Contribution of Aeromagnetic Data to the Structural Discontinuities Identification of Black Volta Catch-ment Aquifer System in Côte d'Ivoire

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Abstract

This study aims to improve the structural knowledge of the fissured aquifers of the Black Volta catchment in Côte d'Ivoire based on the mapping of magnetic lineaments that represent magnetic discontinuities such as magmatic body contacts or tectonic faults. Four filtering methods: pole

reduction (equator), gradient (vertical and hori-zontal), upward extension, and angle tilt were applied to the residual magnetic field map to extract magnetic discontinuities using the Oasis Montaj (Geosoft) program. Euler deconvolution coupled with the analytical signal provided, in addition to the horizontal location of the magnetic contacts, an indication of their depths. The re-sulting structural map contains 458 structures with lengths ranging from 9.03 to 66.54 km. Three directions: NW-SE, E-W and NE-SW were detected, with a predomi-nance of the NW-SE direction. Depths estimated by Euler solutions range from 6.8 to 2847 m. This map is consistent with many faults already recognised or assumed by traditional structural studies and tectonic events affecting the Ivorian basement. These results contribute significantly to the improvement of the structural map of the Black Volta Basin in Côte d'Ivoire. In addition to the major known tectonic faults, numerous lineaments, particularly those at depth, have been highlighted by the pre-sent study.

Introduction

Aeromagnetic data has long been used to support the mapping of geological structures and the faults that affect them or to detect magnetic mineral concentrations through the measurement of magnetite in geological formations beneath the aircraft. Although these aeromagnetic surveys are widely used as a reconnaissance tool, there is growing recognition of their potential in the assessment of prospective areas given the unique information they provide (Reeves, 2005; Abbass et al., 2013). Hydrogeological applica-tions of airborne geophysical methods are, at present, still few and far between and generally concern the structural and lithological. They involve the identification of structures called geophysical lineaments. Geophysical lineaments (gravimetric and magnetic) are linear or curvilinear discontinuities caused by density or magnetization contrasts in the rocks. These lineaments are usually associated with structural features such as faults, fractures, folding axes and lithological contacts. Mapping by conven-tional methods (tracking faults on the ground and by aerial photographs, satellite im-ages and radar) does not allow the identification of all existing lineaments. In fact, air-borne magnetic data, which allow us to see through surface layers such as sand, vege-tation and water, are a powerful tool for highlighting both surface structures and deep, non-flush structures in the crust, whose hydraulic role is essential for exploring un-derground reservoirs. Experience has shown the value of geophysical data for linea-ment mapping and identification of geological structures (Khattach et al.,

2004, Vanié et al., 2005, El Gout et al., 2010). This study aims to establish a fracturing map relevant to water resources exploration in the Black Volta Basin in Côte d'Ivoire, mainly by identifying the structures buried in the subsurface. Indeed, aeromagnetic maps present a uniform geophysical coverage, independent of topography and allowing to distin-guish superficial and deep structures of the crust without constraints. Achieving a less evasive structural map, which can provide information on geometric characteristics by integrating surface, semi-profound and deep information, can be an indispensable tool for a better understanding of complex discontinuous environments.

Geological and hydrogeological framework

The study area (Figure 1) is the interface of the Black Volta transboundary basin in Côte d'Ivoire. It is located between latitudes 7°78 and 9°94N and longitudes 2°49 and 3°35W and delimits a vast geographical area, located in the northeast of Côte d'Ivoire. Its main river, the Black Volta (Mouhoum) River, originates in the Kong Mountains in the Dindéresso Forest Reserve, southwest of Burkina Faso. It is approximately 1,363 km long, and drains a total area of 12,836 km² in Côte d'Ivoire. The relief is not very rugged. The highest peak, the Bondoukou Massif, reaches an altitude of 725 m. Geolog-ically, the basin is located in the eastern compartment of the Precambrian basement called Baoulé-Mossi (Figure 1) of Paleo-Proterozoic age and structured by the Eburnian megacycle (2400-1600 Ma). The eastern zone is covered by a complex set of geological formations classified according to age and unevenly distributed in two domains: the Quaternary domain (Holocene) and the Birimian domain (Figure 1).

From a hydrogeological point of view, the conceptual model accepted in the basement zone is the presence of a superficial film (alterites), capacitive, fed by the surface, followed by a fissured horizon (intermediate decompressed zone), with very high permeability forming the second aquifer level (Lachassagne et al., 2005). The third aquifer level is located in the sound bedrock affected by tectonic fractures (faults). Levels 2 and 3 constitute the semi-captive part of this multilayered aquifer hosting a single water table (Ousmane, 1988).
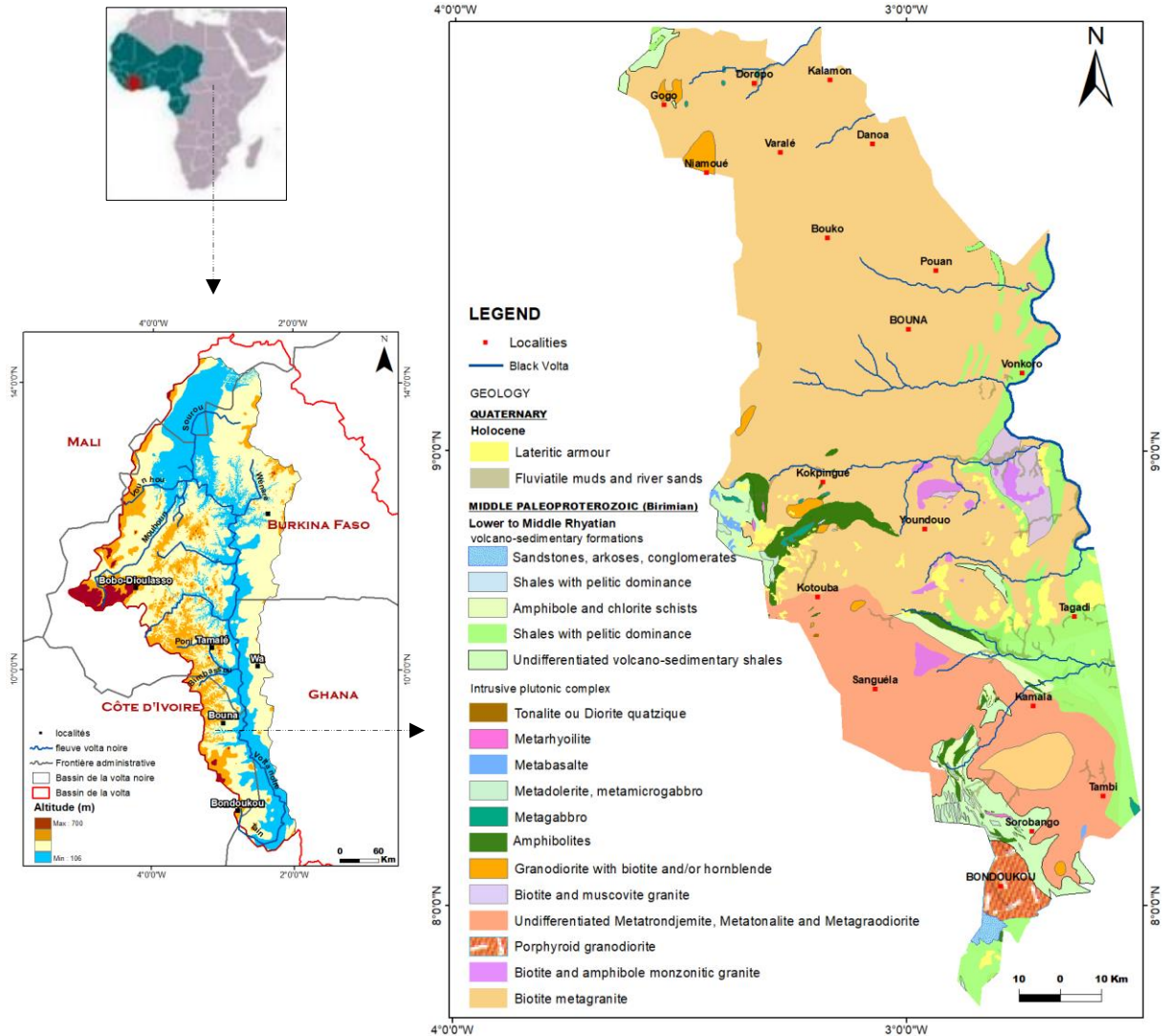
Figure 1. Geological map of the studied area

Methods
Aeromagnetic data

The data used in this study come from the archives of the "Direction la Cartographie et de la Prospection Géologique (DCPG)" of the Ministry of Mines, Petroleum and Energy of Côte d'Ivoire. These data, available in the form of total magnetic field maps, were obtained during aerial surveys carried out by Kenting Earth Sciences Ltd. in 1974 and 1975, as part of a cooperative programme between the Government of Canada and the Government of the Republic of Côte d'Ivoire under the auspices of the Canadian Inter-national Development Agency. The isomagnetic contours

were compiled from magne-tometric recordings made along the N-S oriented flight lines. The flight lines were plot-ted on the 1:50,000 photomosaics and the coordinates of the turning points were de-termined and digitally compiled on magnetic tape. The field strengths were derived ei-ther from analogue magnetometric profiles after digital translation on tape, or from digital profiles at the nodes of a 2.5 mm square grid, according to a simulated polyno-mial variation of the field in the direction perpendicular to the flight lines. The grid was used as the basis for the mechanographic drawing of the original 1:50,000 map without the flight lines. For this work, two sheets covering 92% of the basin were used. The other part, not available, covers the Comoé National Park, which is of no interest for the valorisation of the results of this study.

Digital processing methods for aeromagnetic images

The aeromagnetic data provided in the form of frozen digital maps of the total magnetic field containing iso-values curves were previously corrected (denoising, fence error, diurnal variations). The total magnetic field map was reconstructed using a GIS (Figure 1). The total magnetic field was subtracted from the International Geomagnetic Refer-ence Field (IGRF) and the resulting residual magnetic field values were interpolated to a 50 m square grid. A series of treatments using optimal filters were applied to the grid to extract the maximum amount of structural information.

Reduction at the pole (equator)

The residual magnetic field map was reduced at the pole (equator) using the parame-ters of the local Earth's magnetic field with declination D = -8.2424°; inclination I = 0.1967° and intensity H = 31947 nT. It allowed to remove the bipolarity of the mag-netic anomalies, caused by non-vertical magnetisation directions, by recalculating the magnetic anomaly values as if they had been measured at the magnetic pole, where the magnetic field direction is vertical. In other words, it eliminated the distortions in-duced by the tilt of the Earth's magnetic field vector. It formed the base map for the ap-plication of the various filters and operators later on..

Vertical (dz), horizontal (dx; dy and upward gradients)

These mathematically based operators reinforce the bodies at the origin of the anomaly by freeing them from the regional components of short and long wavelengths, thus highlighting either the location of the bodies or a lithological or structural contact be-tween two bodies. The vertical gradient or vertical derivative of the field was applied to the reduced magnetic anomaly at the pole. The first derivative allowed better individu-alisation of nearby sources. The horizontal gradient along x and y allowed the magnetic

effect of geological contacts to be amplified visually by delineating the perimeter of ge-ological bodies highlighting lithological contacts. An upward extension is carried out on the same slightly wider initial grids, at distances of 200 m.

Tilt Angle

The Tilt-angle (Miller and Singh, 1994; Verduzco et al., 2004; Salem et al., 2008) calcu-lates the inverse tangent of the ratio of the modulus of the horizontal partial derivatives to the vertical derivative of the magnetic field and is written as:

$$\theta = \tan^{-1} \frac{\frac{\partial M}{\partial z}}{\sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial x}\right)^2}} \tag{Eq.1}$$

M being the magnetic field or anomaly map.

The advantage of the transformation is that by calculating an angle, all shapes will be represented in a similar way, whether the anomalies are of low or high amplitude (Bouiflane 2008). This operator is applied to the map of the magnetic anomaly reduced to the equator to discriminate the all-azimuth structures.

Euler deconvolution

The Euler deconvolution method has allowed the precise location of anomaly sources in the horizontal plane as well as the estimation of their depths (Keating, 1998; Asfirane-Haddadj and Galdeano, 2000): it is based on the Euler homogeneity equation (Equation 1) which relates the magnetic field and its gradient components to the loca-tion of the source with a degree of homogeneity that can be interpreted as a structural index (SI) (Thompson, 1982) :

$$(x - x_s)\frac{\Delta B_T}{\Delta x} + (y - y_s)\frac{\Delta B_T}{\Delta x}(z - z_s)\frac{\Delta B_T}{\Delta z} = IS(B_r - B_T) \tag{Eq.2}$$

Where (x_s, y_s, z_s) sont les coordonnées de la source are the coordinates of the anom-aly source, B_T is the field strength measured at a point of coordinates (x, y, z). IS indi-cates the structural index and refers to the geometry of the source. In this work, the Euler Deconvolution solutions were computed with a structural index IS=0 to high-light mainly the structures at depth and those affecting the cover in accordance with the works of Vanié et al, (2005), El Gout et al,. (2009) and Abderbi & Khattach (2010). The new method of localized Euler deconvolution in support of the analytical signal was used instead of the standard Euler deconvolution generally used.

All these treatments were performed using the USGS Oasis Montaj software (Geosoft).

Results

Results and analysis of the transformed maps

Figure 2 shows the residual magnetic field map of the basin. It spatially spreads out the variations in the magnetic properties of the Earth's crust, reflecting geologically de-rived source structures. The reduced magnetic field map at the equator (Figure 3) shows anomalies of size and amplitude, varying between 31700 and 32115 nT. Two localised magnetic domains can be distinguished from north to south. The southern part, in the Gontougo region, is characterised by elongated E-W negative anomalies marked in the volcano-sedimentary formations. Positive anomalies oriented NE-SW and NW-SE are more marked in the Paleoproterozoic crustal rocks in the north. This variation in magnetic intensity reflects the heterogeneity of the underlying geological formations.
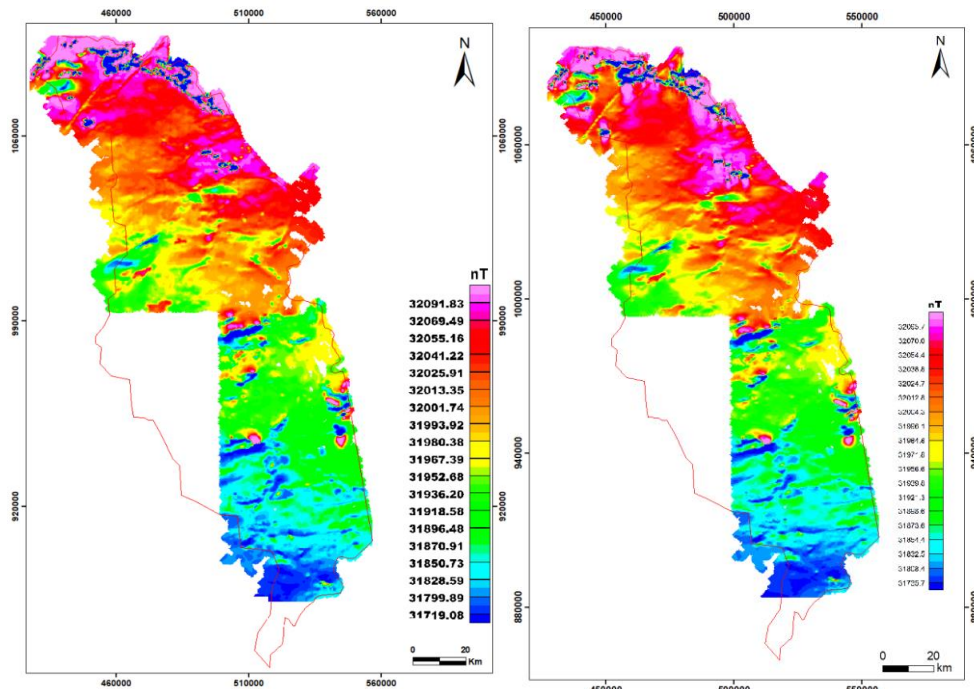

Figure 2. *Transformed maps.*
a) Residual magnetic field map,
b) Map of the reduced field at the equator

The first-order derivative transformed maps are shown in Figure 3. The vertical de-rivative highlights the surface anomalies by comparatively attenuating the long-wave (low frequency) anomalies. As the derivative order increases, the low frequency anom-alies are attenuated. At the same time, the
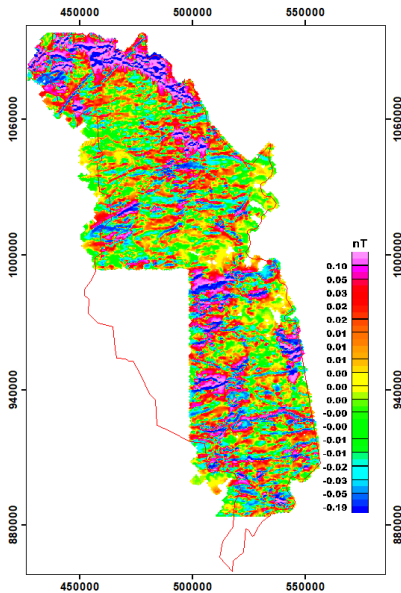
noise in the data is increased. The vertical derivative reveals anomalies that were hardly visible on the residual magnetic field maps. On these maps, the magnetic signatures are dominated by positive anomalies that describe a network of surface magnetic structures with numerous distortions. In general, they are mainly oriented E-W and NW-SW. The horizontal derivative gives a very good visualisation of these lineations. It completely eliminates the long-wave magnetic anomaly in the centre of the map; the E-W and NE-SW lineations are better-imaged and more continuous.

On the upwardly extended map, the signal is smoothed out and the effects of large semi-profound structures are favoured over small surface objects. Only the major anomalies are clearly visible.

The Tilt-angle transformation operator shows a clear structuring of the study area: the magnetic lineations appear more clearly in a similar way, whether the anomalies are of low or high amplitude. Indeed, as we have seen, the interest of this transformation is that, calculating an angle, all shapes are represented at the same time. The map (Figure 3) shows the curve of the angle θ equivalent to the contact which delimits elongated structures oriented E-W. They are largely superimposed on the course of the hydro-graphic network in the basin. NW-SE and NE-SW directions are also shown.
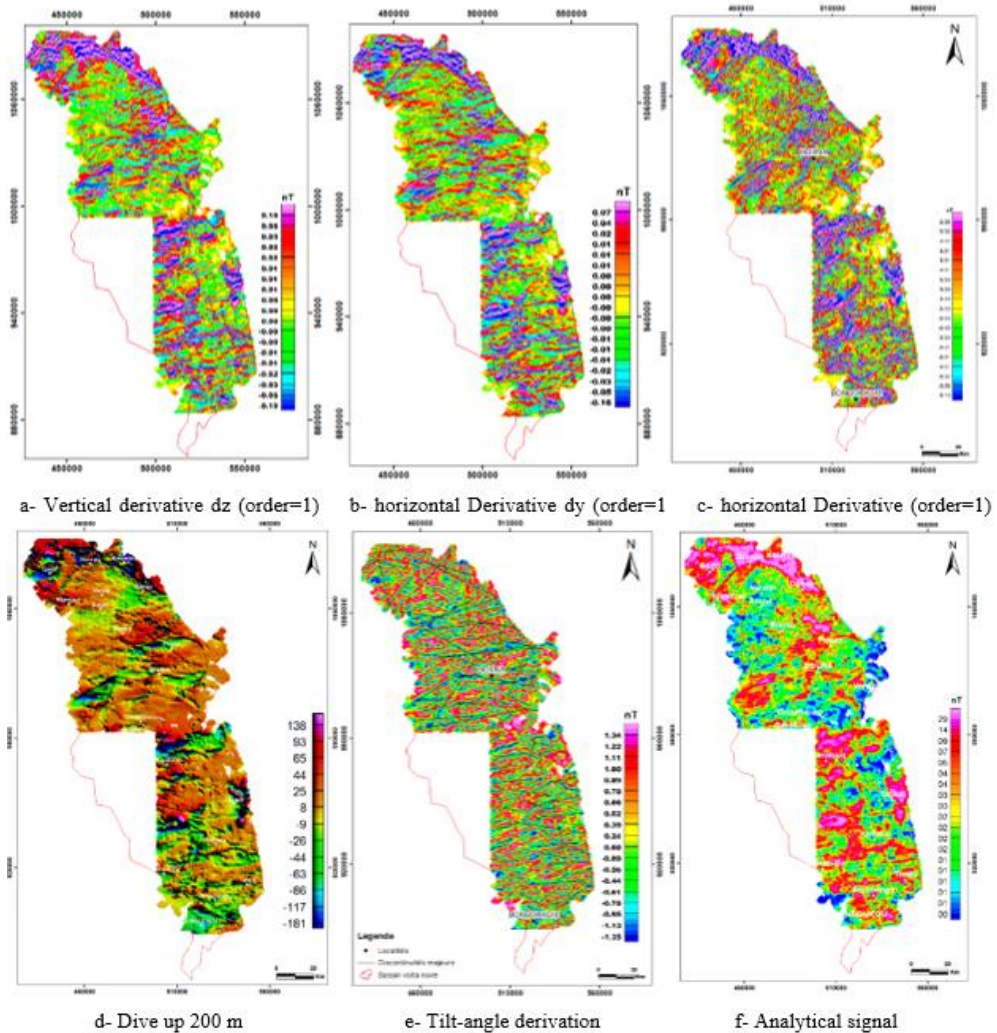
Figure 3. *Magnetic maps transformed by tilt-angle derivation (a, b, c,), induced field extended upwards to 200 m (d), tilt-angle derivation (e) and analytical signal (f).*

Structural map

Figure 4 shows the field of major lineaments resulting from the interpretation of the transformed magnetic images. These structures correspond to: (i) magnetic stripes, i.e. direct observations of magnetic ridges and/or troughs associated with lithological contacts or (ii) intersecting lineaments marked by abrupt breaks or breaks in magnetic susceptibility, with or without displacement. There are 458 lineaments with lengths ranging from 9.03 to 66.54 km with an average of 18.33 km. The length histogram (Figure 5) shows a strong heterogeneity in the distribution of lineament lengths. The direc-tional rosette of the

cumulative lengths (figure 8) indicates a predominance of the NW-SE direction (N120-140) followed by the E-W (N80-90°) and NE-SW (N50-60°) di-rections. This distribution is confirmed by the frequency analysis.
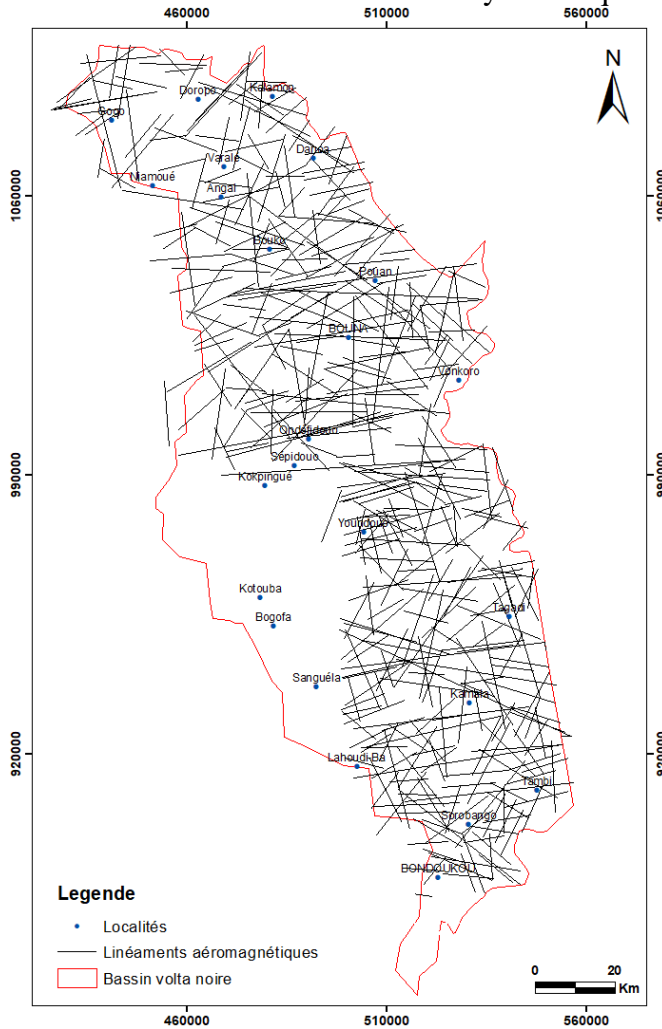

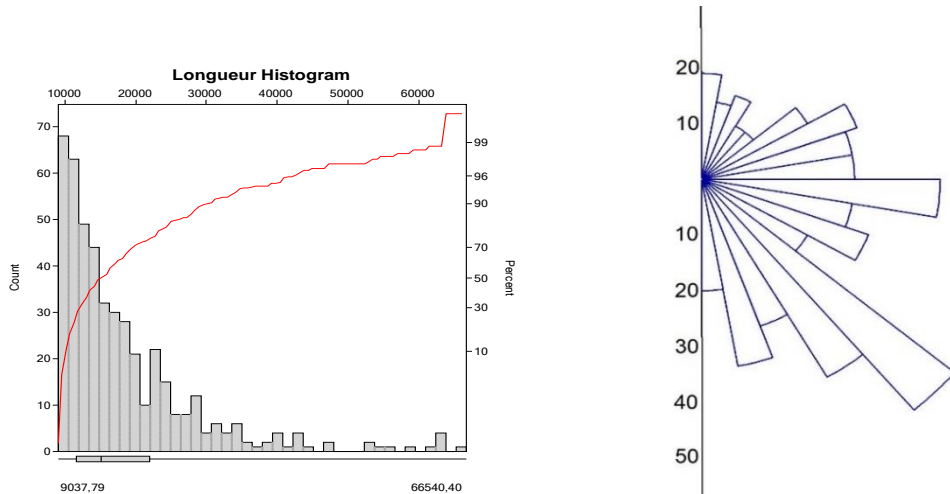*Figure 4. Structural map of the Black Volta catchment in Côte d'Ivoire.*

Figure 5. *Lineament length distribution and Directional rosette of cumulative fracture lengths from transformed magnetic images*

The use of Eulerian deconvolution coupled with the analytical signal was particularly effective in delineating the contacts and assessing their depths. Eulerian deconvolution solutions were obtained for a structural index = 0 (contact model), a window size of 10×10 and a maximum relative error of 15% on the depth. The solutions obtained are presented in (Figure 6a). The coloured dots indicate the depth of the source, and each colour is linked to one of the estimated depths which are divided into seven (7) ranges. The estimated depths range from 6.8 to 2847 m, with a predominance of depths be-tween 1500 and 2000 m in crystalline or metamorphic basement rocks. The superpo-sition of these solutions on the structural cover shows the main contacts highlighted. In general, the Euler solutions show preferential N-S (N0-20°; N160-180°) and NW-SE (N110-120°) trends as illustrated in Figure 6b.
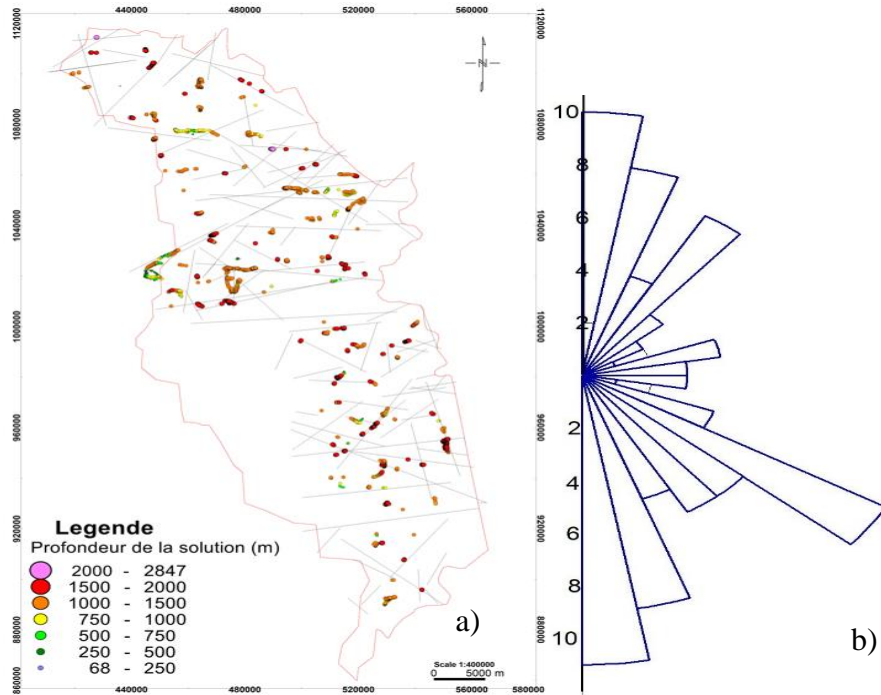
Figure 6. *Euler deconvolution solutions of a) aeromagnetic data (N=0; window=10×10; maximum relative error=15%) ; b) Directional rosette diagram of deep fractures*

Discussion

This study is based on the use of aeromagnetic data in the framework of geophysics applied to structural mapping. Several filtering techniques are used to extract the maximum information on the distribution of magnetic anomalies. In geology, these methods are known either to map magnetic anomalies that may be induced by crystal-line or metamorphic basement rocks or to detect linear anomalies (responses) that are dependent on tectonic and lithological contacts (Grauch et al., 2006). The methods ap-plied in this study have a common approach: to determine the horizontal and/or depth locations of magnetic contacts. Gradients (dx, dy and dy), tilt angle, and analytical sig-nal combined with upward extension methods allowed a multi-scale and all-round analysis of magnetic contacts. These methods are relatively sensitive to noise and ali-asing, and require pole-reduced magnetic data. Here the residual magnetic field data was reduced to the equator due to the strong asymmetry of magnetic anomalies ob-served in low magnetic latitudes (less than 45°) especially in regions close to the magnetic equator such as the Ivory Coast. This transformation has been used in many works, the most important of

which are: (Baranov, 1975) and (Hildenbrand, 1983) in order to eliminate the distortions induced by the tilt of the Earth's magnetic field vec-tor.

The magnetic data of the region processed using the above techniques show three ma-jor directional families: NW-SE, E-W and NE-SW. These identified preferential direc-tions have similarities with the directions of the tectonic events that affected the Ivo-rian Precambrian basement. These are the NE-SW birimian direction in reference to the tectonic-metamorphic deformation of the Eburnian cycle in the volcano-sedimentary formations and the E-W direction characteristic of the Pan-African orogeny (Faillat, 1986). The NW-SE direction, the most marked in the basin, characterises the most abundant and longest fractures mapped by Kouamé et al, (2019) using OLI 8 satellite images in the Volta Noir basin in Côte d'Ivoire.

This study reveals that some subsurface structures have depth values. Euler deconvo-lution has allowed us to delineate these contacts and evaluate their depths. The quality of this assessment depends largely on the appropriate choice of structural index (SI), which is a function of the geometry of anomalies caused by isolated and multiple anomalous sources. It also depends on the window used and the depth tolerance. The structural index or degree of homogeneity defines the type of source sought. According to (Reid et al., 1990), an index between 0 and 1 should be used for mapping contacts and faults. (Thompson et al., 1982) states that the correct index for a given feature is the one that gives the tightest clustering of solutions. He therefore views the SI as a fo-cus control, in which the correct SI produces the most accurate results. In this study IS=0, characteristic of the contacts gave satisfactory results. The new localised 3D Eu-ler method was used instead of the standard Euler method. This is because unlike the standard Euler method, where all grid locations are tested and only those locations whose valid solutions satisfy the input criteria are retained, the localised method first calculates the grid of the analytical signal, finds the peaks in the grid, and then uses these peak locations for Euler deconvolution (Reid et al., 1990). The deep structures revealed by the Euler solutions are oriented along the N-S and NW-SE directions. These directions correspond to those of the discontinuities of the Eburnian orogeny, mainly of N-S direction which influenced the layout of the hydrographic network of the large rivers of the Ivory Coast. In the area, it coincides with the direction of the Volta River, the main watercourse of the basin studied. The NW-SE direction characterises the long outcropping kilometric structures identified on the transformed magnetic images. They correlate well with the topographic fractures highlighted by the parcel studies in the Youan Ta et al, (2008); Jofack-

Sokeng, (2013); Mangoua, (2013); Coulibaly, (2014); Kouamé et al, 2019; Kouamé et al, 2022 (in press).

Conclusion

The use of aeromagnetic maps has revealed a network of superficial and deep struc-tures that have affected the Precambrian basement of the Black Volta Basin in Côte d'Ivoire. These numerous lineaments representing magnetic discontinuities would be fractures and faults. Quantitative analysis of these revealed 458 lineaments with lengths ranging from 9.03 to 66.54 km with a dominance, both in frequency and length, of E-W and NNE-SSW directions. The Euler deconvolution allowed us to delineate some discontinuities and to evaluate their depths. The estimated depths range from 6.8 to 2847 m and the deep structures are organised along two main directions: N-S and NW-SE. These directions mark the different tectonic events that affected the Ivorian Precambrian basement. This study provides new elements on the deep structure of the study area and thus constitutes a contribution to the better knowledge of the aquifer system of the Volta Basin.

Acknowledgements

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