation of this fault's passage through the warm spring is evidenced by Euler solutions, indicating a structural index of one (SI = 1). The spring's placement within an Euler solution cluster suggests a shallow-seated structural origin, spanning depths ranging from 200m to 400m. This contradicts Garba et al.'s (2012) assertion of the fault's subsurface depth exceeding 700 m, aligning instead with Rabiu et al.'s (2021) findings, which delineate potential geologic structures responsible for the spring's evolution within a structural depth range of 100 m to 1,500 m, employing airborne magnetic dataset analysis. The Rafin Rewa warm spring coincides with an area characterized by heightened magnetic structural density, ranging from 0.46 km/km² to 0.61 km/km². Furthermore, a surface structure trending NW-SE intersects the warm spring, possibly mirroring subsurface formations. Notably, surface and subsurface structures intersect directly at the spring's location, indicating potential structural continuities facilitating the upward migration of spring water (Patil, Bhagwat, Sajane, Mulla, & Patil, 2024). The magnetic structure coinciding with the topographic feature is deemed responsible for the fluid's upward migration during the Mesozoic era, concurrent with Nigeria's younger granite series emplacement. Rose diagram trend analysis delineates predominant magnetic structures trending at 38.76% in the NE-SW direction, followed by NNW-SSE at 33.72%, NNE-SSW at 18.22%, and NE-SW at 7.75%. Similarly, surface topographic structural trends depict NNW-SSE as the most prevalent at 38.57%, followed by NW-SE at 34.38%, NNE-SSW at 19.71%, WNW-ESE at 6.38%, and NE-SW at 1.05%.

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