Application of High-Precision Filters on Airborne Magnetic Data: A Case Study of the Ogoja Region, Southeast Nigeria

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Abstract: Aeromagnetic data from the Ogoja region, Southeast Nigeria, were enhanced using high-precision methods including the tilt angle of total horizontal gradient (TAHG), the softsign function (SF), and the improved logistic function (IL) with the aim of creating a new structural map. This new map can help improve the understanding of the trend, spatial distribution, and pattern of the lineaments. The TAHG, SF, and IL methods generated geologic structures with correlating trends, distributions, and patterns. However, the SF and IL techniques mapped the borders of geologic structures more precisely. The lineaments extracted from the SF and IL maps were reduced to equator (RTE) magnetic data, and a GIS was used to create structural maps with NE–SW, NW–SE, NNE–SSW, and NNW–SSE orientations. Furthermore, the depths (0–2100 m) of these geologic structures were estimated using the tilt depth technique (TDT). The high lineament density and thin sedimentation observed in the study area were triggered by the widespread Santonian igneous intrusions associated with the Abakaliki Anticlinorium. The techniques applied in our study can be employed in areas with the same conditions around the world for the precise delineation of geologic structures from magnetic and gravity data.

Keywords: tilt-angle of total horizontal gradient; softsign function; improved logistic function; magnetic method; Southeast Nigeria

1. Introduction

One of the most well-known uses of magnetic and gravity techniques is the visualization of lineaments commonly associated with tectonic intrusions using different filtering procedures [1–6]. These procedures are vital because the identified lineaments usually match the lateral borders of geologic structures [6–10].

Previously, some filters were developed for mapping geologic features employing magnetic and gravity data. The total horizontal gradient (THG) and analytic signal [11,12] have been the most commonly applied filtering methods for geologic structural studies. Even though these traditional procedures are frequently employed to qualitatively interpret magnetic and gravity data [13,14], they often generate diffuse lineament maps [15–18]. However, researchers have proposed several other enhancement operations centered on potential field gradients to reduce the difficulties of the traditional edge-detection procedures [18,19]. The tilt derivative method centered on the arctan function of the vertical gradient-to-THG ratio [20], the tilt derivative of gradient amplitude [21], and the THG
computed by averaging the vertical gradients [22]. Ref. [23] introduced the theta technique that applied the gradient amplitude to normalize the total gradient, while the normalized gradient amplitude technique [24] was also developed. In addition to these, other edge-detection filters that rely on potential field data are well documented [11,12,25,26]. Furthermore, very recent high-precision filters, such as the normalized standard deviation, enhanced horizontal gradient amplitude, softsign function, logistic function of the total horizontal gradient, tilt angle of total horizontal gradient, theta map, hyperbolic tilt angle, horizontal tilt angle, tilt angle of the total gradient, improved tilt angle, improved theta map, improved logistic and fast sigmoid-based edge detection, have all been developed [24,27–30] to accurately map the lineaments originating from near-surface and deep geologic sources. The application of these filters on both theoretical and observed potential field data has shown their efficacy and precision in the qualitative delineation and interpretation of geologic structures [31–35].

The Ogoja region, which is a portion of the Lower Benue Trough (LBT), is of great economic interest because of the extensive occurrence of brine fields, base metals, and polymetallic–magmatic hydrothermal deposits as well as other rift minerals [36–40]. Mineralization is often related to structural control and hydrothermal modifications caused by magmatic intrusions [36].

In general, some previous geologic structural studies in the LBT involved filters such as the first and second vertical derivatives, tilt-angle derivative, total horizontal gradient, analytic signal, downward continuation, and center for exploration targeting [37,41–45]. All these enhancement and filtering procedures permitted the mapping of responses linked to the mineralization, geologic structures, and lithology of the area. From these investigations, it was observed that the lineaments were oriented in the E–W, NW–SE, NE–SW, and NNE–SSW directions and functioned as a pathway for hydrothermal fluid movement and mineralization. Overall, these filters had the disadvantage of being unable to balance the anomaly amplitudes initiated by the structures buried at various depths [33] in order to clearly recognize the horizontal boundaries of deep structures and generate detailed geologic structures of the LBT.

In this study, TAHG [35], SF [32], and IL [46] filters were employed to the high quality aeromagnetic data to enable the generation of a highly precise map of the geologic structures of the Ogoja region. The airborne magnetic data were measured and assembled by Fugro Airborne Surveys, Canada, between 2005 and 2010. These data were acquired using the Flux-Adjusting Surface Data Assimilation System and were observed to be of very high resolution when compared to the 1970 aerogeophysical data [47]. Moreover, the TDT was applied to approximate the depth of the geologic structures of the area. The mapping of these structures is expected to help delineate brine conduit, lead–zinc, barite, and ironstones occurring near the igneous intrusions related to the Abakiliki Anticlinorium and Cameroon Volcanic Line within the Ogoja region. Furthermore, the findings of this study are expected to enhance our understanding of the trend, distribution, and structural pattern of the investigated area.

2. Location and Geologic Setting of the Study Area

Okpoma, Ugaga, Ogoja Town, and the surrounding areas are part of the Asu River Group (ARG) and Mamfe Formation sedimentary sequences. The investigated region is located in the LBT, on the northeastern flank of the Abakiliki Anticlinorium (AA) in Southeast Nigeria (Figure 1). The investigated region is positioned between longitudes 8°30’ E and 9°00’ E and latitudes 6°30’ N and 7°00’ N.

The series of tectonic occurrences that resulted in the creation of the Benue Trough (LB) and its constituent parts have been well documented [48]. The LB is occupied by a thick Cretaceous sediment that overlies the Precambrian basement, which is primarily composed of magmatic and granitic rocks. Outcrops at Ogoja and Ikom, as well as geophysical data, have confirmed the presence of arkosic non-fossiliferous fanglomerates [49]. The Ogoja Sandstone, pre-Middle Albian in age, corresponds to the basin’s early phases
of development [50]. The Ogoja sandstones that correlate laterally with the basal Awi Formation overlie the Obudu Basement complex. The ARG consists of shale with sandstones and sandy limestones [51,52]. Ref [49] provided a more comprehensive report of the assemblage, dividing it into three groups that ranged from the middle Albian to the lower Cenomanian. The existence of mega turbidites and slumps, as well as ammonite and foraminifera assemblages, suggested that the Ekebeligwe Formation was created in a deep-marine asymmetrical turbidite basin during the middle-Albian period [49].

It has been revealed that the tectonic event continued during the basin’s development and infilling (Pre-Aptian-Santonian), as well as in the Santonian occurrence and subsequently Campanian, with its maximum activity during the Albian and Santonian [53]. In the Afikpo–Ugep area, the rocks are predominantly alkaline with tholeiitic tendencies [53,54]. Even though magmatism is widespread in the LBT, magmatic concentrations are concentrated in a few major areas, including Gboko–Ogoja, Workum Hills, Afikpo–Ugep, and Ishiagu [50,53–55]. The igneous rocks are primarily dolerites, with Monzonites, Syenites, and Gabbros, in addition to pyroclastics and basaltic lava flows.

3. Materials

Data Acquisition

Between 2005 and 2010, Fugro Airborne Surveys, Canada, collected high resolution airborne magnetic data. The dataset was measured using the Flux-Adjusting Surface Data Assimilation System with 0.1 km of flight-line space, 0.5 km of tie-line space, and a terrain clearance that ranged from 0.08 to 0.1 km. The flight-line direction in the study area was mainly NW–SE, while the tie lines, which were meant to intersect the main geological strike direction, were oriented predominantly NE–SW [46]. Furthermore, Fugro Airborne Surveys, Canada, subtracted the regional field from the observed aeromagnetic data using the International Geomagnetic Reference Field’s tenth (10th) generation (IGRF). The IGRF’s main advantage is the constancy it provides in potential field explorations, which began after the IGRF was made conventional and readily available. The observed total magnetic intensity data (Figure 2) employed in this investigation were reduced to the equator (RTE)
(Figure 3). Because the data were gathered at a low latitude, the magnetic data were RTE. According to [56], RTE data produce more reliable results, particularly at middle and lower latitudes. Furthermore, the data were upward continued to 100 m using the frequency method (Blakely, 1996) to mitigate the geologic effects associated with very short wavelength anomalies.

Figure 2. Total magnetic intensity data.

Figure 3. Total magnetic intensity data reduced to equator and upward continued to 100 m.
4. Methods

The tilt angle of the total horizontal gradient (TAHG) is one of the frequently applied filters for recognizing geological features. The computation procedure of the TAHG operator can be expressed as [35]:

$$\text{TAHG} = \tan(R_{HG}),$$  \hspace{1cm} (1)

where $R_{HG}$ is the ratio between the derivatives of the total-horizontal gradient, expressed as [35]:

$$R_{HG} = \frac{\frac{\partial HG}{\partial z}}{\sqrt{\left(\frac{\partial HG}{\partial x}\right)^2 + \left(\frac{\partial HG}{\partial y}\right)^2}},$$  \hspace{1cm} (2)

and the total-horizontal gradient ($HG$) of the potential field data $F$ is given by [57,58]:

$$HG = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2}. $$  \hspace{1cm} (3)

Ref. [59] used the logistic function and derivatives of the gradient amplitude to extract the horizontal borders, which are defined by:

$$IL = \frac{1}{1 + \exp[-p(R_{HG} - 1) + 1]},$$  \hspace{1cm} (4)

where $p \geq 2$ will produce better results.

The softsign function (SF) is a new edge delineation method, developed by [32] to recognize the geological features from potential field data. The SF is calculated by the following equation:

$$SF = \frac{k \times \frac{\partial HG}{\partial z} - (k + 2) \sqrt{\left(\frac{\partial HG}{\partial x}\right)^2 + \left(\frac{\partial HG}{\partial y}\right)^2}}{\sqrt{\left(\frac{\partial HG}{\partial x}\right)^2 + \left(\frac{\partial HG}{\partial y}\right)^2} + k \times \frac{\partial HG}{\partial z} - (k + 1) \sqrt{\left(\frac{\partial HG}{\partial x}\right)^2 + \left(\frac{\partial HG}{\partial y}\right)^2}}$$  \hspace{1cm} (5)

where $1 \leq k \leq 10$ will yield the best results.

5. Results

To offer a better understanding of the location, trend, and pattern of geologic structures in the Ogoja region of Southeast Nigeria, enhanced filters including TAHG, SF, and IL were applied to the high-resolution airborne magnetic data (Figure 3). Figure 4 shows the effects plus outputs of the TAHG developed from the tilt-angle filter. The zero-contour line of the tilt angle revealed the lineaments caused by magnetic bodies; nevertheless, sharp edges were not detected by this filter [29]. The SF map (Figure 5) displayed a more detailed delineation of the geologic structures, which were much easier to visually qualitatively interpret. Furthermore, a high-resolution lineament map (Figure 6) of the investigated area was generated from the IL filter. Interpretation of an IL-derived lineation map is often without complications [3]. This filter was reported by [3] to be able to accurately map the edges of regional and deeply seated geologic structures. The SF and IL filters were not affected by the depth of the magnetic bodies, and their highest values were near the true boundaries, even for deeper magnetic bodies [29]. Overall, the peaks of the SF (Figure 5) and IL (Figure 6) responses were placed directly over the magnetic source borders, and these filters provided sharper responses over the source edges than the TAHG filter (Figure 4). Figure 4 created more connective linear structures that were somewhat diffused. This linkage of lineations made visual interpretation of the geologic structures somewhat problematic [20]. Figures 5 and 6 balanced the low and high amplitude signals.
emanating from geologic structures, simultaneously. The filters (SF and IL) delineated distinctly several lineaments caused by the Santonian AA [60] that were not recognizable in Figure 4. In general, the lineament maps (Figure 8) generated from Figures 4 and 5 and a GIS indicated geologic structures that trended in the NE–SW, NW–SE, NNE–SSW, and NNW–SSE directions (Figure 9). The southeastern and northeastern flanks, shown in Figure 8a, were characterized by curvilinear geologic structures, which were indicative of folds related to the Santonian intrusions of the region. These folds were also identified in Figures 4 and 6. Furthermore, the SF- and IL-generated structural map (Figure 8a) showed well defined clusters of lineaments with a regular NE–SW trend, while the GIS structural map (Figure 8b) revealed sparsely distributed structures with dominant NW–SE and NE–SW directions. In general, Figure 9 revealed that the geologic structures within the study area were oriented predominantly in the NE–SW direction. The regional NE-SW trend of the BT [53,61,62] matched the dominant direction of the lineaments of the study area.

To evaluate the depths of these lineaments in the investigated area, the TDT [25,63,64] was applied. The key benefit of the TDT (Figure 7) is that it does not involve the use of window-size, magnetization, or structure-index unlike the standard Euler deconvolution [36,38,43]. Figure 8 shows a depth range of 0–2100 m and reveals that these mapped geologic structures (Figures 4–6) were not deeply seated beyond 2100 m. The thin sedimentation and high concentration of lineaments are believed to have been initiated by the wide-ranging occurrence of near-surface Santonian intermediate-mafic igneous, calc-alkaline lavas, and tuffs intrusions, as well as highly baked shales [45,60] in the study area.

Figure 4. TAHG map of the study area.
Figure 4. TAHG map of the study area.

Figure 5. SF map of the study area.

Figure 6. IL map of the study area.
6. Discussion

The structural framework of the BT controls the sedimentation as well as the basement topography [53,60] and dominant trend of lineaments. The TAHG, SF, and IL (Figures 4–6) filters were used to create enhanced structural maps from the airborne magnetic data. Furthermore, the SF and IL filters delineated the borders of the shallow, deep, and regional geologic structures appropriately [28]. In this study, lineaments were extracted from the SF and IL methods (Figure 5), and a GIS was used to create structural maps of the Ogoja region (Figure 8). Moreover, the combined maps were matched taking into consideration the spatial characteristics as well as location, orientation, number, and subdivision of the created geologic structures. Based on this, the trend analysis of the delineated geologic structures was statistically calculated and presented as a rose diagram (Figure 9). The interpretation of the structural map indicated three main groups of frequency NNE–SSW, NNW–SSE, NE–SW, and NE–SW and a secondary orientation of NW–SE. To a certain extent, one of the major NE–SW lineament trends generated matched the basic structural orientation of the BT and AA, which was NE–SW [60]. This trend was observed to be very regular and
dominant in the SF-RTE generated structural map (Figure 8a). Similar structural trends have been previously observed in the LBT [37,43,44]. These near-surface geologic structures were triggered by the widespread intrusions [60], as well as metamorphosed Albian shales [39,42,43,60] interrelated to the Santonian AA [38]. The related tectonic perturbations caused the high concentration of lineaments in the Ogoja region, which served as pathways for the movements and entrapments of brines [36] and lead–zinc [38] in the region. The results obtained showed that there was a relation between the geologic structures extracted from the magnetic data and the mineralization, demonstrating the success of the magnetic data in mapping the pathways of the mineral deposits [4]. Furthermore, in terms of the trend analysis of the geologic structures obtained from the TAHG, SF, and IL (Figures 4–6), an obvious consistency was witnessed from the lineament trends. However, the SF and IL generated structures that were sharper, well-defined, and correlated relatively well. Overall, the findings showed that the combination of the SF and IL filters alongside the surface geologic structural mapping can serve as potent tools for imaging lineaments in a complex geologic area characterized by multiple phases of deformation [28] such as the LBT.

Figure 8. Lineament maps extracted from (a) SF and IL and (b) the GIS results.

Figure 9. Equal area rose diagrams of (a) softsign function and (b) GIS-generated lineament maps from the TMI and SRTM data, respectively.

7. Conclusion

To create improved structural maps of the Ogoja region in Southeast Nigeria, airborne magnetic data were enhanced using high precision filters such as TAHG, SF, and IL. Before application of the enhanced filters, the magnetic data were reduced to the equator. The TAHG, SF, and IL filters produced geologic structures that were relatively well correlated. Furthermore, the SF and IL filters correctly mapped the boundaries of shallow, deep, and regional geologic structures. The lineaments extracted from the SF and IL of the RTE data and a GIS were used to generate structural maps of the Ogoja region. The generated maps revealed structural trends such as NE–SW, NW–SE, NNE–SSW, and NNW–SSE. In general, most of the geologic structures followed the structural orientation of the BT and AA and trended in the NE–SW direction. The depths to these lineaments were determined using TDT, and the obtained result showed a depth range of 0–2100 m. Overall, the extensive occurrence of Santonian intrusions is thought to be the primary cause of the high concentration of geologic structures and thin sedimentation in the study area.
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