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Discussion on the Curie point depths in south-western Cameroon Volcanic Line derived from aeromagnetic data and their geothermal implications for thermal-springs and hydrocarbon resources

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Abstract:

Magnetic interpretation over the southern Cameroon Volcanic Line revealed the possible existence of a geothermal energy resource. This study extends the analysis of Curie isotherm depth, geothermal gradient, and heat flow using high resolution aeromagnetic data. By applying the centroid method to the aeromagnetic dataset, we obtained insights into geothermal energy resources and tectonic activity of the study area. The results of this investigation revealed that the depth to the Curie isotherm in the studied area is approximately ~16.73 km, which a geothermal gradient of ~33.17 °C.km⁻¹ and a heat flow of ~83 mW.m⁻² derived from the Curie isotherm depth obtained. The shallow Curie isotherm depth may result from tectonic activity associated with the Central African Shear Zone, a significant active fault running through the Cameroon Volcanic Line, coupled with frequent eruptions of Mount Cameroon. Numerous thermo-mineral springs have been discovered in this area, concentrated along the corridor of the Cameroon Volcanic Line, indicating that the shallow Curie isotherm depth may have generated clean geothermal energy by driving hot water upward to the surface through fractured igneous rock. Many hydrocarbon fields are located immediately above this area, and are concentrated within the two most productive basins, suggesting that the high heat flow and geothermal gradient may have played a crucial role in reaching the temperature threshold required for hydrocarbon maturation in sedimentary basins.

Keys words: Southern Cameroon Volcanic Line, Curie point depths, Geothermal gradient, Heat flows, Hydrocarbon and Thermo-mineral springs.

43 1. Introduction

44 The study area, south-western Cameroon is a part of the Cameroon Volcanic Line
 45 (CVL), a long chain of mountains crossing Cameroon from N70°E at Mount Cameroon to
 46 N30°E at Lake Chad (Fitton and Dunlop, 1985). It is bounded to the south by the Atlantic
 47 Ocean, and to the north by the Adamawa massif (Fig. 1). South-western Cameroon region
 48 poses many geological challenges due to the present of Cretaceous to Quaternary sedimentary
 49 rocks associated with elongated sub-basins, which are dominated by low-elevation terrain.
 50 These structures are observed locally in the northern part (Mamfe rift basin), the south-
 51 western part (Rio-Del-Rey coastal basin) and the south-eastern part (Douala-Kribi-Campo
 52 coastal basin). Tertiary to Recent Volcanic rocks associated with the Cameroon Volcanic
 53 Line, dominated by high- elevation terrain, are observed in the central and north-eastern parts
 54 (Fitton and Dunlop 1985; Itiga et al., 2004; Fosso et al., 2005; Déruelle et al., 2007; Moundi
 55 et al., 2007, Tsafack, 2009). Since the juxtaposition of different sediments rock layers and
 56 structures covered by volcanic rocks constitutes a source of hydrocarbons and reservoirs
 57 blocks, no field studies have been carried out in the area to image the morphology of the Pan-
 58 African basement, except for the work of the National Hydrocarbons Corporation (SNH),
 59 which has highlighted many hydrocarbon and petroleum blocks within the two coastal basins.
 60 The most relevant geophysical and hydrogeological field studies carried out in the area
 61 include gravity (Kenfack et al., 2017; Feumoe et al., 2022), magnetic (Noutchogwe et al.,
 62 2010; Ghomsi et al., 2022), seismic (Tokam et al., 2010; Reusch et al., 2010) and
 63 petrographic data (Zangmo et al., 2021; Wembenyui et al., 2020). These field studies have
 64 focused on: (1) identifying brittle crustal basement lineaments and major structural provinces,
 65 (2) estimating both basement and Moho depths, (3) highlighting the geothermal potential of
 66 Cameroon through a review of the literature associated with this energy source (Keutchafo et
 67 al., 2021) and (4) delineating the springs within areas dominated by volcanic rocks that are
 68 frequently associated with the Cameroon Volcanic Line (Le Maréchal, 1976). Additionally,
 69 the presence of a significant active fault namely the Central African Shear Zone (CASZ),
 70 which runs along the Cameroon Volcanic Line, emphasized by springs and an active volcano-
 71 Mount-Cameroon with its frequent eruption, can therefore favor the formation of geothermal
 72 energy potential that could be exploited by the government.

73 Curie point depth (CPD) is the depth at which rocks lose their magnetic mineralogy
 74 and properties under the effect of high temperature, generally set at 580°C (Aboud et al.,
 75 2016; Geng et al., 2023). Estimating the CPD in a specific region is crucial for better
 76 understanding the regional lithospheric tectonic processes and the Earth's thermal structures
 77 (Ben Mather et al., 2018). Additionally, the Curie isotherm depth provides insights into
 78 resources frequently associated with geothermal reservoirs, hydrocarbons and petroleum.
 79 Several techniques can be used to approximate the Curie point depth, including bottom-hole
 80 temperatures associated with well depths (Carrillo-de la Cruz et al., 2020; Geng et al., 2023)
 81 and aeromagnetic data (Feumoe and Ndougsa-Mbarga, 2017; Saibi et al., 2015; Elbarbary et
 82 al., 2022). Thus, the Curie point depth was calculated in this study using the conventional
 83 centroid method. Geothermal gradient and heat flows were derived from the Curie depth
 84 obtained, based on the hypothesis that temperature varies vertically with a constant thermal

gradient, which allow us to improve our understanding of the tectonic activity and frequent eruptions of Mount Cameroon. Additionally, these thermal structures help us to better understand the concentration of springs and the abundant hydrocarbon activity within the two most productive basins. Therefore, this study can serve as a guide for future mining and petroleum exploration. Table: 1 outlines the physical parameters and properties, anomaly sources, and depth of investigation for magnetic methods.

2. Regional geology and geothermal hot springs

Cretaceous to Quaternary sedimentary rocks characterize south-west Cameroon while areas of high relief correspond to terrain where Tertiary to Recent Volcanic rocks are well exposed and are associated with abundant geothermal springs (Fig. 2a, b). The crustal basement is mostly composed of igneous and metamorphic rocks made up of undifferentiated granites and gneisses of Pan-African age, which outline the Central African Shear Zone (CASZ) a significant active fault system that runs along the Cameroon Volcanic Line (Njanko, 1999; Ngako et al., 1991; Van Houten, 1983, Ngounouno et al., 2000, 2003; Fitton, 1980, 1983).

2.1 Cretaceous to Quaternary sediments rocks

Cretaceous to Quaternary sediments rocks in Cameroon primarily consist of a sequence transitioning from marine Maastrichtian-Tertiary shale, limestone, and sandstone to continental Albian sandstones. In the study area, they correspond to thick sedimentary successions in basins formed by tectonic rifting during the break-up of Gondwana.

- *The tectonic rift sedimentary basin*

The Mamfe basin is a WNW-ESE elongated tectonic rift basin intimately associated with the extension of the Lower Benue Trough in Cameroon during the Early Cretaceous (Fairhead and Binks, R M, 1991; Eyong, 2013). The basin is bounded by a granito-gneissic basement of Pan-African age, by the Oban Massif to the south, and by the Obudu Massif to the north, forming a structural trough. It is characterized, on the total magnetic field map, by a positive low magnetic anomaly (crustal thinning) and was influenced by the Cameroon Volcanic Line to the east (Genik et al., 1992). The tectonic evolution of the basin is related to three phases of deformation: (1) an initial rifting phase characterized by extensive basement faulting; (2) a drifting phase associated with growth faults and potential mantle uplift and (3) a later compressional phase dominated by associated volcanism. The stratigraphy map of the basin clearly shows that sedimentary rocks have been identified at several stratigraphic levels, including Albian-Cenomanian lacustrine/continental deposits. The depositional setting is characterized as an intra-continental rift basin filled with Cretaceous sediments such as conglomerates, sandstones, limestones and shales with thicknesses exceeding 4.5 km, which were subjected to a very low-grade metamorphism (Moreau et al., 1987).

- *The Coastal sedimentary basins*

The study area contains two main producing coastal basins along the Atlantic margin, separated by the Cameroon Volcanic Line.

The Rio-Del-Rey basin is a NE-SW trending producing basin closely associated with the extension of the Niger-Delta into Cameroon (Ntamak-Nida et al., 2010). The basin is bounded by Pan-African -age Precambrian basement, by the Niger-Delta to the west, and by Mount Cameroon to the east, forming a structural trough. It is characterized on the total magnetic field map by a positive high magnetic anomaly (crustal thinning) and was influenced by the Cameroon Volcanic Line along its eastern margin. The tectonic evolution, which began in the Late Jurassic and continued through Early Cretaceous (Ntamak-Nida et al., 2010) is characterized by three phases of deformation including: (1) a syn-rifting sequence consisting of thick, faulted continental, fluvial and lacustrine deposits associated with structurally controlled graben-fill sediments, (2) a rift-drift transition phase separating the early rift stage from the later drift stage, marked by major tectonic realignment and (3) a post-rift phase dominated by marine, thick deltaic, and progradational sediments. The depositional setting is dominated by thick Tertiary deltaic deposits exceeding 6.0 km in thickness.

Douala-Kribi-Campo basin is an NNW-SSE trending coastal producing basin formed during the opening of the south Atlantic Ocean. Its structure comprises two sub-basins bounded by Precambrian basement (Nguene et al., 1992, Secke et al., 2024). It is characterized on the total magnetic field map by a positive high magnetic anomaly (crustal thinning) superimposed with a negative low anomaly (sediment-filled areas). Its tectonic evolution follows a rift-to-drift sequence, beginning with Neocomian-Turonian syn-rift faulting (producing horst, and graben structures) followed by Albian-age drifting and marine incursion, which developed facies such as conglomerates, sandstones and claystones (Ngon et al., 2019).

2.2 Tertiary to Recent Volcanic rocks

Tertiary to Recent Volcanic rock in the study area are associated with a large 1600 km line of alkaline magmatism, driven by mantle plumes and lithospheric fractures along the Cameroon Volcanic Line (Fitton and Dunlop, 1985; Nkoumbou et al., 1995). Built on the Pan-African basement and cut by the Central African Shear Zone, a significant active fault, the volcanic rocks observed are generally basaltic to trachytic and phonolitic, including alkaline mafic lavas associated with Cenozoic volcanism. This line is characterized by a large negative, low-magnetic anomaly with long wavelengths on the total magnetic field map, striking and striking approximately SW-NE from Mount Cameroon to the Adamawa plateau, and approximately WSW-ENE from the Adamawa plateau to Lake Chad.

2.3 Geothermal springs

Numerous thermal springs with temperature ranging between 23°C and 74°C, were identified in Cameroon by Le Maréchal (1976), most of which are located within the Tertiary to Recent Volcanic rock of the Cameroon Volcanic Line (Fig. 3). This is probably due to the presence of a major active fault, the Central African Shear Zone (CASZ) which runs along the Cameroon Volcanic Line and is associated with the frequent eruptions of Mount Cameroon, acting as a source of geothermal energy potential. Regions with geothermal hot springs in the

study area are characterized by low-intensity, long-wavelengths anomalies on the total field map, reinforcing the hypothesis that these magnetic bodies have higher magnetic susceptibility than the granite-gneissic basement formations, since sources with high positive magnetic susceptibility at low-latitude regions typically produce low-intensity of anomalies on the total magnetic field anomaly map (Ojo, 1990 ; Amigun et al., 2015; Faruwa et al., 2021).

2.4 Hydrocarbons resources

In the study area, source rocks have been identified at several stratigraphic levels within the two main producing coastal basins in the southern part. All the oil originates from source rocks deposited in a marine environment.

Hydrocarbon-rich have been encountered at nearly every stratigraphic level, from the Miocene down to the Aptian- Abian. The Pan-African basement is covered by 4.5~6.0 km of thick sedimentary rocks (Anudu et al., 2020), and none of the boreholes have reached the basement (Secke et al., 2024).

3. Aeromagnetic anomalies and Transformed maps

3.1. Geomagnetic field

The total magnetic anomaly in geophysical prospecting represents the sum of the effects of all magnetic bodies within the crust, independently of the intensity and direction of magnetization (Maus, 2005; Wang and Li., 2018), which are related to the geomagnetic field intensity. The geomagnetic field intensity, or IGRF, is the negative gradient of the magnetic scalar potential, frequently expressed in spherical coordinates as follows (Langel and Hinze, 1998):

$$y(r, \theta) = - \frac{M \cos \theta}{4\pi r^2} \quad (1)$$

where r is the distance to the point of interest, θ is the angle between the vector magnetic moment and the position vector, and M is referred to as the magnitude of the magnetic moment. The vector components of the geomagnetic field, or IGRF, can be obtained as follows (Wang and Li., 2018):

$$\begin{aligned} H &= - \frac{\partial y(r, \theta)}{r \partial \theta} = \frac{M \sin \theta}{4\pi r^3} \\ Z &= - \frac{\partial y(r, \theta)}{\partial r} = \frac{2M \cos \theta}{4\pi r^3} \end{aligned} \quad (2)$$

where H is the horizontal component of the geomagnetic field vector, directed along x toward magnetic north and along y toward magnetic east. Z is the vertical component, directed along z , downward along the vertical axis. Consequently, the intensity of the geomagnetic field (IGRF) is derived as follows:

$$IGRF = (H^2 + Z^2)^{\frac{1}{2}} = \frac{M}{4\pi r^3} (1 + \cos^2\theta)^{\frac{1}{2}} \quad (3)$$

The total magnetic anomaly intensity, frequently used in applied geophysics, can be obtained by subtracting the geomagnetic field (IGRF) from the magnetic field measured at the point of interest.

3.2. Aeromagnetic data

The total magnetic anomaly intensity datasets used in this study were obtained from the UK Geophysical Society, GETECH Group Plc. The airborne magnetic data were acquired between 1970 and 1981 by five different organizations, with specifications summarized in table 2. Corrections were made to the airborne datasets by their respective contractors, to reduce effects that affect the data, including temporal variation of the geomagnetic field (IGRF), instrumental malfunctions, diurnal variation and levelling problems. All grids of values were combined into a single anomaly grid for the study area before subtracting the IGRF-1983, to produce the requisite TMI (Total Magnetic Intensity) anomaly grid. The UK Geophysical society GETECH Group Plc upward- continued this single grid of data to a height of 1.0 km before the aeromagnetic dataset was re-gridded at a cell size of 1.1 km.

The IGRF calculator was used to compute the large-scale geomagnetic field for the years 1983 and 2026 (Fig. 4a, b). By comparing the statistical histograms of IGRF-1983 and IGRF-2026 (Table. 3), we observed that only the orientation of the IGRF has rotated, from approximately NW-SE to WNW-ESE, without significant variation in geometry and intensity of anomalies. This suggests perfect induction. Most crustal anomalies originate from the remanent magnetization of the rocks that make up the Earth's crust. These rocks recorded the direction and intensity of the Earth's magnetic field at the precise moment of their cooling. Apart from the corrections carried out by their contractors in 1983 to reduce effects that affect the data, no further corrections have been made by the authors, since the data collected from 1970 to 1981 spanning various years without significant geological change, as verified by the IGRF maps.

3.3. Aeromagnetic anomaly and analysis

We compare the total magnetic intensity (TMI) map in Fig. 5a with the magnetic anomalies reduced to the equator (TMI-RTE) in Fig. 5b to highlight the direct link between magnetic anomaly and their sources. The TMI-RTE map (Fig. 5b) shows significant changes in both the positions and the amplitudes of anomalies compared to those observed on the TMI map (Fig. 4a). On this map (Fig. 5b), we observed similarity with the geological map (Fig. 2a, b). Over the Tertiary to Recent volcanic rocks in the central and north-eastern parts of the study area, the anomaly intensity is low, with amplitudes reaching up to -250 nT. Originating from the Cenozoic volcanism of the Cameroon Volcanic Line, these rocks were emplaced onto the Pan-African basement and the Central African Shear Zone, with an approximately SW-NE orientation. Over the Cretaceous to Quaternary sediments rocks in the northern, southern and western parts of the study area, the anomaly intensity is moderate, with

amplitudes ranging between -50 to 05 nT originating from the undifferentiated granite-gneissic crustal basement.

3.4. Gradient maps and analysis

The TMI-RTE map (Fig. 6a) was used as input data for the gradient calculations. The gradient maps (Figs. 6b-d) show significant variation in gradient amplitude, geometry and trend of geological features such as folds, faults, and other deformation structures in the lithosphere, with a preponderance of orientations including SW-NE; SE-NW; WSW-ENE; ESE-WNW and E-W. This variation in geometry and trend reflects the orientation of the regional stresses that prevailed across the region throughout its geological evolution, from the Early Cretaceous to the Present. A system of short-wavelength negative low (dark blue) anomalies (-200 nT/km), rimmed by high-positive anomalies (~100 nT/km), is clearly visible in the central and north-eastern parts of the study area, coinciding with regions of low-intensity of anomaly (Fig. 5b). Geologically, these high gradients coincide with regions of geothermal hot springs associated with Tertiary-to-Recent volcanic rocks. This correlates well with the presence of high magnetic susceptibility, associated with Tertiary to Recent magnetic rocks, which drive hot water upward from fractured igneous rocks to the Earth's surface (Le Maréchal, 1976). A system of short-wavelength, low negative (dark green) anomalies (-08 nT/km), rimmed by low-positive anomalies (~10 nT/km), is clearly visible in the western, the northern and south-eastern parts of the study area, coinciding with regions of hydrocarbon activity. This correlates well with the presence of thick layers (~6 km) of Cretaceous-to-Quaternary sedimentary rocks overlying the undifferentiated granite-gneissic basement. The crustal basement of the study area consists of an assemblage of magmatic and metamorphic rocks which high thermal conductivity, overlain by Tertiary-to-Recent volcanic and Cretaceous to Quaternary sediments rocks. Analysis of the gradient maps (Figs. 6b-d) reveals that the undifferentiated granite-gneissic basement corresponds to highs.

3.3. Upward continuation maps and analysis

This is the calculation of the potential field at an elevation higher than that at which the total field is measured, and it is applied to both magnetic and gravity data. It is a mathematical projection of the magnetic field that reveals magnetic sources deeper than half of the upward continuation height (Jacobsen, 1987). Upward continuation smooths out near surface effects and highlights the signature of deep magnetic anomalies. This filter was applied to the TMI-RTE anomaly map (Fig. 5b) at heights of 1 km, 2 km, 3 km, and 4km.

The 1 km and 2 km upward continued magnetic maps (Figs. 7a, b) images magnetic sources below 0.5 and 1 km respectively and clearly reveal disappearance of the short-wavelength magnetic anomaly that cross-cut the large, negative, low-magnetic anomalies of SW-NE orientation observed on the TMI-RTE map (Fig. 5b). These anomalies merge with the negative lows observed at 3 km (Fig. 7c) and disappeared entirely on the 4 km upward-continued map (Fig. 7d), which images magnetic sources at depths below 2 km. This result clearly shows that the magnetic anomaly observed on the total-field maps originate mainly within the Pan-African basement and within the Tertiary-to --Recent volcanic rocks that overlie it.

4. Methodology

4.1. Conventional centroid method

Many researchers use the 2D Fourier transform of magnetic anomaly to estimate the depths of magnetic sources, the so-called Curie isotherm depths. Curie point depth (CPD) is the depth at which rocks lose their magnetic mineralogy, composition, and properties under the effect of high temperature generally set at 580°C (Feumoe and Ndougsa-Mbarga, 2017; Wang and Li, 2018; Geng et al., 2023), which is crucial for a better understanding the regional lithospheric tectonic process, and the Earth's thermal structures (Ben Mather et al., 2018). The Curie isotherm depth also highlights insights into resources frequently associated with geothermal reservoirs, hydrocarbons and petroleum. This technique is based on the analysis of the power spectrum energy of the magnetic dataset (Dolmaz et al., 2005; Feumoe and Ndougsa-Mbarga, 2017; Wang and Li, 2018; Geng et al., 2023). The decay of the power spectrum energy provides information about the depths of deep and shallow magnetic sources. The depths of the deep magnetic source (Z_0) can be related to the power energy by the following formula:

$$\text{Ln} \left\{ \left[P(|k|) \right]^{\frac{1}{2}} / k \right\} = \text{Ln}(A) - 2\pi |k| Z_0 \quad (5)$$

where A is a constant and k the wavenumber. The slope of the part of the curve generated by Eq (5) at low wavenumber can be used to obtain the depth to the centroid Z_0 , associated with signals from deep magnetic sources. The depths to the top (Z_t) of magnetic sources is derived from the slope of the part of the curve at low to intermediate wavenumbers, generated by Eq (6) below:

$$\text{Ln} \left\{ \left[P(|k|) \right]^{\frac{1}{2}} \right\} = \text{Ln}(B) - 2\pi |k| Z_t \quad (6)$$

Knowing both the centroid depth (Z_0) and top depth (Z_t) derived from the slope of the power spectrum, the Curie point depth (Z_b) can be estimated as follows (Geng et al., 2023):

$$Z_b = 2Z_0 - Z_t \quad (7)$$

The uncertainty in the Curie point depths can be expressed using the following formula (Martos et al., 2017):

$$\Delta Z_b = \sqrt{4\Delta Z_0^2 - \Delta Z_t^2} \quad (8)$$

where ΔZ_b , ΔZ_0 , and ΔZ_t are the uncertainties associated with Z_b , Z_0 , and Z_t , respectively. ΔZ_0 and ΔZ_t can be estimated using the following equation (Okubo and Matsunaga, 1994):

$$\Delta Z = \frac{\sigma}{2\pi(k_2 - k_1)} \quad (9)$$

where σ is the standard deviation, and k_1 and k_2 are respectively the lower and upper wavenumber limit where the depth Z_0 and Z_t are, respectively, the lower and upper wavenumber limits used to derive the depths Z_0 and Z_t by linear fitting.

4.2. Heat flow and thermal gradient estimation

The Curie isotherm is defined as the temperature at which rocks lose their magnetic properties. To relate this temperature to the Curie isotherm depth, several authors (Stampolidis et al., 2005; Maden, 2010) have obtained satisfactory results in various regions by assuming a direct relationship between the Curie point depth and the Curie isotherm along the vertical direction only. The geothermal gradient can then be expressed as follows:

$$\frac{dT}{dz} = \frac{T_c - T_0}{Z_b} \quad (10)$$

where T_c and T_0 are the Curie temperature and Earth's surface temperature, which were set at 580°C and 25°C, respectively. For this reason, the geothermal gradient can be directly related to the heat flow q as follows:

$$q = \lambda \frac{dT}{dz} = \lambda \frac{T_c - T_0}{Z_b} \quad (11)$$

where λ is thermal conductivity constant. From Eq. (11), we clearly observe that the CPDs are inversely proportional to heat flow.

4.3. Implementation of the centroid method

The Centroid methodology assumes that the window size used to calculate the Curie point depth must be directly proportional to, and five times, the depth of the deepest magnetic source in the study area (Bouligand et al., 2009; Salem et al., 2014). Assuming that the surface-to-Curie-isotherm depths are generally less than the crustal depths over the southern Cameroon Volcanic Line, which vary between 28-30 km beneath Mount Cameroon in the south-western part, are set at about 25 km beneath the Kumba graben and Mamfe rift tectonic basin in the north, and range between 33~36 km beneath the highlands in the east (Tokam et al., 2010). The study area's coverage 20,000 km², and the 25 to 36 km crustal base evaluated area by (Tokam et al., 2010) suggest that our spatial window needs to be 100 to 200 km wide to properly capture the required low wavenumber. The compromise window size chosen for the CPD calculation was therefore set at 150 km x 150 km, close to the dimensions of the entire study region (100 km x 200 km). This allows us to investigate magnetic sources effects at depths of around ~30 km in the study area, which correlates well with the hypothesis that the Moho depths (25~36 km) are deeper than the Curie point depths in south-west Cameroon.

The TMI-RTE magnetic anomaly data (Fig. 5b) were used as input dataset calculating the Curie isotherm depth. To highlight the effects of the deepest regional magnetic anomaly, which is suitable for estimating the Curie point depth, we first calculated the azimuthally averaged logarithmic power spectrum energy of the TMI-RTE dataset (Fig. 8a), where the vertical dotted line indicates the lower limit of the low-pass filter ~3.9 km⁻¹ associated with

the effects of all magnetized bodies with short and long wavelengths in the crust. This could affect the centroid estimation. Many authors have shown that wavelengths longer than 10 km are reasonable for estimating the CPD (Trifonova et al., 2009; Manea, 2011; Andrés et al., 2018; Yaro et al., 2023; Meng et al., 2026). To generate the anomaly grid required for Curie point depths estimation (Nigussie et al., 2023), a band-pass filter (10~65 km) was applied to the original dataset in Fig. 8a, where the blue box represents the lower and upper limits of the filter's amplitude response. This allows for the isolation and processing of specific noise and interference. Fig. 8b shows the 2-D Fourier transform analysis after applying the band-pass filter for the Curie isotherm depth calculation. The lower limit of the low-pass filter becomes approximately $\sim 2.26 \text{ km}^{-1}$, which is 1.5 times shallower than the value before filtering ($\sim 3.9 \text{ km}^{-1}$).

5. Results

5.1 Band-pass filtering maps and analysis

These filtering maps (Fig. 9a, b) show only the effects of magnetism associated with deep-seated magnetic sources, corresponding to wavelengths between ~ 10 and ~ 65 km and wavenumbers between 0.09 and 0.63 rad.km^{-1} . This map (Fig. 9a) reveals a positive magnetic anomaly response with sub-circular shapes, trending north-east, occurring in the central part over the Tertiary-to-Recent volcanic rocks. These positive magnetic anomalies might be caused by a deeper crustal magnetic body within the brittle basement. Magnetic minima are observed south-west of Mount Cameroon, south-east of the northern termination of the Douala basin, north-east of tectonic Mamfe rift basin, west of the Rumpi-Hills and north of the coastal Rio del Rey basin. These low-magnetic anomalies coincide with transitional zones between sedimentary and volcanic rocks and may be related to high susceptibility. Fig. 9b shows the magnetic anomaly map with unwanted frequencies removed (below the low cut-off $\sim 0.09 \text{ rad.km}^{-1}$ and above the high cut-off $\sim 0.63 \text{ rad.km}^{-1}$).

5.2 Curie isotherm depth and analysis

Fig. 10a and Fig. 10b show the results of the 2D Fourier analysis obtained after applied the centroid method to the magnetic data of south-western Cameroon (Fig. 8b). Using a straight line over the wavenumber range 0.09 and 0.2 rad/km , the centroid depth was estimated at 08.89 km (Fig. 10a), while a straight-line over the wavenumber range 0.2 and 0.6 rad/km gave a depth to the top of the magnetic source of about 1.05 km (Fig. 10b). From the centroid depth of 08.89 km and the depth to the top of 1.05 km, the CPD was calculated at 16.73 km for the study area using the centroid method with a band-pass filter, by means of Eq. (7). However, this value appears shallow given the crustal thickness of the study area determined in previous studies (Adams, 2022; Fantah et al., 2024; Ngu and Njinju, 2026). Thus, the Curie point depth beneath south-west Cameroon is estimated at approximately ~ 16.73 km below ground level, which allows the southern Cameroon Volcanic Line to be characterized as an area of shallow Curie point depth. An uncertainty of approximately ~ 3.07 km was obtained, representing an error of around $\sim 3\%$ of the calculated Curie isotherm depth of ~ 16.73 km.

5.3 Geothermal gradient and heat flows analysis

The geothermal gradient and heat flow of the study area were estimated using the derived Curie point depth, through Eqs. (10) and (11), respectively. The results show a geothermal gradient of approximately $\sim 33.2\text{ }^{\circ}\text{C.km}^{-1}$ and, using a constant thermal conductivity of $\sim 2.5\text{ mWm}^{-1}\text{ }^{\circ}\text{C}^{-1}$ for the metamorphic rocks of southern Cameroon, Feumoe and Ndougsa-Mbarga, the heat flow was approximated at $\sim 83.0\text{ mW.m}^{-2}$ (Table. 4). This result indicates that, south-western Cameroon exhibits a higher geothermal gradient and heat flows than typical continental crust values of $\sim 25\text{ }^{\circ}\text{C.km}^{-1}$ and $\sim 64.7\text{ mW.m}^{-2}$, respectively (Wolfson, 2011; Davies, 2013). This suggests that the southern Cameroon region is a tectonically unstable part of the sub-continent. These results correlate well with the presence of a major active fault, the Central African Sear Zone (CASZ), and with the frequent eruptions of Mount Cameroon.

6. Discussion of the results

6.1 Factors affecting the Curie point depth

Many factors can influence the obtained Curie point depth including, surface heat flow, tectonic activity, magmatic and volcanic intrusion, and crustal composition and mineralogy, or a combination of all these factors. To correlate the Curie isotherm depth with tectonic activity in the southern Cameroon region, we compare the Curie isotherm depth with Moho depths, gradient maps and hot spring temperature.

6.1.1 Moho depths

Table 5 shows the Moho depths obtained by Tokam et al., 2010 over the south-western Cameroon region using seismics data. The results clearly show that Moho depths vary between 25 and 36 km across the study area, with a mean of 32 km. The central and south-eastern parts exhibit shallow Moho depths of 25-30 km, reaching depths of 30-36 km in the north, south-west and south-east within the elongated sedimentary basins. Over the study area, the Curie point depth is 8-20 shallower than the Moho depths. The shallow Moho depth. This shallow Moho depth implies that the hot upper mantle is closer to the surface, resulting in a steep geothermal gradient.

6.1.2 Tectonic activities

The tectonic structures characterizing the study area consist of three main sedimentary basins filled with 4-6 km of Cretaceous to Quaternary sedimentary rocks, which were influenced by the Tertiary to Recent volcanic rocks of the Cameroon Volcanic Line. The Pan-African basement is mainly composed of terranes made up of crystalline granite-gneiss, consisting of undifferentiated granites and gneisses. The gradient maps show significant variation in gradient amplitude, geometry, and trends of geological features such as folds, faults, and other deformation structures in the lithosphere, with a predominance of orientations including SW-NE; SE-NW; WSW-ENE; ESE-WNW and E-W. These variations reflect the orientation of the regional stresses that affected the region throughout its geological

evolution, from the Early Cretaceous to the Present. These maps (Figs. 6b-d) reveal magmatic centers associated with the frequent eruptions of Mount Cameroon, while the Pan-African basement shows highs associated with active faulting, notably the Central African Shear Zone, which pushes the Curie point depth closer the surface.

6.2 Thermal springs

Temperature measurements from hot thermal springs (Table 6), where discharged water flows up to the surface, range from 25 to 28°C (Le Maréchal, 1976). These elevated temperatures result from groundwater heated by shallow magma bodies, which push the Curie isotherm closer to the surface.

6.3 Geothermal implications

6.3.1 Thermal spring

Many thermo-mineral springs have been identified in the study area and are concentrated within the Tertiary to Recent volcanic rocks (see Table 6). For example, Abang, Ahio-Ekanjo, Ayukaba, Bare-1, Bare-2, and Ebuku (Le Maréchal, 1976) are springs concentrated immediately above or on the margins of localities with magmatic centers, indicating that high thermal structures associated with a shallow Curie point depth could have generated clean geothermal energy through hot water circulating in fractured igneous rocks, mainly composed of basaltic to trachytic and phonolitic alkaline lavas characterized by higher thermal conductivities at shallow depth.

6.3.2 Hydrocarbons resources

Many hydrocarbon fields have been discovered in the study area and are concentrated within the most productive basins (Secke et al., 2024). For example, Bomono, Etinde-Exploitation, Kombe-Nsepe, Tilapia, Ntem and Elombo hydrocarbon fields, located within the coastal Douala-Kribi-Campo sedimentary basin and the Ndian, Bakassi and Bolongo fields, located within the coastal Rio-Del-Rey sedimentary basin, are concentrated immediately above or on the margins of areas where the basement exhibits highs. This indicates that the high heat flow and high geothermal gradient associated with the shallow Curie point depth have caused the over maturation of source rocks.

7. Conclusion

The centroid method was used to estimate the Curie isotherm depths of southern Cameroon. The thermal structure was the derived from these Curie isotherm depths. Careful analysis of the filtered aeromagnetic anomaly data allowed us to draw the following conclusions:

- The depth to the bottom of the magnetic layer is about ~16.73 km in the study area. The geothermal gradients and heat flow associated with this depth are approximately ~33.2 °C.km⁻¹ and ~83 mW.m⁻², respectively.

- The shallow Curie isotherm depth obtained may result from (i) tectonic activity related to the Central African Shear Zone, a major active faulting running along the Cameroon Volcanic Line, coupled with frequent eruptions of Mount Cameroon in the central part. Numerous thermo-mineral springs occur directly above this area, suggesting that the shallow Curie isotherm depth could support clean geothermal power generation from hot water produced in fractured igneous rock, as these zones coincide with shallow Moho depths of 25-30 km, and (ii) the mineralogical composition of the undifferentiated granite-gneiss basement, with higher thermal conductivity. These rocks transmit heat away from the mantle more efficiently, shifting the depth at which Curie isotherm occurs.
- The results indicate a potential geothermal resource in the study area, as the basement exhibits high geothermal gradient and high heat flow. Furthermore, numerous hydrocarbon fields and thermal springs are located within this area, suggesting that the shallow Curie depth may have implication, as well as for the generation of clean geothermal power through is thought the upward flow of hot water to the surface, a source that could be exploited by the government.

- **Credit authorship contribution statement**

Alain Narcisse S. FEUMOE: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Evariste NGATCHOU:** Software, Validation, Writing – review & editing. **Parfait N. ELOUMALA:** Formal analysis, Resources, Supervision, Writing – review & editing. **Marcelin P. MOUZONG:** Writing – review & editing. **Armel C. FANTAH:** Data curation.

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- **Data availability statement**

Data will be made available on request. For requesting data, please write to the corresponding author.

- **Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

- **Ethics approval**

Not applicable.

- **Consent to participate**

Not applicable.

- **Consent for publication**

All the authors agree to the submission and publication of the paper.

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FIGURE CAPTION

Fig. 1. Simplified geological map of the study area. Volcanic areas that are part of the CVL are shown in black.

Fig. 2. (a) Topography and (b) geology maps of Southern Cameroon. In (a), red contour lines are Cenozoic Cameroon Volcanic Lines and white circles are recent seismic events with their respective magnitudes. The point sets of thermal spring values over the volcanic area are represented by colored circles. In (b), the location of thermal springs, volcanoes and faults are highlighted as well as the sediment covers.

Fig. 3. Presentation of some major thermal springs of the Cameroon Volcanic Line.

Fig. 4. Large scale geomagnetic field (a) at the date of 1983 and (b). at the date of 1926.

Fig. 5. (a) Total magnetic intensity (TMI) and (b) differential reduction-to-equator (DRTE) map of the southern Cameroon Volcanic Line. The black lines indicate the ground boundary.

Fig. 6. (a) Total-field magnetic anomalies reduced to the equator; (b)-(d) are the ΔX , ΔY and ΔZ gradient of the vector magnetic anomalies maps. The altitude of the magnetic anomalies for (a)-(d) is 1 km.

Fig. 7. Total-field magnetic anomalies reduced to the equator calculated at the altitudes of (a) 1 km; (b) 2 km; (c) 3 km and (d) 4 km.

Fig. 8 Azimuthally averaged logarithm power spectrum energy (a): of the total magnetic anomaly reduced to east magnetic equator. The vertical dotted line shows the lower limit of low pass filter. The box represents the band-pass filter amplitude response. The response function of the band-pass filter is also shown (b): of the total magnetic anomaly reduced to east magnetic equator after applying the band-pass filter.

Fig. 9. (a): The band-pass full pass 10~65 km ($0.09 \sim 0.63 \text{ km}^{-1}$) filtered map used for the calculation of Curie Point Depth and (b): Unwanted frequencies map. These maps were obtained by assuming 10 and 65 km for long and short wavelengths.

Fig. 10. Power spectrum for estimation of the CPD using the two-dimensional magnetic anomaly data of the area of (100 x 200 km²). **08.89(a)** and **1.05(b)** km are obtained as the centroid and the top bound using the gradient of spectra defined as $\ln(P^{1/2}/|s|)$ and $\ln(P^{1/2})$, where $|s|$ is the wavenumber and $P(s)$ is the radially averaged power spectrum energy.

Table 1: Summary of magnetic methods and their characteristics applicable to exploration and geoenvironmental studies.

Table 2: Survey details parameters used in magnetic surveys.

Table 3: Statistical analysis of IGRF-1983 and IGRF-2026.

Table 4: Curie depths, heat flow and geothermal gradient estimation from the total field magnetic data.

Table 5: Summary of crustal structure by geological terrains.

Table 6: Location of the thermo-mineral springs.

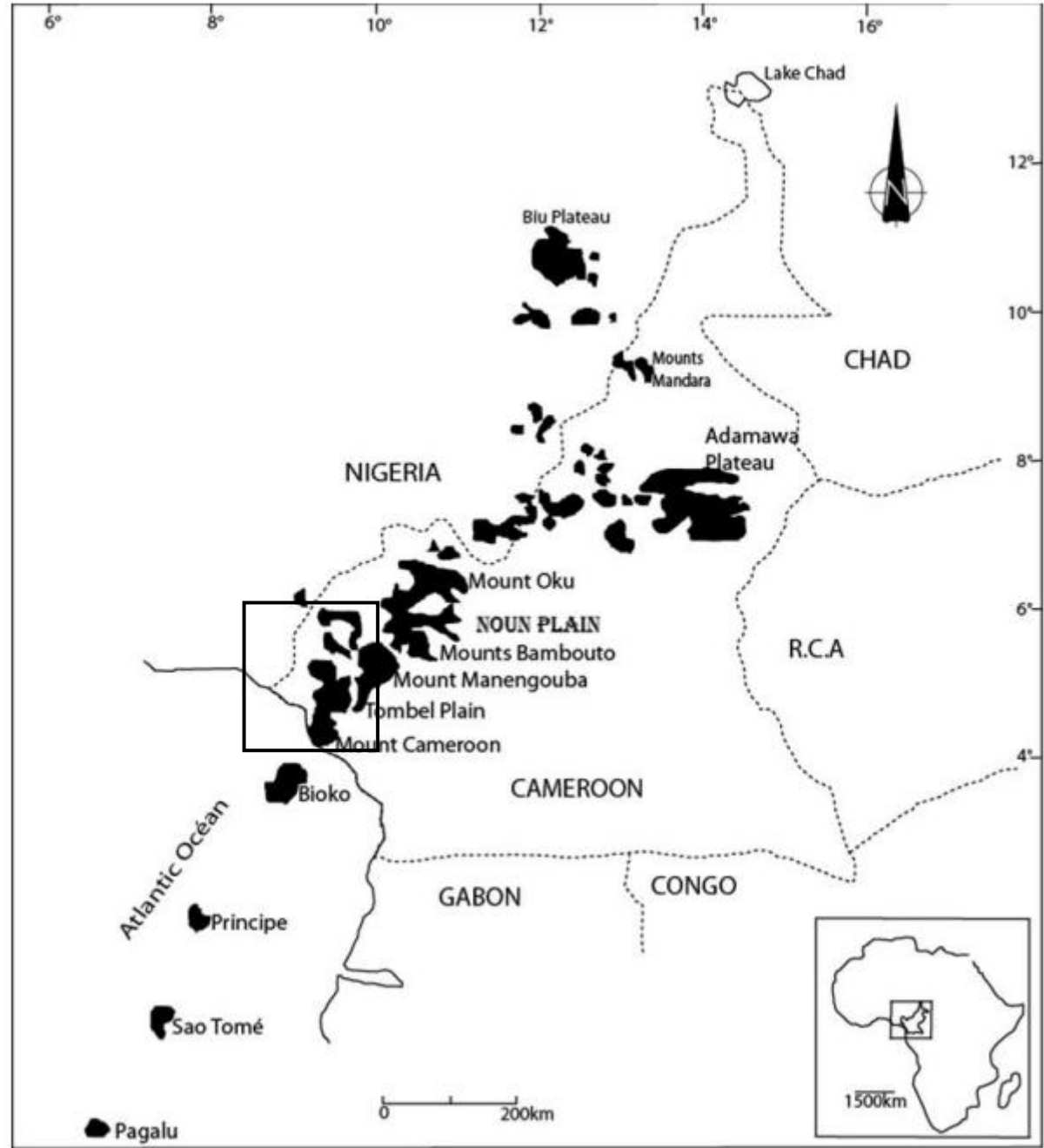


Fig. 1

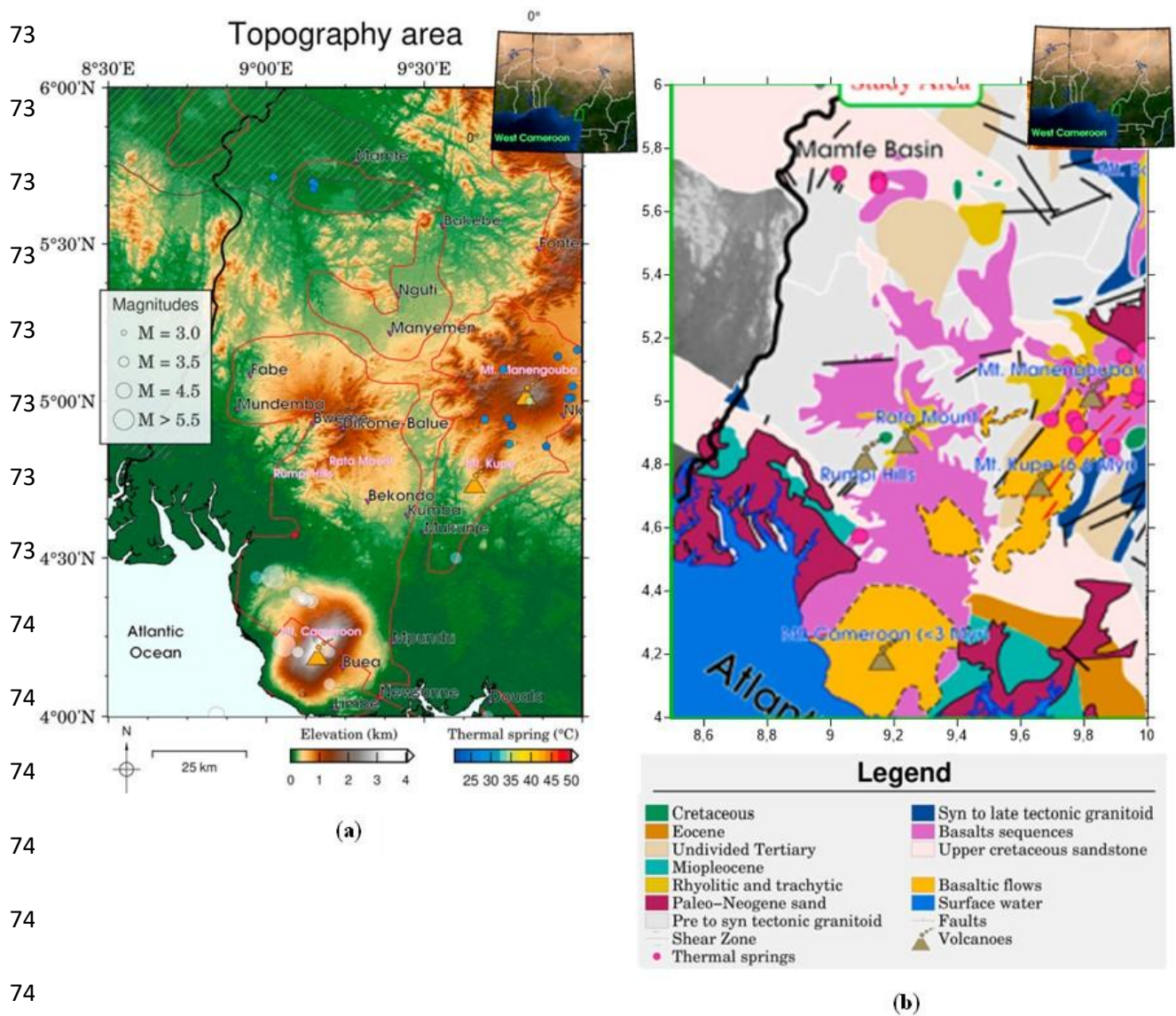


Fig. 2

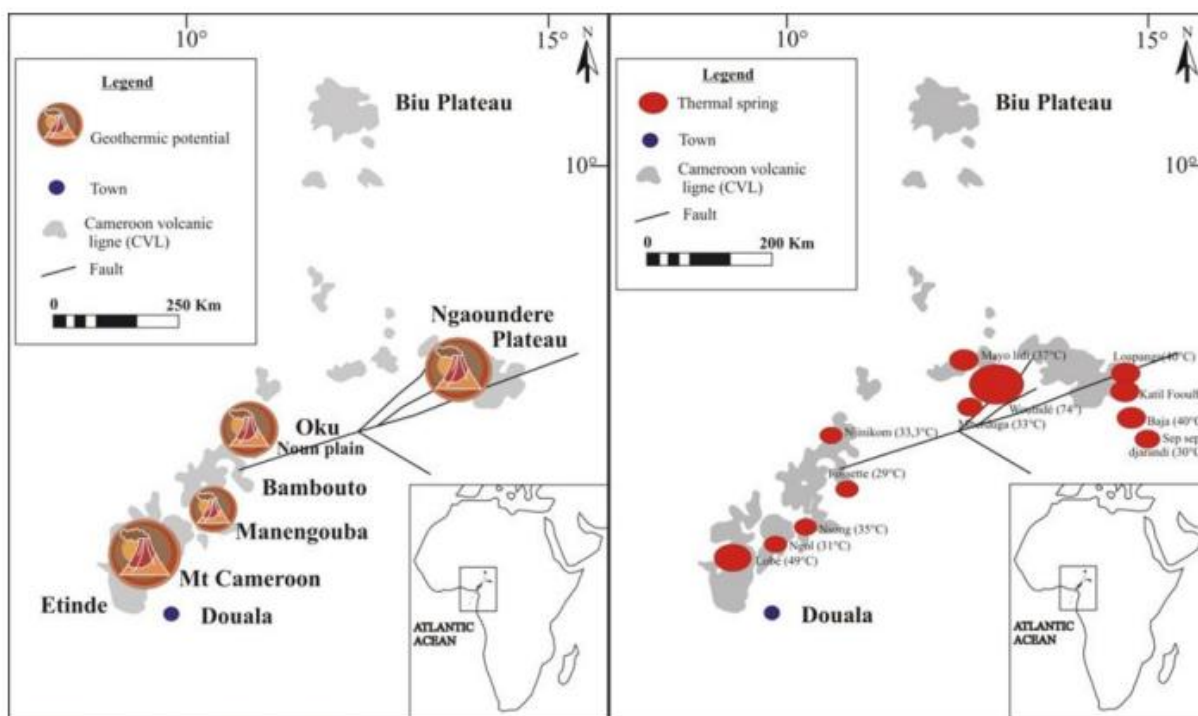


Fig. 3

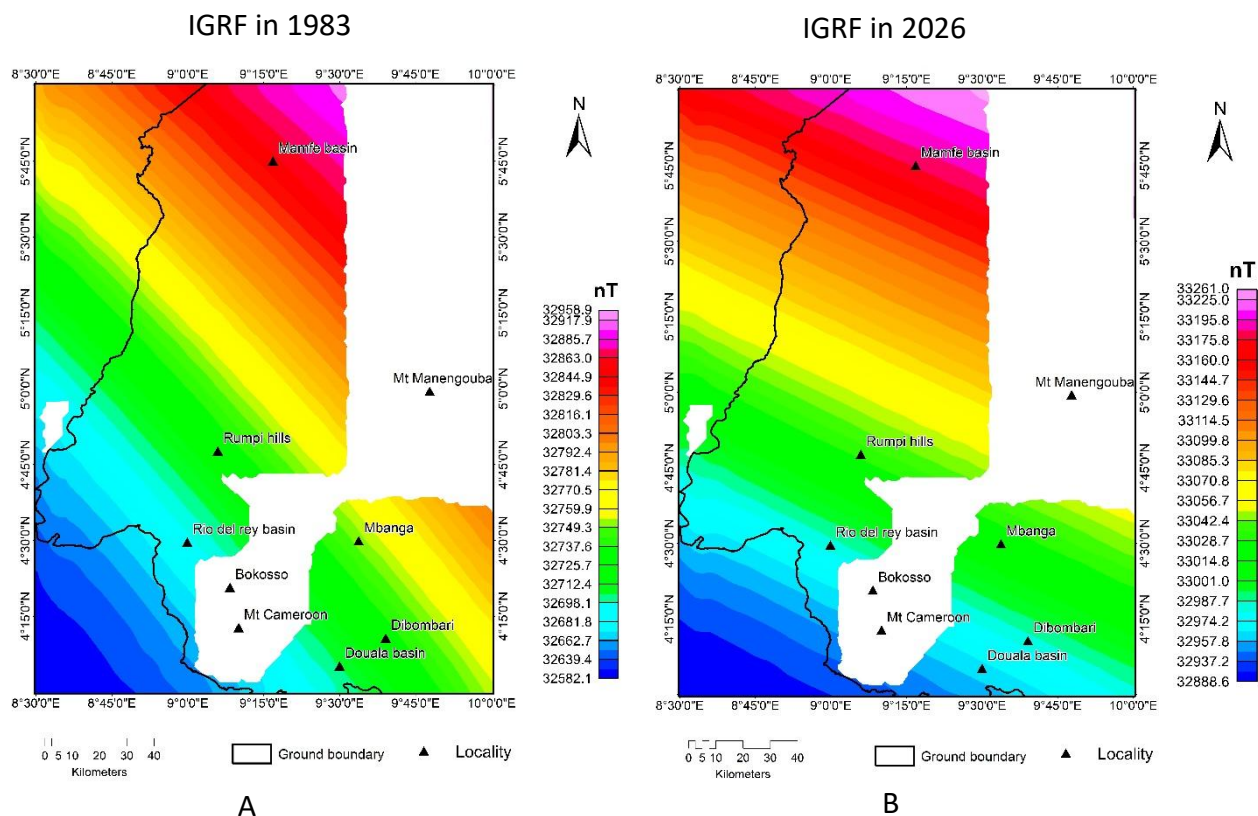


Fig. 4

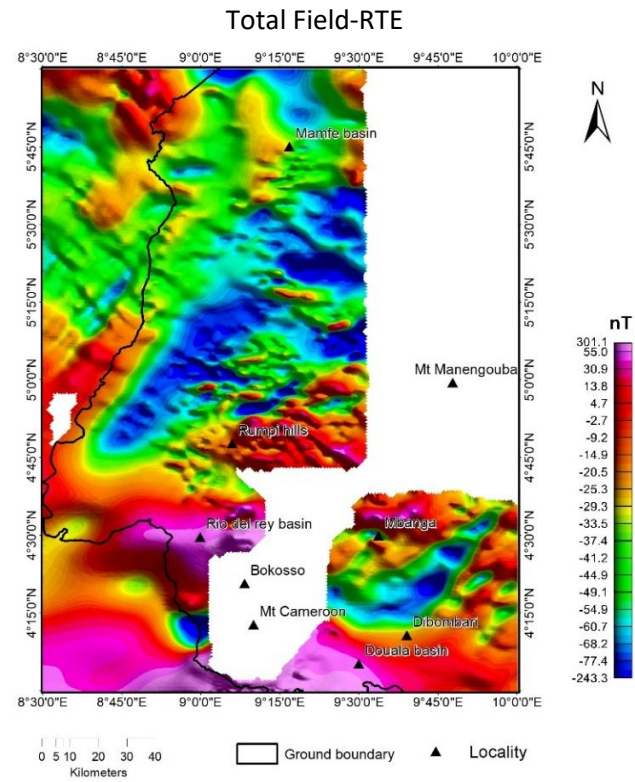
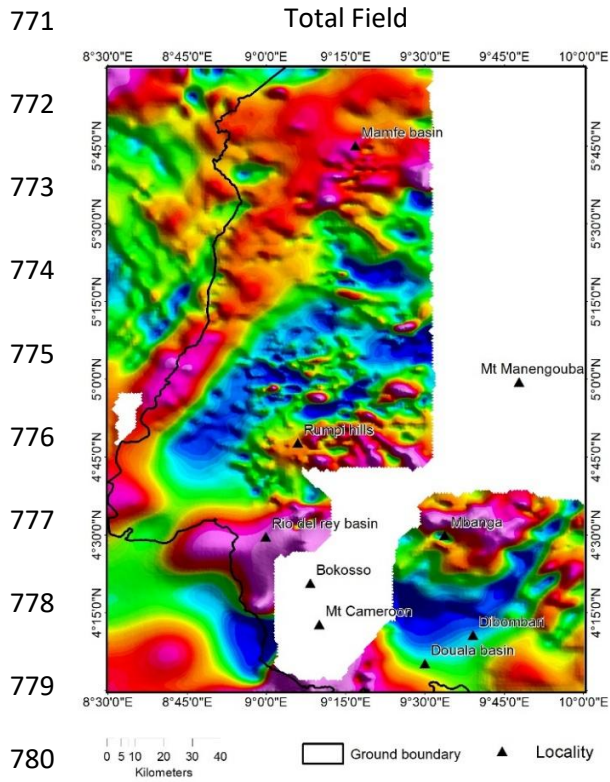
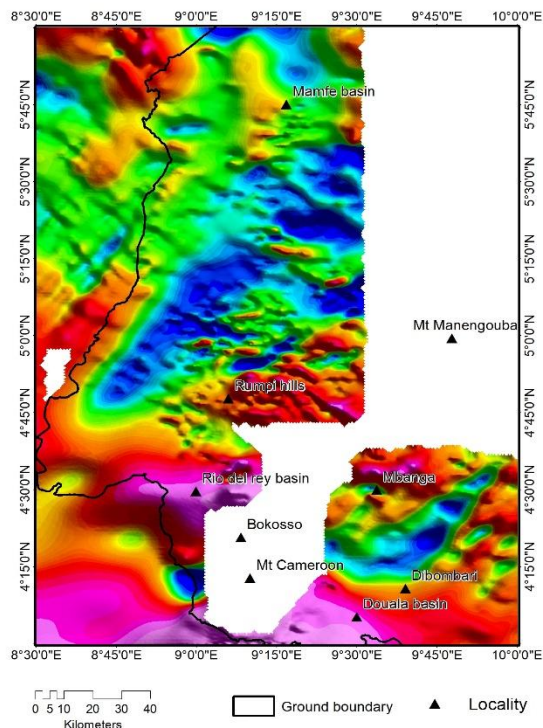


Fig. 5

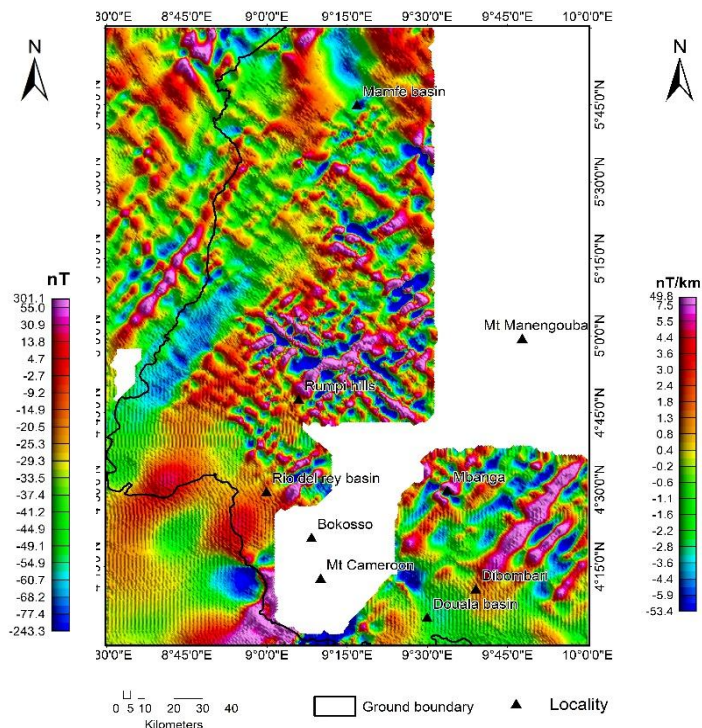
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Total Field-RTE



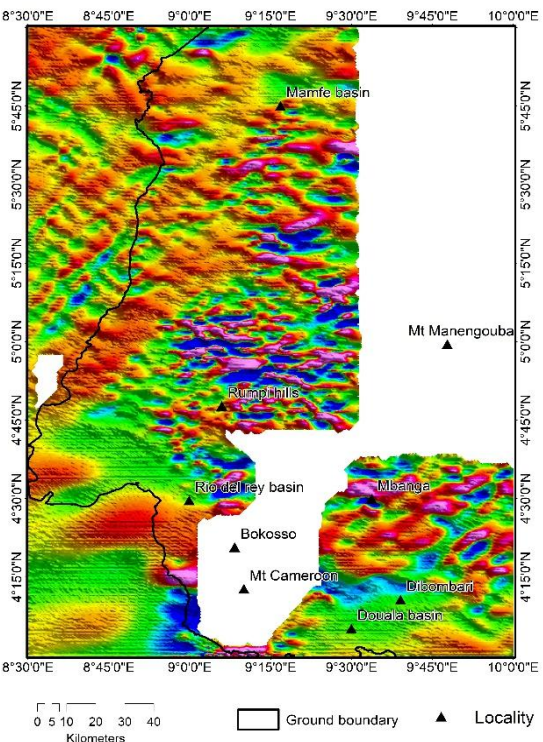
A

F_x (North)



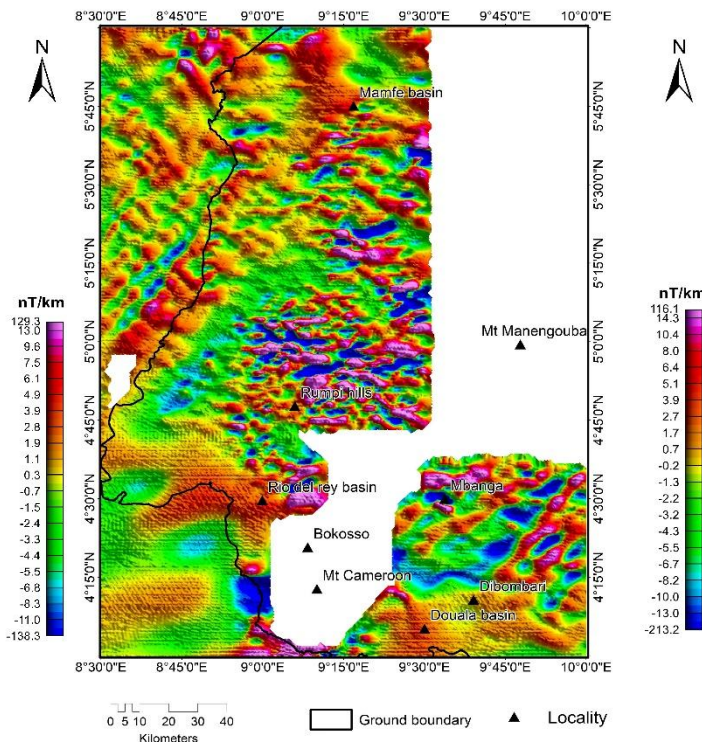
B

F_y (East)



C

F_z (Vertical)



D

Fig. 6

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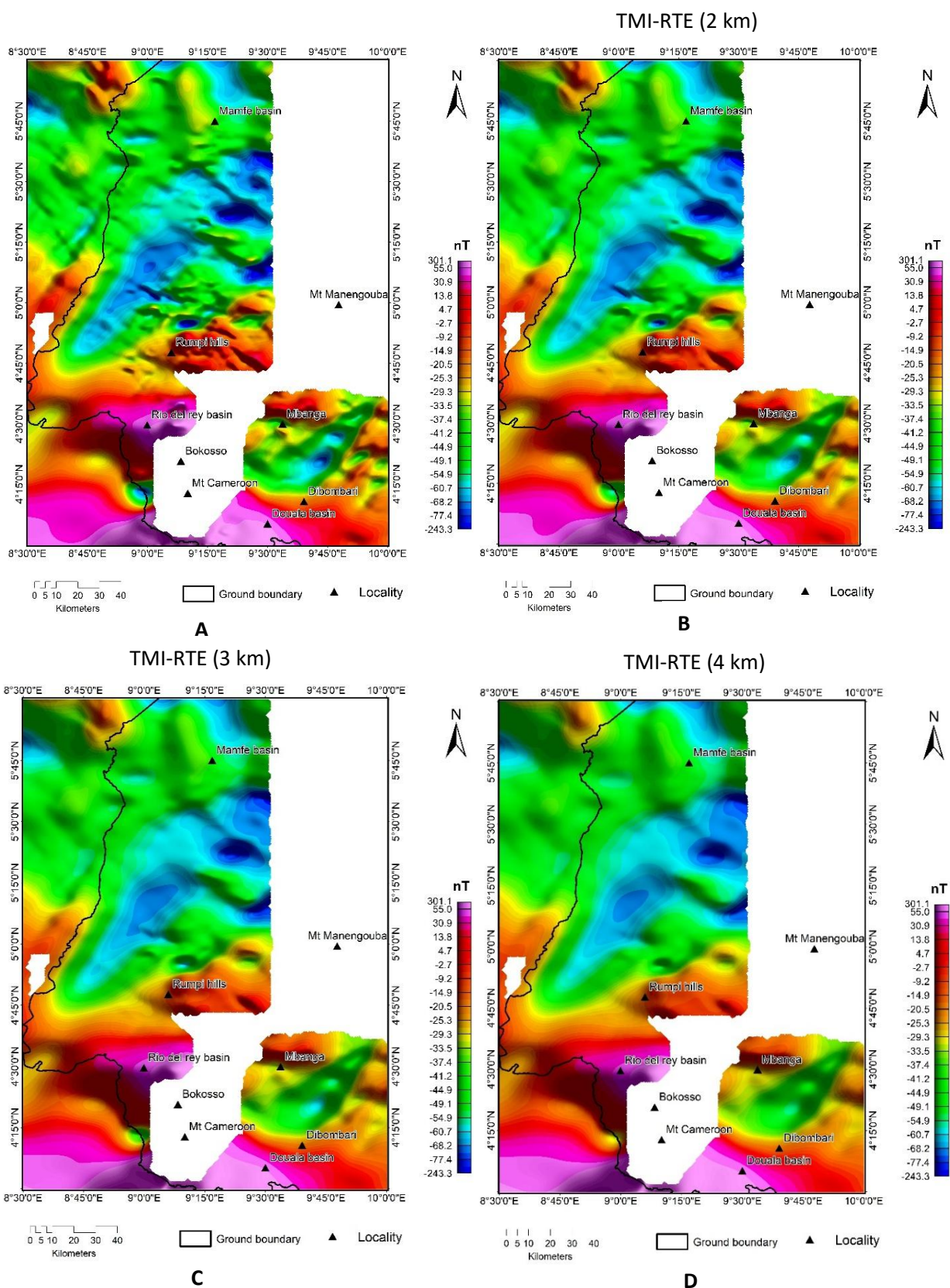


Fig. 7

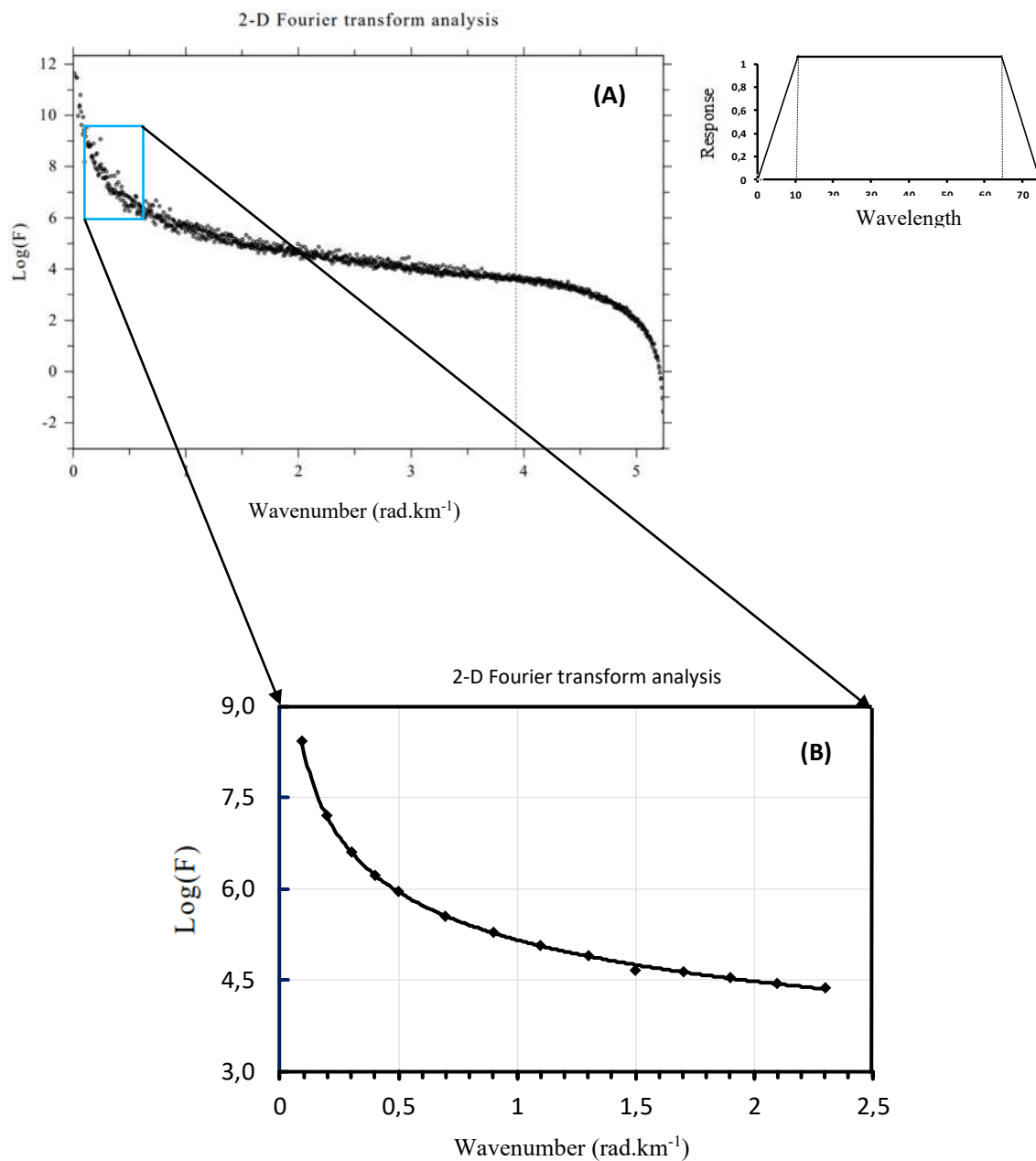


Fig. 8

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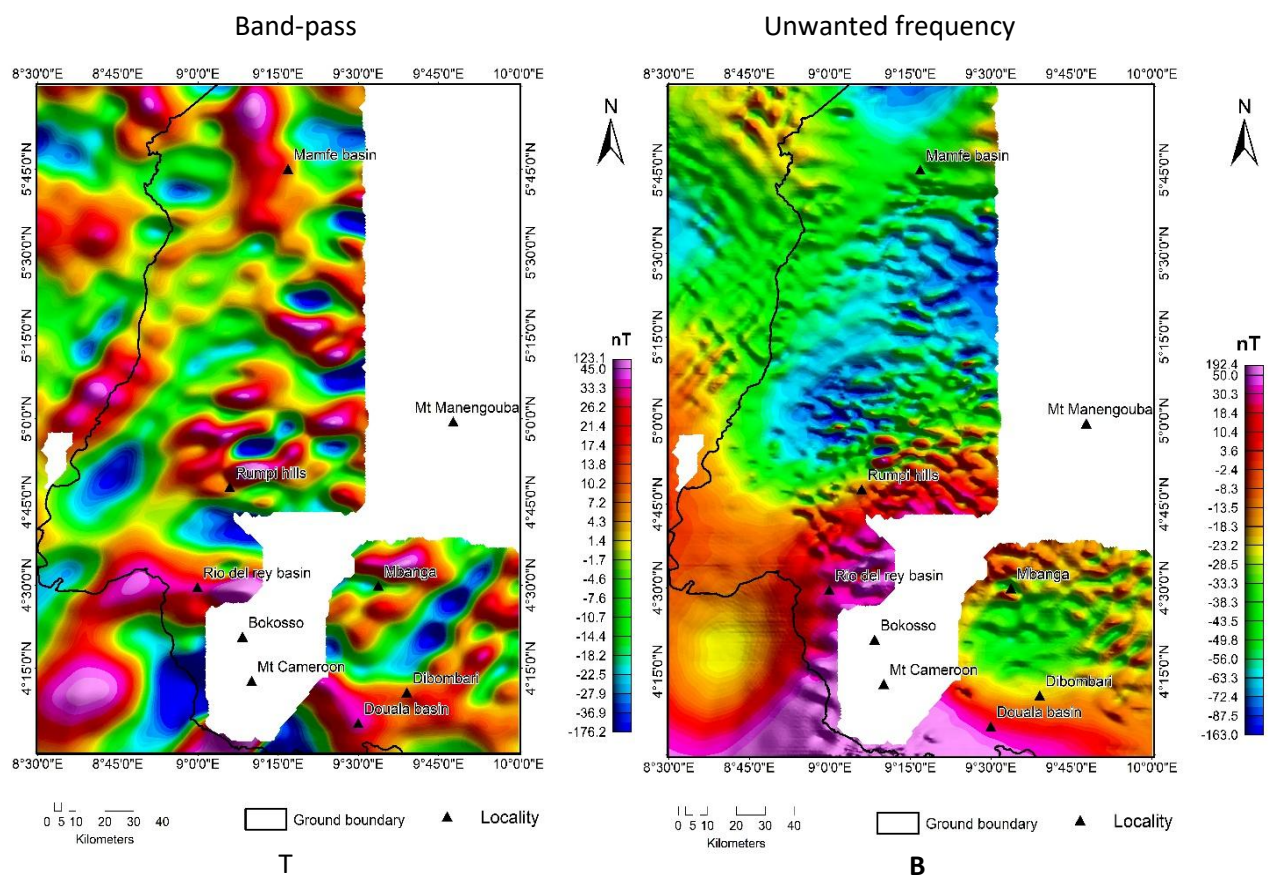


Fig. 9

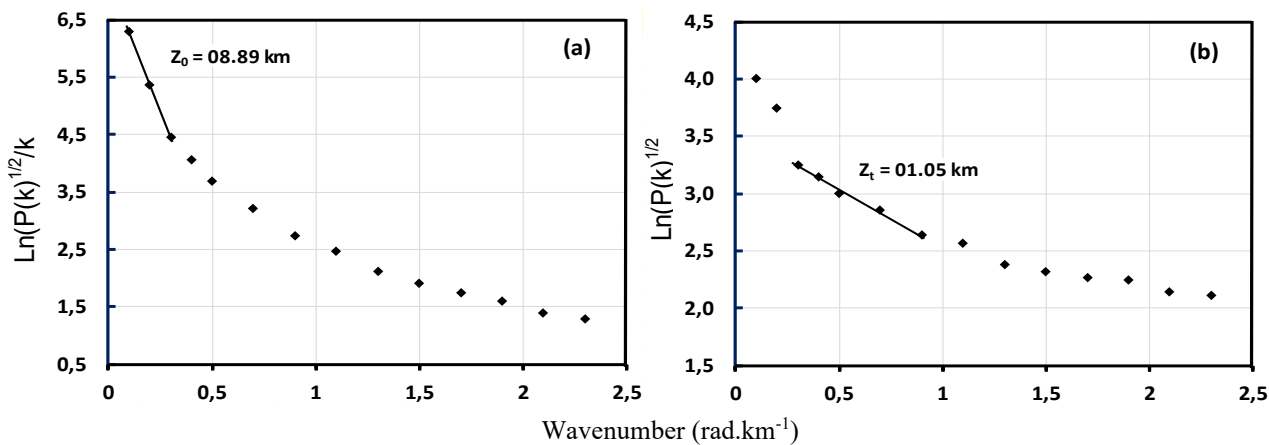


Fig. 10

Table 1

Method	Physical parameters measured	Typical units	Relevant physical property	Typical source of anomaly	Depth of investigation
Magnetic prospecting	Vector component or total attraction of Earth's geomagnetic field	Nano-Tesla (nT)	Magnetic susceptibility (SI)	Magnetic susceptibility contrast (SI)	Surface to Curie isotherm or Curie point depths (km)

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Table 2

Survey	Client	Contractor	Year	Line spacing (m)	Line direction (°)	Flying height (m)	Country
1142	ELF	CGC	1981	1000	0	400	CAMEROON
1143	ELF	CGC	1980	2500	0	400	CAMEROON
2579	CIDA	SURVAIR	1970	1000	0	235	CAMEROON
1018	MINES AND POWER	POLSERVICE-GEOPOL	1976	2000	150	150	NIGERIA
1145	MINES AND POWER	POLSERVICE-GEOPOL	1975	4000	20	760	NIGERIA

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Table 3

IGRF	Number of data points	Minimum	Maximum	Mean	Orientation
IGRF-1983	3655	32582	32958	32770	NW-SE
IGRF-2026	3655	32888	33261	33074	WNW-ESE

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Table 4

Terrain	Z ₀ (km)	Z _t (km)	CPDs (km)	Geothermal gradients (°C/km)	Heat flow values (mWm ⁻²)
Sedimentary and volcanic rocks	08.89	1.05	16.73	33.2	83.0

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Table 5

Terrain	Station	Crustal thickness (km)	Curie point depth (km)	Difference (km)	Average Crustal thickness (km)	Average upper mantle Vs (km.s ⁻¹)	Average crustal Vs (km.s ⁻¹)
Southern Cameroon Volcanic Line	CM09	25	16.73	8	32	4.5	3.7
	CM15	33		16			
	CM16	36		19			
	CM19	36		19			
	CM20	33		16			
	CM13	28		11			
	CM18	31		14			

Table 6

Springs	Longitude	Latitude	Temperature (°C)
Abang	09° 45' 50"	04° 56' 40"	25.2
Ahio-Ekanjo	09° 41' 00"	04° 56' 30"	28.0
Ayukaba	09° 08' 50"	05° 41' 55"	28.6
Bare-1	09° 58' 00"	05° 00' 35"	25.8
Bare-2	09° 58' 10"	05° 02' 50"	26.4
Ebuku	09° 57' 20"	05° 00' 30"	26.5