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Filtering of gravity and magnetic anomalies using the finite element approach (fea)

T. Ndougsa-Mbarga, M. Bikoro-Bi-Alou[1,2], T.C. Tabod[1] and K. Kant-Sharma[3]
Department of Physics, Advanced Teacher's Training College, University of Yaoundé 1, P.O. Box 47 Yaoundé, Cameroon.
[1]Department of Physics, Faculty of Science, University of Yaoundé 1, P.O. Box 812, Yaoundé, Cameroon.
[2] Department of Renewable Energy, Higher Institute of the Sahel, University of Maroua, P.O. Box 46 Maroua, Cameroon.
[3]School of Earth and Atmospheric Sciences, Department of Applied Geology, Guindy Campus, University of Madras, Chennai - 600 025, India.
E-mail: theopndougsa@gmail.com/tndougsa@yahoo.fr

ABSTRACT
The separation of both the Bouguer and the total magnetic field anomaly into regional and residual anomalies is one of the most important and crucial steps in the processing of Bouguer gravity and aeromagnetic data. This paper develops an approach based on the concept of shape functions used in finite element approximation. As for the application, we have written a computer code with the MATLAB software using the eight nodes grid rectangle. We have chosen to calculate the regional anomaly of the Mykawa region of Texas (USA) from published data to test the validity of our code. We have also carried out gravity investigations over the Yagoua sedimentary region located in the Far North of Cameroon, and an aeromagnetic investigation over the Ebolowa-Djoum region located in the south of Cameroon. The qualitative analysis of regional and residual gravity maps revealed respectively: (1) a non homogeneous basement and (2) the observed gravity lows as due to the sedimentary infill, and the relative gravity highs associated to structural highs or the presence of either metamorphic or volcanic rocks. Based on the magnetic study, we have subdivided Ebolowa-Djoum area in to five subzones with different particular magnetic responses. Some responses reveal a more or less important signature of iron ore deposits, while others highlight the region's fault network.

INTRODUCTION

During the last decade, the uses of potential field methods in geophysical exploration have been on the rise in the search for minerals and hydrocarbons. The first and the most crucial step in the gravity and magnetic method of data processing is the removal of the effect of deep-seated structures from the observed Bouguer gravity field or total magnetic field so as to enhance the signatures of shallow bodies (Mallick and Sharma 1999, Ndougsa et al, 2007). The targets for specific anomalies are often small structures buried at shallow depths, and these targets are embedded in a regional field that arises from sources that are usually larger and deeper than the targets or are located farther away (Erdem et al, 2005). These shallow bodies are associated in mining exploration to minerals (gold, diamond) with a different density from the surroundings (gravity exploration) and secondly to substances (magnetite, hematite) which have magnetic properties (magnetic exploration).

A space domain-technique based on the finite element approach (FEA) using the eight nodes grid rectangle has been applied to separate the regional and the residual gravity or magnetic field components. The theory of the finite element approach that has been developed is based on that of Mallick and Sharma (1997, 1999) and Kaftan et al, (2005). For application, we have written a computer code with MATLAB software (using the eight nodes grid rectangle) that permits us not only to automatically calculate different anomalies but also to present the obtained results as gravity and magnetic maps of the anomalies. Here, we have chosen to calculate the regional anomaly of the Mykawa region of Texas (USA) to test the validity of our code. We have also carried out gravity investigations over the Yagoua sedimentary region located in the Far North of Cameroon and aeromagnetic investigation over the Ebolowa-Djoum region located in the South of Cameroon.

THEORY

Generally, during the separation of the Bouguer anomaly (or total magnetic field anomaly) into individual anomalies, there are essentially two steps:

- the estimation of the regional anomaly (reg);
- subtract the regional anomaly from the Bouguer anomaly (or the total magnetic field anomaly) (bg) to obtain the residual anomaly (res).

In estimating the regional anomaly, we consider on one hand that, it is regular with a slope that slightly varies and on the other hand, we model it using an analytical surface (2-D modelling). The construction of an analytical regional anomaly using the finite element approach uses the concept and the properties of shape functions (Mallick and Sharma 1999). This approach based on element shape functions used the finite element analysis, has been developed by some authors (Mallick and Sharma 1997, 1999, 2001, Sharma et al., 1999) who have focused its applications on gravity interpretation. According to this approach the weighted sum of the variation of the analytical regional anomaly at any point (x,y) in the survey space can be expressed as a series, which is in fact, the weighted sum of the values at the node of the regional anomaly.

$$greg(x,y) = \sum_{i=1}^{n} P_i(x,y) g_i \text{ ------------------------- } (1)$$

where
n is the number of nodes of the finite element,
g_i is the value of the regional anomaly at the i node,
(x,y) is the coordinate couple of a point on the prospecting zone,
$P_i(x,y)$ are the weighted coefficients also called shape functions.

In general, the polynomials $P_i(x,y)$ are written in the form(Garrigues, 2002):

$$P_i(x,y) = \sum_{k=1}^{n} a_k B_k(x,y) \text{ ------------------------- } (2)$$

where
a_{ik} are the elements of a regular matrix to be determined,
$B_k(x,y)$ are vectors of n dimension basis that generate the n shape functions. This basis is an extract of the canonical basis of the polynomial space whose dimension depends on the degree of these polynomials and the number of variables of the study area (Table.1).

The shape functions satisfy the following condition:

$$P_i(x_j,y_j) = \delta_{ij} \text{ ----------------------------------- } (3)$$

where
δ_{ij} is the kronecker symbol,
(x_j,y_j) are the coordinate of the j^{th} node.

Combining (2) and (3) gives

$$\sum_{k=1}^{n} a_k B_k(x_j,y_j) = \delta_j \text{ ---------------- } (4)$$

Equation (4) helps us to calculate the a_{ik} coefficients.

The final variations of the analytical regional anomaly are given by:

$$reg(x,y) = \sum_{i,k=1}^{n} a_k B_k(x,y) g_i \text{ ------------- } (5)$$

Table 1: Dimensions and canonical basis of the polynomial space with degrees from 1 to 5 for the polynomials with 2 variables

Degree	Dimension	Canonical basis
1	3	$\{1,x,y\}$
2	6	$\{1,x,y,x^2,xy,y^2\}$
3	10	$\{1,x,y,x^2,xy, y^2,x^3,x^2y,xy^2,y^3\}$
4	15	$\{1,x,y,x^2,xy,y^2,x^3,x^2y,xy^2,y^3,x^4,x^3y,x^2y^2,xy^3,y^4\}$
5	21	$\{1,x,y,x^2,xy,y^2,x^3,x^2y,xy^2,y^3,x^4,x^3y,x^2y^2,xy^3 ,y^4,x^5,x^4y,x^3y^2,x^2y^3,xy^4,y^5\}$

Once the regional anomaly has been estimated, the residual anomaly can be calculated from the following formula (Pawlowski,1994; Ndougsa et al, 2007):

gres(x,y) = bg(x,y)-reg(x,y) ------------------(6)

For the present study, the regional is approximated by a weighted sum of discrete potential fields values (gravity or magnetic) at the node of the regional anomaly and the computation is directly done in the real space on the concern potential fields (gravity or magnetic) anomaly map, after it is digitised and discretised through a subroutine inserted in a Matlab code. This automatic discretization is realized by using eight stations coinciding with eight nodes of second order isoparametric elements on the digitized map space. This innovation has solved the problem of using the reference space for computation with the shape functions acting as weighting factors and subsequently translated to the real map space. The determination of the regional anomaly exploits the hypothesis according to which the limits of the prospecting area are sufficiently far off in such a way so as to neglect the influence of the residual anomaly at the boundary. Consequently, the available values of the potential field (gravity or magnetic) anomaly at the boundary are related to those of the regional anomaly.

The calculation of the values of the Bouguer anomaly and the total magnetic field at each point of the prospecting area necessitates the availability of a finite number of data at the border and inside of the study area and uses the same finite element approach.

APPLICATIONS

Validation of our code

For the validation of our code built in Matlab, we have computed data from Mykawa area compiled from Mallick and Sharma (1997). Looking at these different results, there appears a net resemblance in the calculated values (Table.2) and on the observed maps (Fig.1 and Fig.2). This confirms the validity of our code.

First case study: the Yagoua sedimentary basin and surrounding areas

General geology and gravity data source

The Yagoua region in the far North region of Cameroon (Fig.3 (A) & (B)) lies between latitude 9°45′ and 11° North and between longitude 14°20′ and 15°50′ East. It covers an area of about 24820 km^2. According to some investigators (Genik, 1992, Vicat and Bilong, 1998), the region was affected by the Pan African orogeny (750-550 Ma), which produced major basement lineaments and faults of Paleozoic (550-130 Ma), Cretaceous (130-75 Ma), Maastrichtian-Paleogene (75-30 Ma) and Neogene-Recent (30-0) age. The area contains quaternary alluvium and sandstones, and post Cretaceous volcanisms such as basalts. The basement consists of granites and gneisses (Vicat and Bilong, 1998; Schuster et al, 2005).

On the basis of t he Bouguer anomaly map (Fig.4) (Njandjock et al, 2006), we have assumed an

Table 2: Comparing results obtained by our code (reg2) to those of Mallick and Sharma, 1997(reg1).

X(mi)	Y(mi)	Reg1(mgal)	Reg2(mgal)
0	0	2.5	2.50
0	7.5	3.3	3.30
0	15	4.0	4.00
7.5	0	4.0	4.00
7.5	15	3.5	3.50
15	0	6.0	6.00
15	7.5	2.9	2.90
15	15	4.2	4.20

eight nodes grid in real space (Fig. 5) and extracted 251gravity field values. Our computer code has used these data for regional-residual separation.

Analysis of the Bouguer anomaly map

The Bouguer anomaly map of the study area (Fig. 4) (Njandjock et al, 2006) and the one derived from our computer code (Fig. 6) correspond to each other both shape and magnitude wise. We observe two major relative gravity lows. The first one encompasses the western portion of the study area with a NE-SW orientation (comprising Maroua, Dargala, Moulvouday, Mindf, Kaele). This gravity low is limited to the north, east and south by belts of relative gravity highs. The second relative gravity low has a NW-SE orientation. That one is located in the north-east portion of the study area and encompasses the Magoa zone. There are gravity highs on the north, south and west corresponding to Ouale Lasso, Bongor and Yagoua and Kay Kay regions. The removal of the effects of deep structures from the Bouguer anomaly will bring out more details about the shape or the possible nature of the observed anomalies.

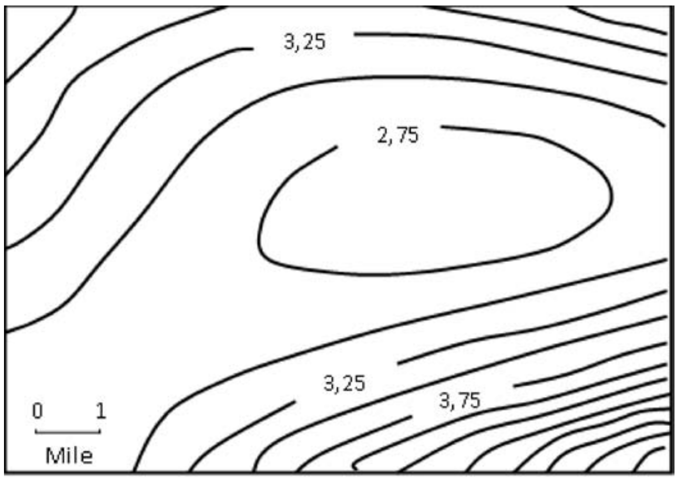

Figure 1. Regional anomaly map of Mykawa region (after Mallick and Sharma, 1997).

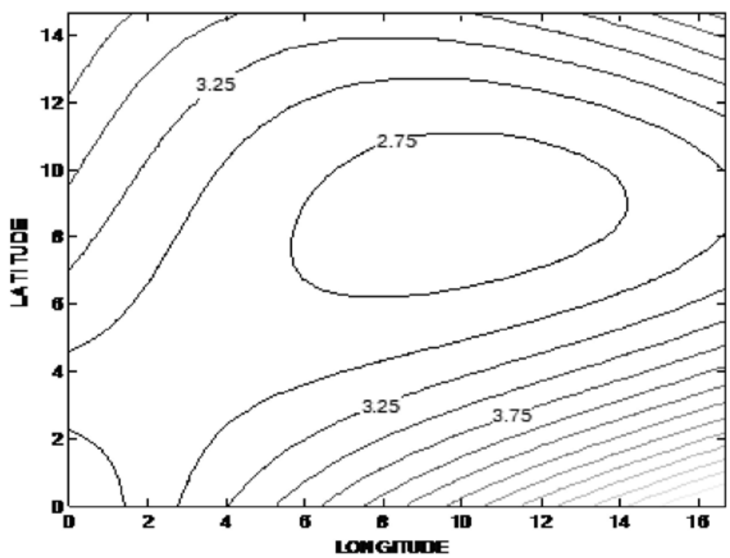

Figure 2. Regional anomaly map of Mykawa region derived from our computer code. Longitude and latitude in miles. Regional anomaly in mGal

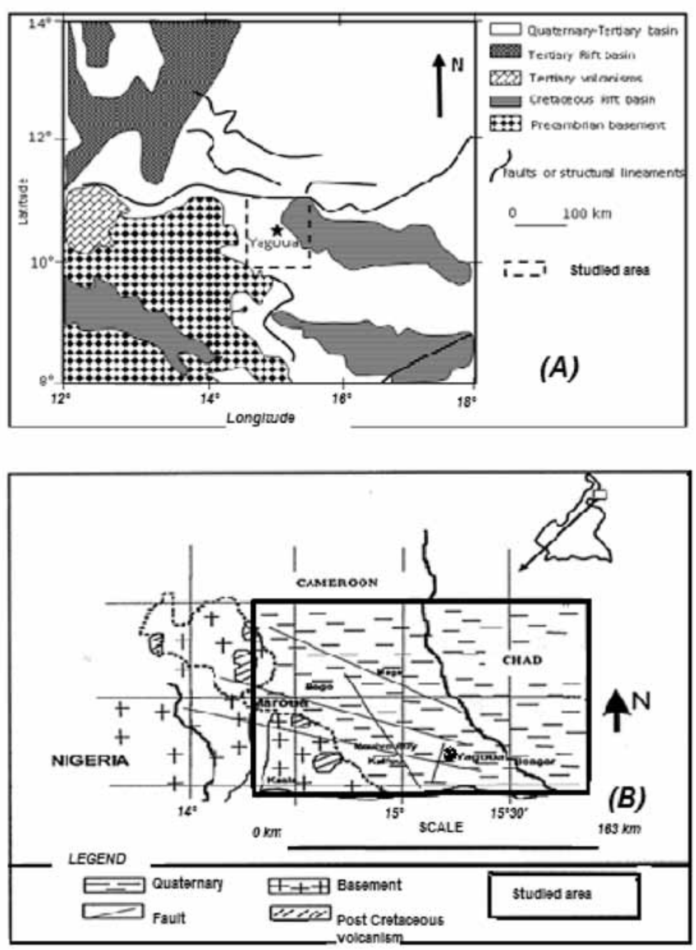

Figure 3. (A): General geological map of Yagoua sedimentary basin and surrounding areas (Genik 1992); (B): Simplified geological map of Yagoua area from Schuster et al.(2005).

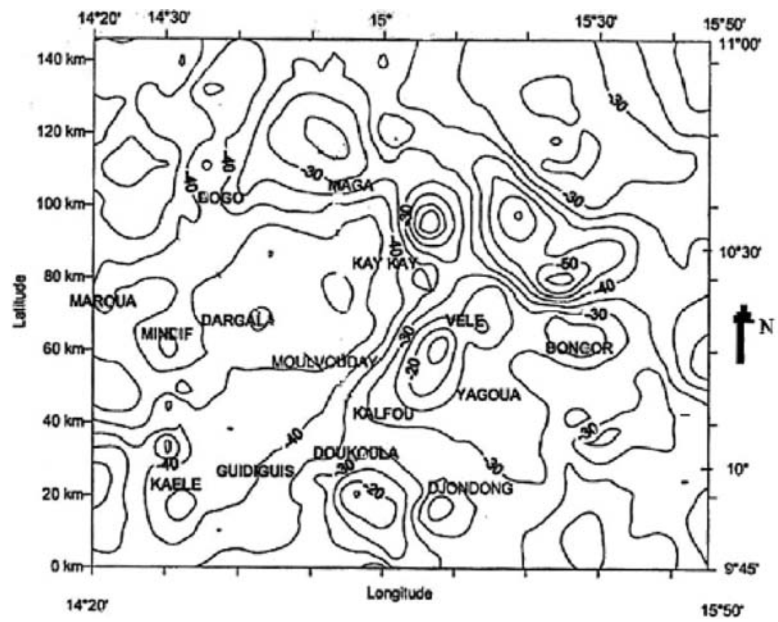

Figure 4. Bouguer anomaly map of the Yagoua sedimentary region by Njandjock et al., 2006.

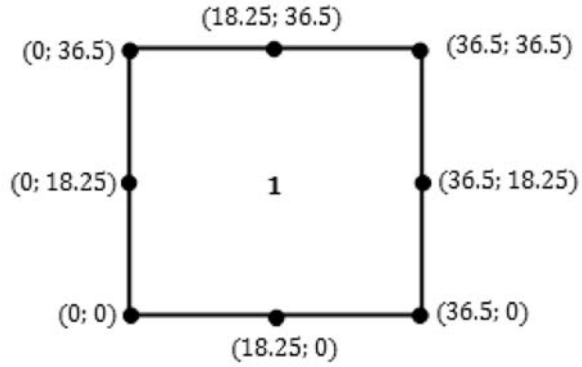

Figure 5. The finite element number 1 with the coordinates of its eight nodes. Coordinates are in kilometres. Finite elements in real space with eight nodes grid, each element has eight nodes and a number for its identification.

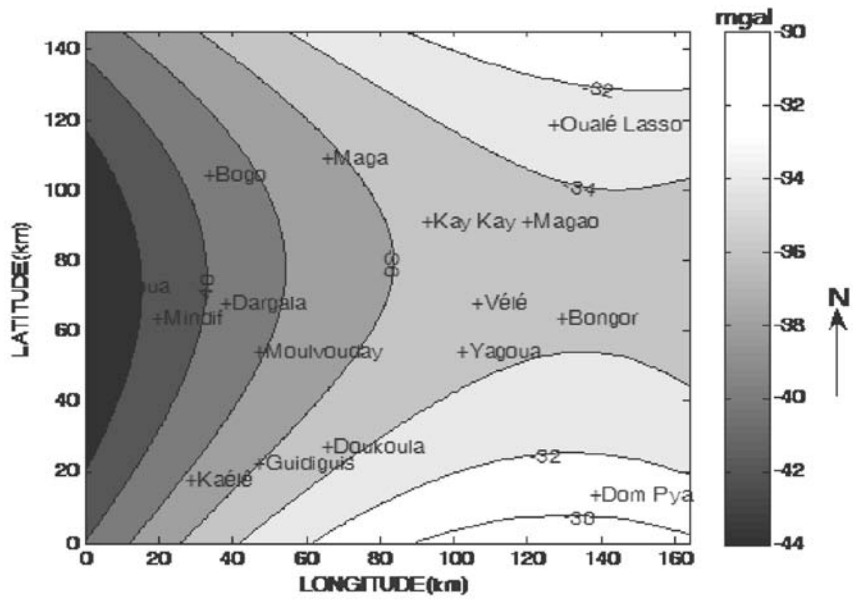

Figure 6. Image of the Bouguer anomaly of the Yagoua sedimentary region with contour details derived from application of our computer code. Contour interval 5mGals

Analysis of regional anomaly map

The computed regional gravity anomaly (Fig.7) has no closed low or high gravity values. In general we observe an E-W gravity gradient. With that result we can infer that the basement of the study area is associated with faulted structures. This fact is in accordance with general geology of the area.

Analysis of the residual map

The residual anomalies correspond in magnitude and shape to those expected from the qualitative analysis of the Bouguer anomaly. In the residual anomaly map (Fig.8), we can observe two major and four minor gravity lows. The first major gravity low with a NE-SW trend encompasses the towns of Dargala and Moulvouday to the west and south respectively with the minimum of -10 mGal. From its eastern limit to the centre, it shows 1.4 mGal/km gravity gradient. The second major gravity low, with a trapezoid shape is oriented in NW-SE direction encompassing Magao region with the minimum of -15 mGal. Minor gravity lows are located at Dom Pya (-10mGal), Kaele (-5 mGal), south west of Mindif (- 5mGal) and north west of Maga (-5 mGal).

All these anomalies indicate that the Yagoua sedimentary basin has a complex structure, being

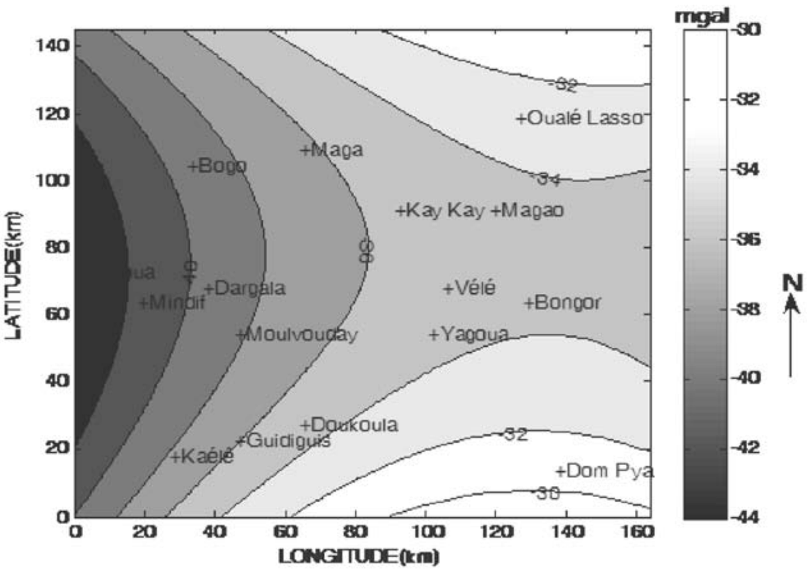

Figure 7. Image of the Regional anomaly of the Yagoua sedimentary region with contour details derived from our computer code. Contour interval 2mGals

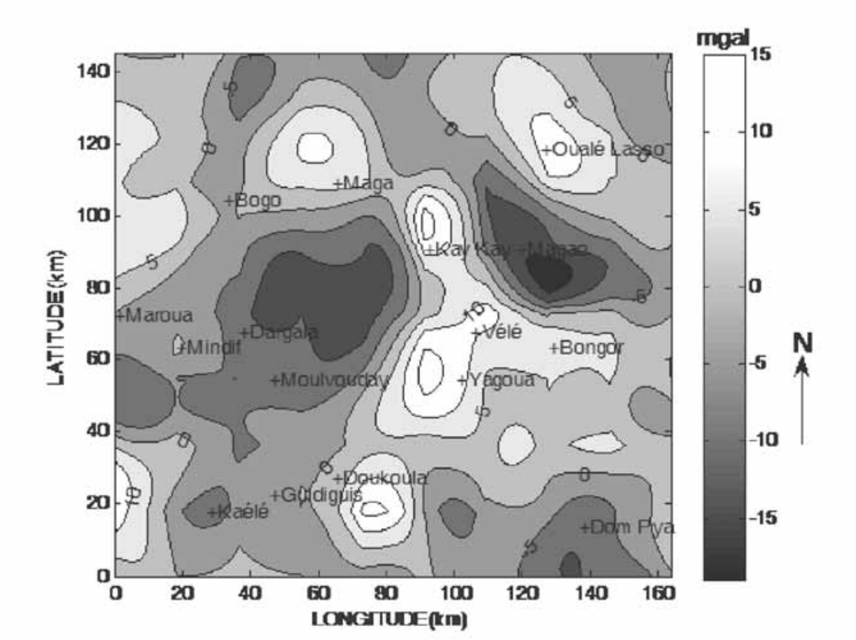

Figure 8. Image of the Residual anomaly of the Yagoua sedimentary region with contour details derived from our computer code. Contour interval 5mGals

constituted by three sub-basins separated by structural highs (between Moulvouday and Magao, the major one, and Dom Pya the minor one).

Between Moulvouday and Dom Pya gravity lows, we observe two major positive anomalies with approximately NE-SW orientation: the Yagoua closed gravity high and the Doukoula closed gravity high with a maximum of 15 mGal at both places. In Magao, on the northern side of Mouvouday, the anomalies show a 10 mGal. The gravity high of Ouale Lasso, with a NW-SE orientation, is situated in the northern side of Magao. In the north of Maroua features a positive residual anomaly that is inferred to be due to volcanic rocks from Cameroon volcanic line. We interpret the gravity lows to arise out of the sedimentary infill, and the relative gravity highs associated to structural highs or the presence of either metamorphic or volcanic rocks.

Second case study: Ebolowa- Djoum area

General geology of the area

Located between longitudes 11°30′ and 13°00′ East and latitudes 2°30′ and 3°00′ North, Ebolowa-Djoum area (Fig. 9) belongs to the South region of the Republic of Cameroon and a small portion is located in the administrative East region of Cameroon. The area of Ebolowa-Djoum is largely overlain by pyroxene granite and gneiss. These rocks are Archean formations (Regnoult, 1986), and have been dated as the oldest metamorphic rocks of Cameroon. Gneisses have the same mineralogical composition as pyroxene granites only with differing texture. Migmatites that transgress from east to west are described as iron-rich quartzitic gneiss (Paterson et al, 1976) and form well-marked peaks like Mount Ngoa. In the North-east of the study area, the granites are in contact with chloritic schists by faults. These faults, with others, show two directions which are respectively NE-SW and NW-SE (Bessoles and Lasserre 1977).

Aeromagnetic data source

Based on the total field magnetic anomaly map prepared by Paterson et al, (1976), we made a grid of 216 rectangular elements with eight nodes each in real space and 709 data points were collected.

The magnetic units have been identified by using the approach developed by many authors (Paterson et al, 1976; Prieto, 1996 ; Wong and Laughlin, 1998) based on the anomaly characteristics. The criteria are:
Mean anomalies amplitude;

- The polarity of anomalies;
- The shape and the patterns of the anomaly contours.

Analysis of magnetic anomaly map of the total field

The Ebolowa-Djoum area presents a complex magnetic response. This is a characteristic of a metamorphic terrain (Keary and Brook, 1991). Here the magnetic contours are of variable forms; some in closed mini loops and others in large elongated loops. From Fig. 10 two zones are distinguished: the first is the northern half of the study area mainly granitic and the second is its southern half mapped principally by pyroxene gneiss (Champetier and Aubage, 1956).

In the northern half, the magnetic contours are in two directions. One is NW-SE and the other NE-SW. Both directions follow the orientation of observed faults. The highest and lowest magnetic intensities are at Kamelon (maximum=33400Gammas, minimum= 31800Gammas).

In the southern half, the magnetic contours are of S-E direction. This zone provides an exceptional high magnetic field above the background noise in the west of Mvangan and at Ngoa where the highest intensities are recorded (maximum=33200Gammas).

Analysis of the regional magnetic anomaly map

Here the magnetic contours are not closed (Fig.11). This suggests that the anomalies observed in the total field magnetic map are the manifestations of surface magnetic bodies. However, the division of the study area into two subzones is more visible here around the latitude 2°45′. This cleavage seems to materialize the contact between the granites and gneisses of the North and South respectively.

Analysis of the residual magnetic anomaly map

The residual magnetic anomalies map in Fig.12 enables to subdivide the region into different units (Fig.13). The magnetic units have different magnetic characteristics which are: mean anomalies amplitude, the dominant polarity of anomalies, the shapes of the profiles of the anomalies, the lengths of the patterns of anomaly contours.

Unit I
It is characterized by reduced anomalies (200 gammas), with irregular shapes and normal polarity, that corresponds to rocks having a minimal magnetite content. These rocks contain less ferromagnetic material than the gneisses and granites. Unit I is located in the central part of Djoum area.

Unit II
It is characterized by long, narrow and linear anomalies. The mean amplitudes are between 200 and 800 gammas. A normal and inverse polarity is observed. These anomalies probably indicate formations of thin layers whose shapes resemble

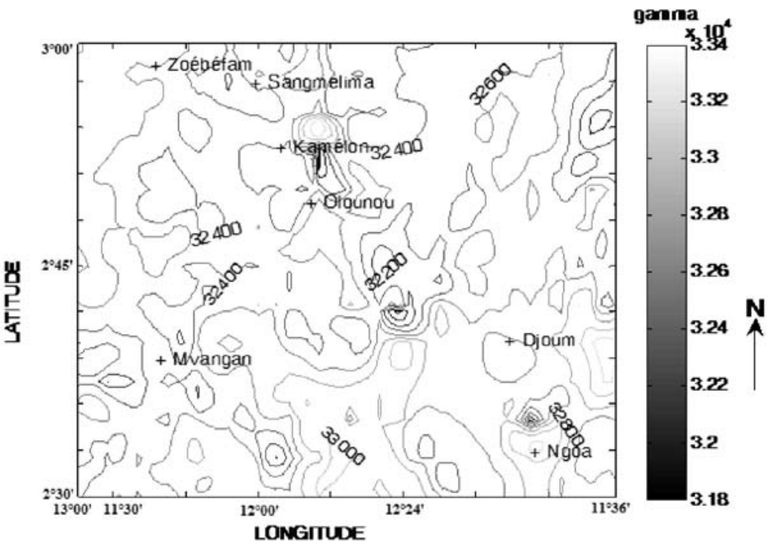

Figure 10. Magnetic anomaly map of the total field of the Ebolowa-Djoum region derived from our computer code. Contour interval=200 Gammas.

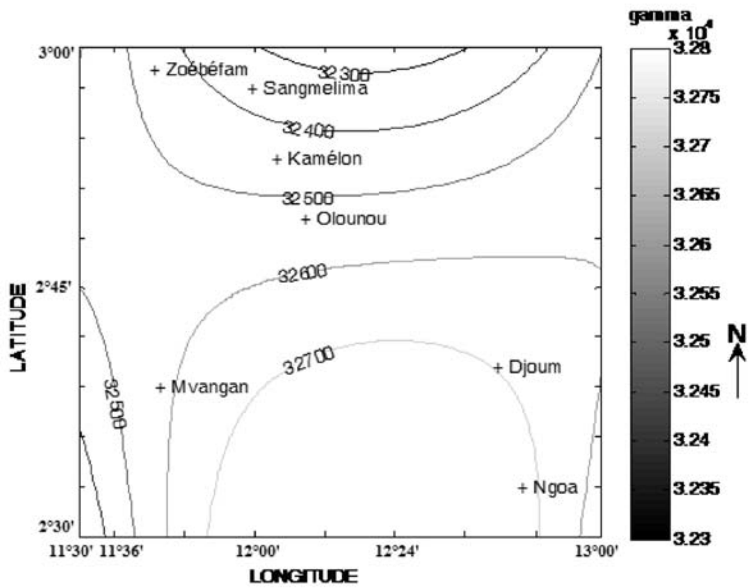

Figure 11. Regional magnetic anomaly map of the Ebolowa-Djoum region derived from our computer code. Contour interval=100 Gammas

veins or dykes, and are oriented in the NE-SW of the observed faults directions. Unity II is clearly visible to the northeast of the study area.

Unit III

Unit III contains anomalies less continuous, more twisted and with an average magnetic response ranging between 200 and 400 gammas. A normal polarity is observed. It is interpreted as relics of formations rich in iron intercalated with acidic granites in rich pyroxene. The magnetic contour patterns of this unit are in two directions: one is NW-SE and the other NE-SW. These patterns are visible in the west and east of Sangmelima.

Unit IV

The strongest magnetic anomalies in this unit are generally long and linear, and often occur in pairs

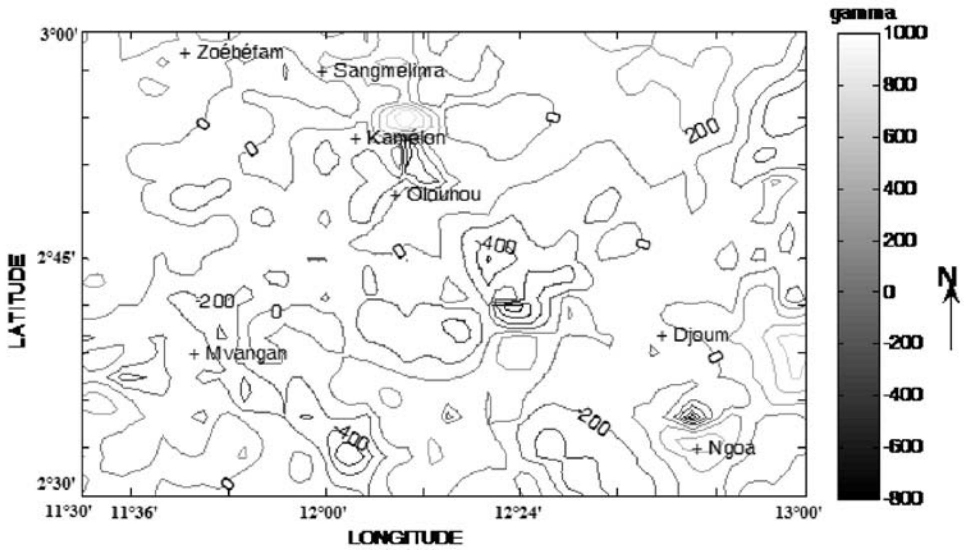

Figure 12. Residual magnetic anomaly map of the Ebolowa-Djoum region derived from our computer code. Contour interval=200Gammas

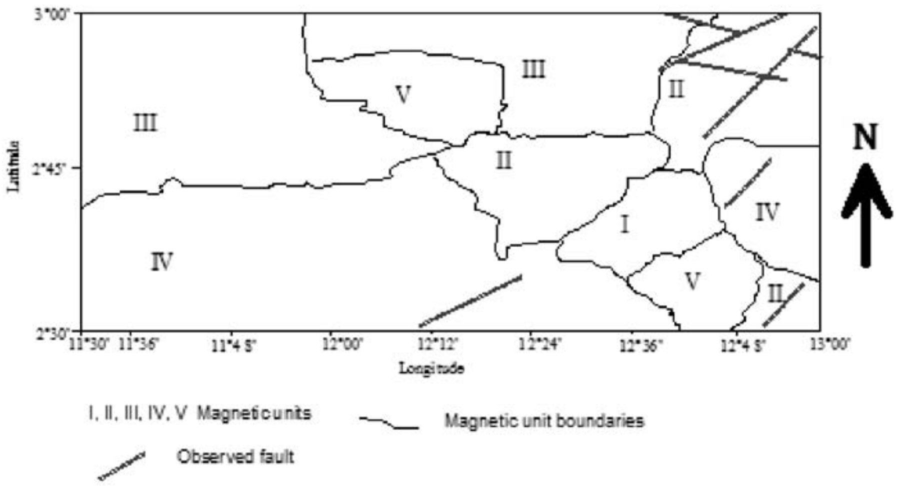

Figure 13. Magnetic units map of Ebolowa-Djoum region

with opposite polarities. They are interpreted as ferrous formations. In fact, the geological inference regarding the presence of a ferrous formation was found in a quarry around Mvangan. This unit could be a response of a magnetic body rich in iron, pleated and tucked within gneisses and granites.

Unit V

This unit includes the most significantly high anormalies in the Ebolowa-Djoum region. These are the Kamelon anomaly, the Ngoa anomaly and that between Djoum and Olounou. The magnetic contour patterns of the Ngoa and Kamelon anomalies are similar to that of magnetic dipole. Such a signature is a characteristic of formations rich in iron that are found almost everywhere in the Ebolowa-Djoum region.

CONCLUSIONS

In this paper, the objective was to build a code in Matlab environment, based on the concept of element shape functions used in finite element analysis, in order to enhance the accuracy of potential fields data filtering. The automatic test on published data construction has validated the code. In the present procedure of filtering and map, the mesh was made directly in real space. With this, the gravity and magnetic maps were obtained directly with the actual coordinates of the study areas. Moreover, the separation of gravity and aeromagnetic data has been supplemented by a qualitative analysis of different maps. The qualitative analysis of regional and residual gravity maps revealed respectively a non homogeneous basement on one hand; and the observed gravity lows are correlated to the sedimentary infill, and the relative gravity highs associated to structural highs or the presence of either metamorphic or volcanic rocks, in other hand. The qualitative magnetic study derived from the application of the finite element has permitted to subdivide Ebolowa-Djoum area in five subzones with different particular magnetic responses. Some responses reveal a relative important signature of iron ore deposits, while others highlight the region's fault network. The results obtained in this work can be useful in future for a quantitative analysis of these data.

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Prof. Dr. T. Ndougsa-Mbarga completed his B. Sc., PGDE in Physics & the M.Sc. and PhD in Geophysics, respectively at the Advanced Teacher's Training College (ATTC) and the Faculty of Science in the University of Yaoundé 1. He obtained Diplomas in Mining Exploration-Exploitation and Petroleum Operations Management respectively in Witwatersrand and Pretoria Universities (South Africa Republic) and in PETRAD Programme (NPD, Norway). He is presently Associate Professor of Exploration Geophysics & Astronomy in the Department of Physics, ATTC (ENS), and Sub-Director in charge of mining exploration activities, mineral inventories and natural disaster prevention in the Ministry of Mines, Industry and Technological Development of Republic of Cameroon. He has more than 12 years experience in teaching physics, geophysics and mining exploration courses. His current research interest includes filtering potential field data using finite element, Fourier analysis and wavelet and their 2.5D modeling in one hand; the magnetotelluric (tensorial AMT), data collecting and interpretation using the Bostick, in addition radiometric data processing for mining in the other hand. He has published 18 articles in international journals, and supervised over 28 M.Sc. & PGDE in 12 years of research. Currently he's supervising 7 PhD Theses; and one has been defended in October 2011.

Mr. M. Bi-Alou Bikoro completed his B. Sc., PGDE in Physics & M.Sc. in Geophysics respectively at the Advanced Teacher's Training College (ATTC) and the Faculty of Science in the University of Yaoundé 1, and he is presently pursuing his PhD in the same University. He is an Assiastant Lecturer at the Department of Renewable Energy, Higher Institute of the Sahel, University of Maroua. His current research interest includes filtering of potential field data using finite element and Fourier analysis, and their 2.5D modeling. He has submitted some papers in international journals.

Prof. Dr. T.C. Tabod is an Associate Professor at Department of Physics, Faculty of Science, University of Yaoundé 1 & Dean of the Faculty of Science at the University of Bamenda. He holds a B.Sc. and "Maitrise" in Physics, University of Yaoundé 1 and M.Sc. and PhD in Geophysics, University of Leeds. He has supervised over 20 M. Sc. and 2 PhD students in nineteen years of teaching and research experience. He has published more than 15 articles in international journals. His specific topics are seismological and gravity investigation of Crust and Upper Mantle beneath Cameroon.

Dr. K.K. Sharma obtained his M. Sc. and Ph. D. degrees in Exploration Geophysics, from Osmania University, Hyderabad in 1977and 1984. His research interests include potential field data processing and use of geophysics in exploration. He has been associated with the work related to use of geophysics as a part of integrated approach to demarcate and delineate zones of pollution with special reference to urban landfill pollution. He is presently Professor and Head at the Department of Applied Geology and Centre for Environmental Sciences, University of Madras. He is presently a member in the working sub group of Tamilnadu State Planning Commission.