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Interpretation of Gravity Data and Contribution to the Study of the Geological Structure of the Province of Mai-Ndombe in Dr Congo: Implications in the Exploration of Hydrocarbons.

Willy Biliki Kilembe[1], Franck Tondozi Keto[1-2-3], Eli-Achille Manwana Mfumukani[2], Grace Tshimanga Kamba[3], Anscaire Mukange Besa[1], Robert Muanda Ngimbi[1].

[1]Department of Physics, Faculty of Sciences, University of Kinshasa, Kinshasa, DR Congo.
[2]Department of Internal Geophysics, Center of Research in Geophysics (CRG), Kinshasa, DR Congo.
[3]Department of Exploration and Production, Faculty of Oil, Gas and New Energies, University of Kinshasa, Kinshasa, DR Congo.

Abstract:- This study is focused on the recognition of the geological structure of the province of Maï-Ndombe in DR Congo based on the analysis and interpretation of gravity data. These data were processed using regional-residual separation methods, horizontal and vertical derivatives, and upward continuation. The integration of all the geological information resulting from the interpretation of gravity maps has enabled us to develop a structural map that improves our knowledge of the geological structures of major petroleum interest in this area. Reading this structural map shows us that the Inongo high is the highest geological structure while the Lokoro depocenter is the deepest geological structure in this province. These two structures being close, a part of the oil formed in the Lokoro depocenter could easily migrate along the large faults to be trapped in the upper stages located in the Inongo high. As such, these two structures represent the most important oil targets in this region and should be the subject of much more seismic exploration.

Keywords:- *Gravity, Geological Structure, Petroleum, Depocenters.*

I. INTRODUCTION

The exploration of the Congo basin began in the 1950s. The first exploration project was carried out between 1952 and 1956 by the 'Société de Recherche Minière en Afrique' (REMINA) and consisted of a geological prospecting, a combined gravity and magnetic survey, the acquisition of 600 km of seismic refraction profiles and 131 km of seismic reflection profiles as well as the drilling of two stratigraphic wells approximately 2,000 m deep (Samba-1 and Dekese-1) (Delvaux and al., 2015 [1]). Then several additional studies based on geochemistry, geology, geophysics and the drilling of two new exploration wells more than 4,000 m deep (Mbandaka-1 and Gilson-1) were carried out in order to improve the understanding of the geology and petroleum system of this basin (ECL, 1988 [2]). These made it possible to retain that this gigantic sedimentary basin would have a major petroleum interest by highlighting source rocks, migration routes, reservoir rocks and possible traps (Mello, 2006 [3]; ENI, 2011 [4]). As part of this study, we will deepen our knowledge of the structural geology of the province of Maï-Ndombe in order to guide future oil prospecting in the region.

II. MATERIAL AND METHOD

2.1 MATERIAL

We used a gravity database of the Congo basin which was provided to us by the 'Société Nationale des Hydrocarbures du Congo' (SONAHYDROC) in Excel format. A range of processing and modeling software in earth sciences was essential to carry out this work.

2.2 METHOD

The method used to carry out this study can be summed up in three stages:

- The first step concerns data acquisition. It consisted in listing all the gravity measurements located in our study area in a database. These stations come from a compilation of geophysical surveys carried out by the 'Société de Recherche Minière en Afrique' (REMINA) between the years 1952-1956 and by the 'Compagnie Générale de Géophysique' (CGG) in 1986 for mineral and oil exploration in the Congo basin;
- In the second step, we made the data processing and the mapping of the results obtained. To do this, the methods of regional-residual separation, vertical and horizontal derivatives as well as upward continuation have enabled us to develop several maps identifying multiple gravity signatures that can be associated to geological structures with petroleum interest;
- The third step was to interpret the results. At this stage, it was a question of giving a geological significance to the gravity signatures identified on the produced maps.

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III. GENERAL OVERVIEW OF THE STUDY AREA

3.1 GEOGRAPHICAL OVERVIEW

The province of Mai-Ndombe is, since 2015, one of the provinces of the Democratic Republic of Congo following the break-up of the former province of Bandundu. It is between 16 ° and 21 ° East longitude and between 0 ° and 4 ° South latitude. It is thus bounded to the north by the province of Equateur, to the west by the Congo river which separates it from the Republic of Congo, to the south by the Kasaï river and the province of Kwango and to the east by the province of Kasaï-Occidental. Its area is approximately 127,314 km^2. Administratively, it is subdivided into 8 territories, 19 sectors and 52 groups. The capital of the province is Inongo, which is also its largest city (fig. 1).

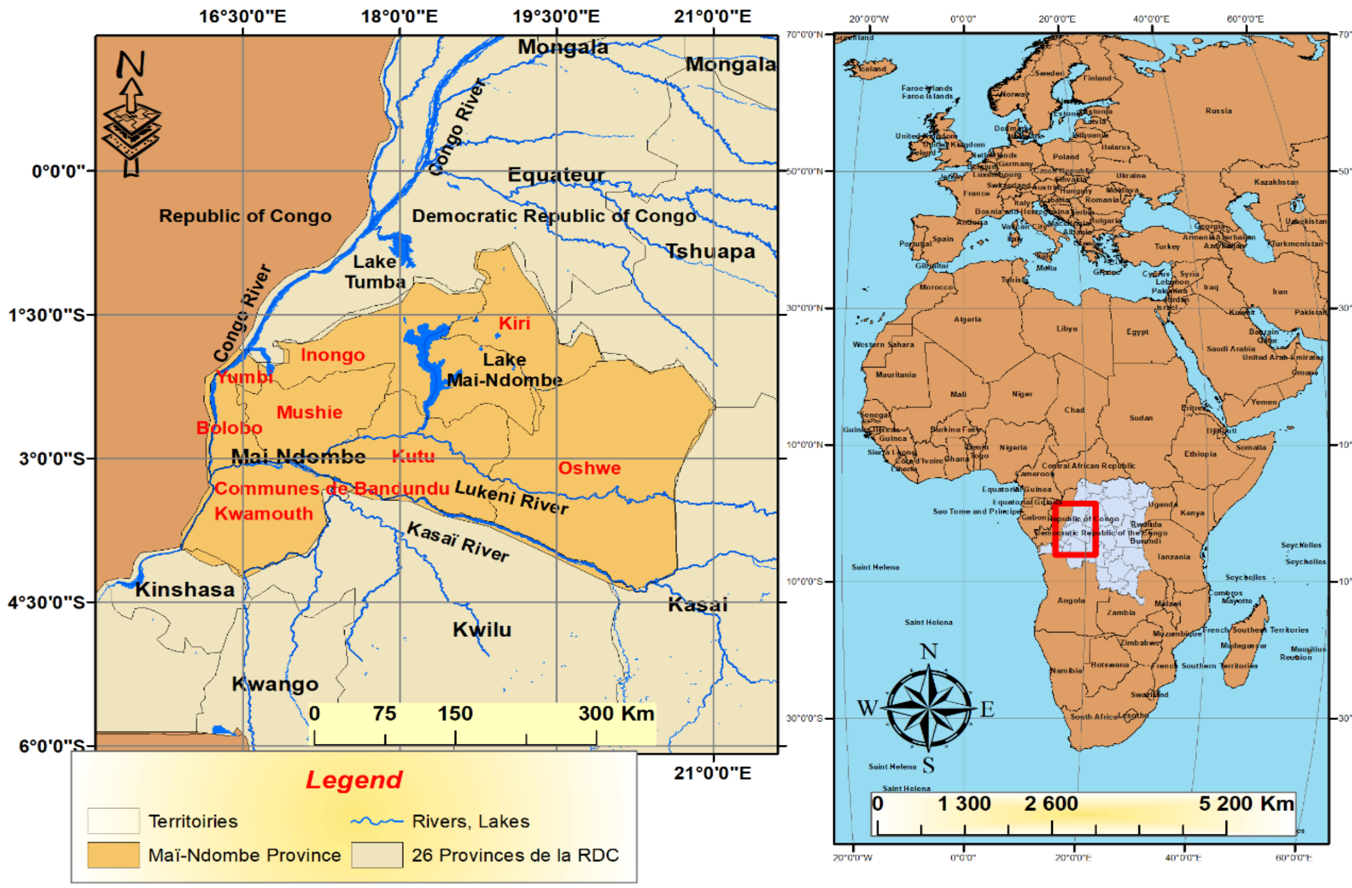

Figure 1: Map of the location of Maï-Ndombe province.

The province of Maï-Ndombe is located in the Congo Basin. From east to west and from north to south, it presents a low and monotonous relief with a low altitude of 500 m on average. The province experiences a transition climate which is between the equatorial climate and the tropical climate, characterized by an average temperature of 25 °C, a low annual thermal amplitude of less than 1 °C from the city of Inongo to the North (Kiri and Oshwe territories) and 1 °C to 3 °C for the rest of the province. This climate is also characterized by abundant rains with annual precipitation of around 1,600 mm in the west, 1,800 mm in the center and 2,000 mm in the north, and a clear and well-marked dry season. There are two rainy seasons and two dry seasons. The great rainy season runs from February to May and the great dry season runs from May to September. As for the short rainy season, it is between the month of September and the month of January, while the short dry season runs from mid-January to mid-February. The average temperature is 28 °C during the rainy season and 24 °C during the dry season.

The vegetation of the province is varied and is presented as follows:

- From the city of Kutu to the territory of Kiri in the north, there is an evergreen forest, it is the equatorial forest with large trees forming a continuous dome of 35 to 45 m;
- From the city of Kutu to the territory of Kwamouth in the south, the vegetation is characterized by woodland and savannah.

In addition to Maï-Ndombe Lake, the province is crossed and bathed by the country's major rivers: The Congo River as well as the Kasaï, Lukenie, Lokoro, Mfimi and Molibampe rivers.

3.2 GEOLOGICAL OVERVIEW

Geological, geophysical and geochemical studies as well as the drilling of exploration and stratigraphic wells have contributed to the understanding of the surface and deep geology of the Congo Basin. In this zone, the soils are in direct relation with the vegetation: they are of the sandy to sandy-clayey type in the forest region while in the savannah region they are of the very sandy type succeeding each other in the south by clayey soils.

The regional stratigraphy was studied by the Gilson-1 exploration well (19°54'30"E; 02°44'10"S). This borehole cuts through 998 m thick interbedded red sandstones with mudstones, and then 2,269 m thick red sandstones, dark brown siltstones and red-brown mudstones and conglomeratic sandstones. This section overlies 1,229 m thick interbedded sandstones with limestones and dolomites. The hole terminates at a depth of 4,645 m in the dolomites (Bastien Linol and al., 2015 [5]).

From a tectonic point of view, this basin was marked by a crustal extension during its initial development in the Neoproterozoic which certainly initiated the development of other peripheral Neoproterozoic basins such as the Sembe-Ouesso, Fouroumbala-Bakouma and Bangui (Kadima and al., 2015 [6]). It should be noted that lithostatigraphy, the structural aspect and the paleo-environment confirm this hypothesis (Delpomdor and al., 2015 [7]). The sediments were later affected by the Pan-African and Permo-triassic (Hercynian) compressive events, phenomena which will be the basis of the tectonic imprints in the Congo Basin. The involvement of salt tectonics observed on most of the seismic profiles also contributed to the structural evolution of this basin. It should be noted that this basin is currently tectonically active along the margin of the East African Rift (Delvaux et al., 2010 [8]).

IV. PRESENTATION OF GRAVITY DATA

The gravity data used in this work come from a compilation of geophysical surveys carried out by the ‘Société de Recherche Minière en Afrique’ (REMINA) between the years 1952-1956 and by the ‘Compagnie Générale de Géophysique’ (CGG) in 1986 for mining and oil exploration in the Congo basin in the DRC. These data were provided to us by the ‘Société Nationale des Hydrocarbures du Congo’ (SONAHYDROC). They were then corrected using the classic Bouguer anomaly formula for a reduction density of 2.67 g/cm^3 in which a series of corrections is applied to the raw measurements in order to eliminate the non-geological causes of gravity variations, including topographic correction. Table 1 below shows the database used for this study. Note, however, that it is not easy to list all the stations present in the database due to their multitude, which justifies the choice of the first five stations, by way of illustration.

Table 1: Sample of gravity data used.

N° Station	Longitude (°)	Latitude (°)	Elevation (m)	Gravity (mGal)	Free-Air Anomaly (mGal)	Bouguer Anomaly (mGal)
01	16.2283	-2.1717	326	977933.3	-5.2	-41.7
02	16.2367	-2.235	311	977938.4	-5.2	-40
03	16.2383	-2.325	311	977939.9	-4.3	-39.1
04	16.2383	-2.3783	330	977933.7	-5	-42
05	16.2433	-2.6367	309.5	977929.2	-17.9	-52.5

In gravity survey, the purpose of data processing is to separate the anomalies, to better specify the depths of sources, to represent geological limits such as contacts or faults, etc. (Dubois and al., 2011 [9]). A variety of processing methods are therefore available depending on the desired goal. The objective of this work being to carry out the structural study of an area of major petroleum interest, we used the methods of regional-residual separation, the horizontal and vertical derivatives as well as the upward continuation of the Bouguer anomaly.

V. INTERPRETATION OF GRAVITY MAPS AND DISCUSSIONS

The Bouguer anomaly maps are the most important documents in gravity prospecting. It is through the readings, analyzes and interpretations of these maps that prospectors, geologists and geophysicists find geological hypotheses by analyzing the variation in density of geological formations found within a sedimentary basin. Thus, in order to carry out a more complete structural study, the following maps have been produced:

- Bouguer anomaly map;
- Regional and Residual anomaly maps;
- horizontal and vertical derivative maps;
- Upward continued maps.

Subsequently, a map summarizing the structural interpretation obtained from the analysis of the above gravity maps was also developed.

3.3 BOUGUER ANOMALY MAP

The Bouguer anomaly map of the province of Maï-Ndombe reveals the existence of a regional gradient highlighted by values ranging from -110 to -30 mGal. Thus, heavy anomalies values varying between -70 and -30 mGal are observed mainly which are synonymous with an uplift of the crystalline basement mainly in four zones: in the North-West (Inongo high), in the South and in the Southeast of the province. As for the slight anomalies, they are observed to the North, South and East of the Inongo high (fig. 2). These therefore represent the large depressions of the basement filled by a substantial sedimentary thickness. In the rest of the province, anomalies are observed with average values.

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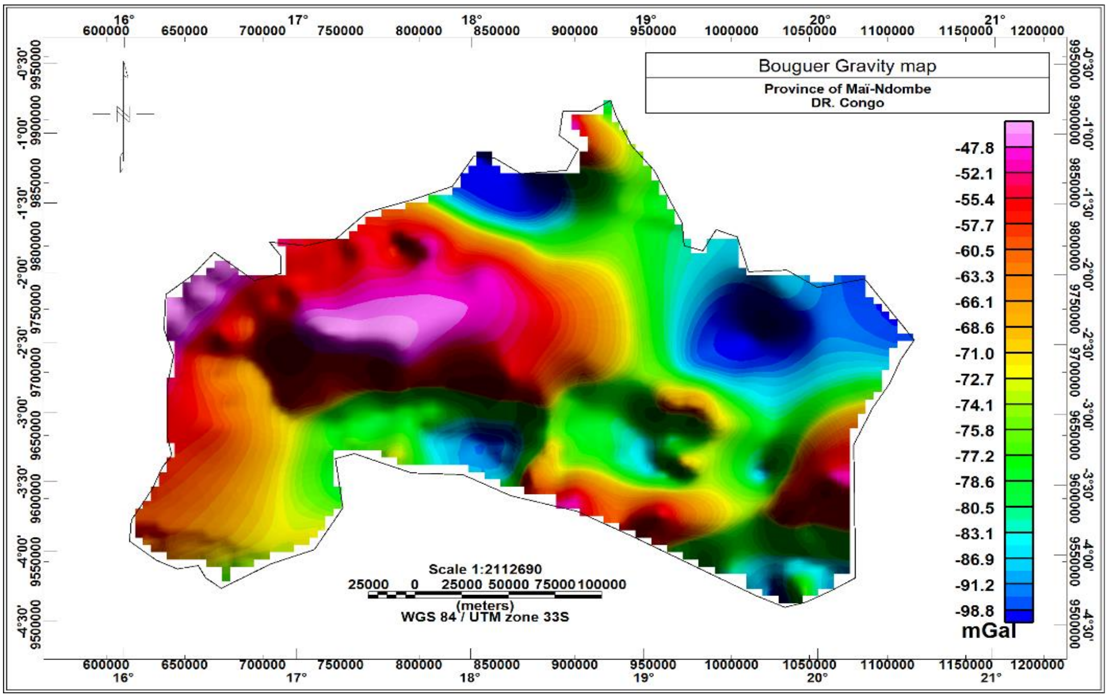

Figure 2: Bouguer gravity map.

3.4 REGIONAL ANOMALY MAP

The spatial distribution of regional anomalies is identical to that of the Bouguer anomaly map. However, we note that the relief of the regional anomaly map has a little less roughness due to the attenuation of the high frequencies of the signal by the application of the low pass filter during the data processing phase. Regional scale structures such as the three depocenters and the Inongo high become clearly visible on this regional anomaly map. As for the rest of the province, we still observe the same variations in anomalies (fig. 3).

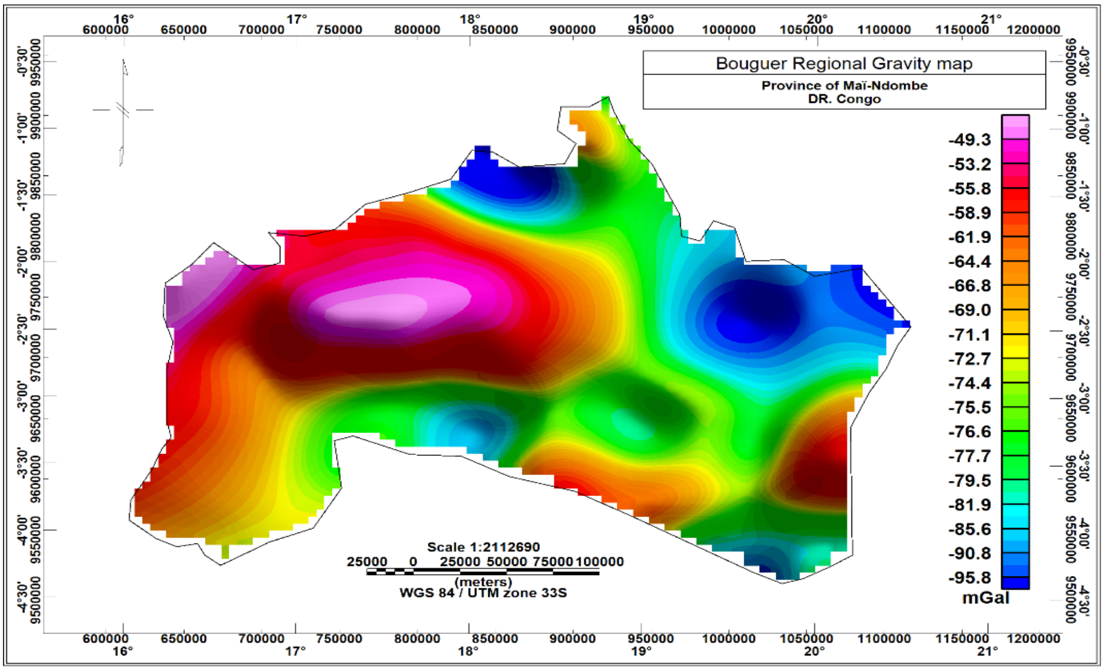

Figure 3: Regional anomaly map.

3.5 RESIDUAL ANOMALY MAP

The sources generating these short wavelength anomalies are generally the geological structures located in the sedimentary cover (salt dome, faults, folds, etc.) (Tondozi and al. 2018 [10]). The residual anomaly map (fig. 4) was therefore obtained by difference between the Bouguer anomaly and the regional anomaly.

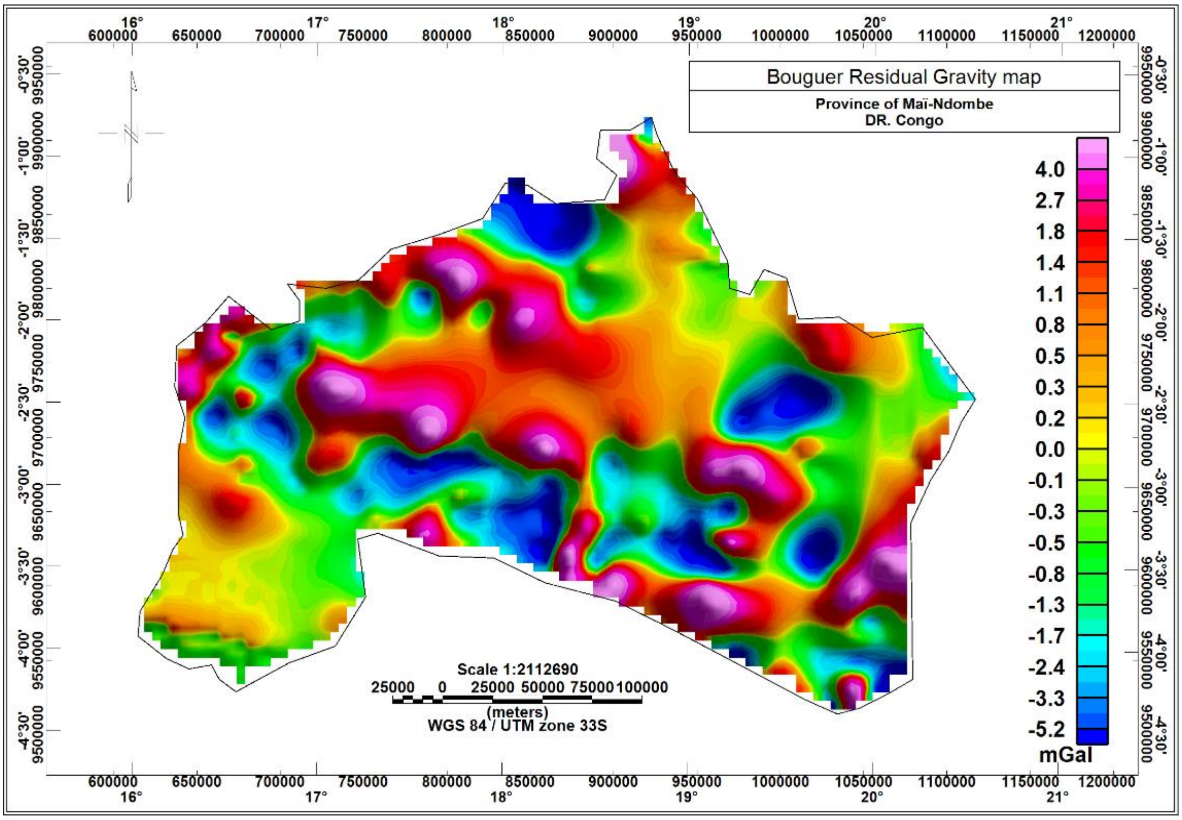

Figure 4: Residual anomaly map.

On the map above, we see a strong attenuation of the large regional anomalies. The three depocenters and the Inongo high give way to several positive and negative anomalies of low extent. Positive uplifts indicate the presence of antiform folds formed by compressive movements in this area or high density mineral substances, while negative anomalies reveal the presence of synform structures or low density mineral substances.

3.6 HORIZONTAL AND VERTICAL DERIVATIVES MAPS

3.6.1 HORIZONTAL DERIVATIVES

Gravity data is generally rich in information about geological structures. They are particularly useful for identifying deep faults, and characterizing their extension and ramifications (Everaerts and al., 2001 [11]). Faults and geological boundaries are lineaments that bring blocks of different densities into contact and appear on a map of the Bouguer anomaly as zones of gradients. The Bouguer anomaly above a vertical contact (fault or lithological contact) is materialized by a curve having a minimum on the side of low density rocks and a maximum on the side of high density rocks (N. El Goumi and al., 2010 [12]).

The horizontal gradient method makes it possible to identify all these areas of gradients and present them as maxima. It should be noted that the calculation of a horizontal gradient in a given direction makes it possible to bring out most of the lineaments of said zone in a direction perpendicular to that of the filter applied. Thus, in order to highlight a maximum number of lineaments in our study area, we filtered the Bouguer anomaly map in the X and Y directions (fig. 5).

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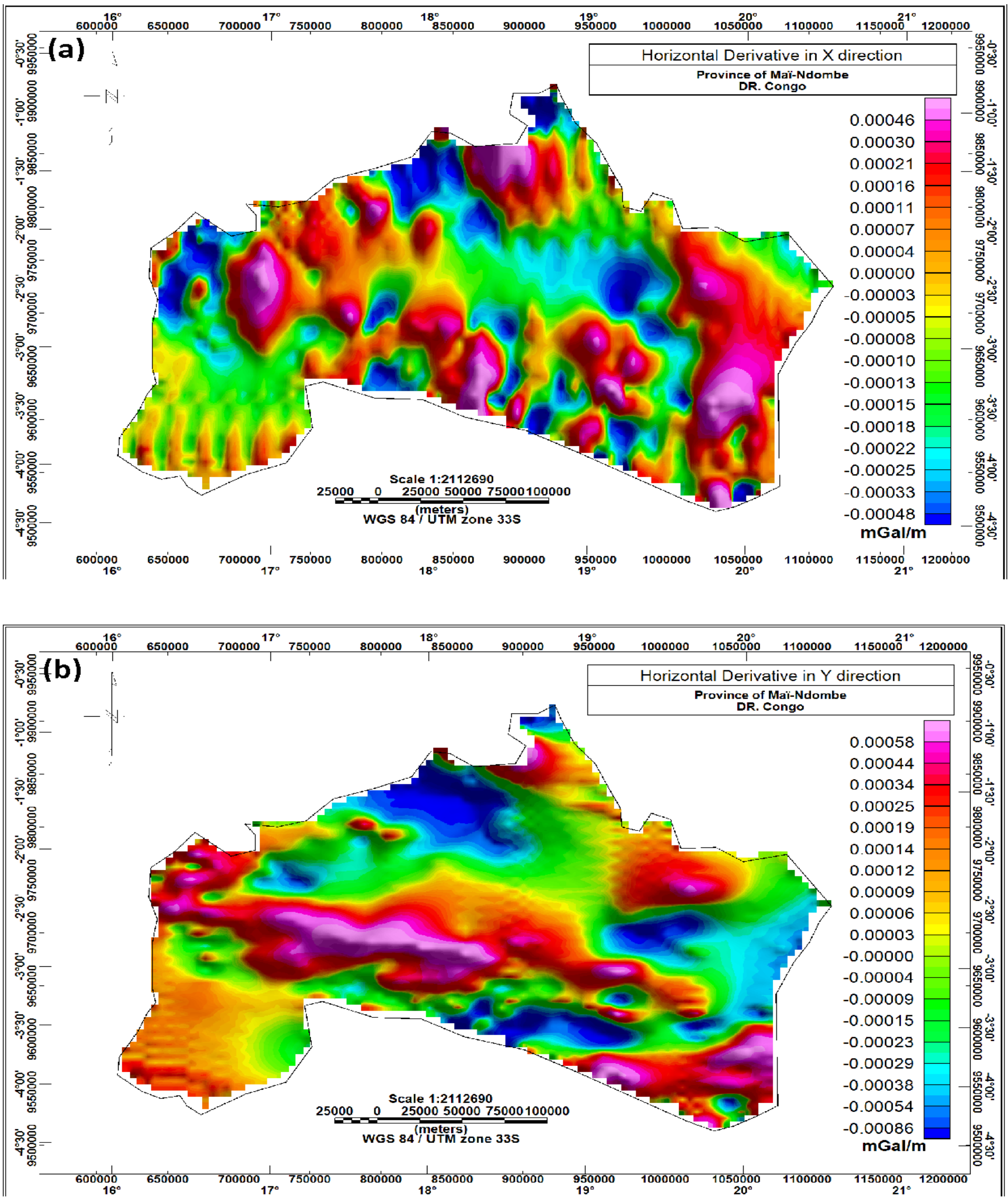

Figure 5: Gravity horizontal derivative maps: (a) in X direction; (b) in Y direction.

These horizontal derivatives filters along the two directions made it possible to determine the zones of lateral density contrast that can be positive or negative according to the sign of their intensity. These density contrast zones are lineaments that reveal the presence of structures such as faults or lithological contacts.

3.6.2 VERTICAL DERIVATIVES

The first and second vertical derivatives attenuate long wavelengths (associated to deeper geologic structures) and significantly improves the resolution of shallow structures. The use of these two filters on the Bouguer anomaly map amplified the effect of shallow sources by attenuating the effect of deep sources and made it possible to further define the geometric limits of bodies (fig. 6).

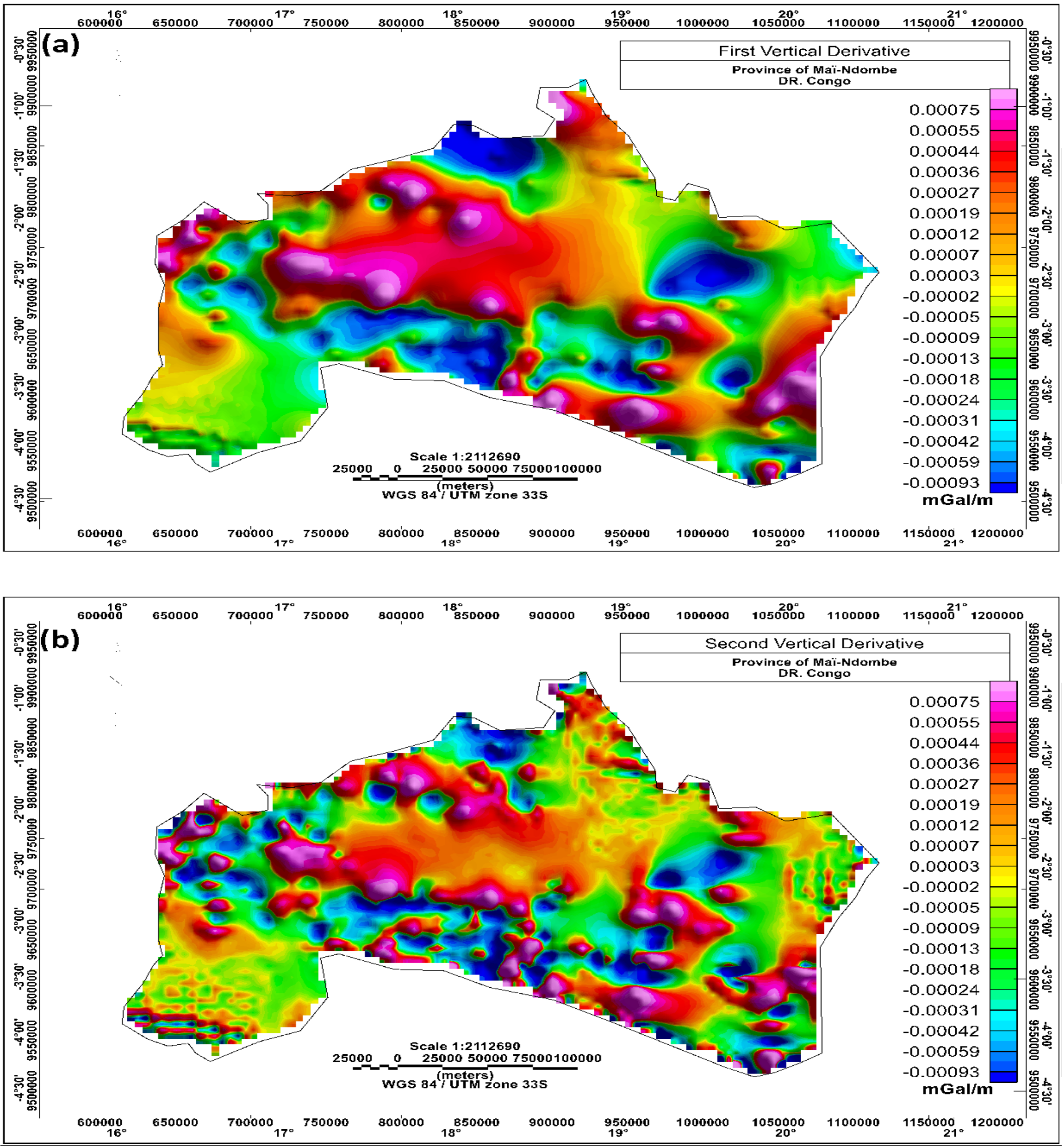

Figure 6: Vertical derivative maps: (a) first derivative; (b) second derivative.

We find that like the residual anomalies, the first vertical derivative map (Fig. 6a) shows several positive and negative circular anomalies. The Inongo high as well as its surrounding depressions clearly visible on the Bouguer and regional anomaly maps are replaced by small extent anomalies whose sources are associated to swallow masses. The second vertical derivative accentuates this effect by further individualizing the anomalies (fig. 6b).

3.7 THE UPWARD CONTINUATION MAPS

Unlike vertical derivative filters which accentuate short wavelengths, the upward continuation makes it possible to highlight long wavelength anomalies (Yvette H. Poudjoum, 1993 [13]). This filter has the effect of highlighting deep regional anomalies to the detriment of superficial anomalies. Such an operation is therefore equivalent to low-pass filtering. This is how the new values of the Bouguer anomaly can be calculated on parallel planes in 5, 10 and 15 km over our sedimentary basin (fig. 7). More ones go up, deeper we record information about thickness. We know that the Cuvette Centrale is a sedimentary basin that can reach sedimentary thicknesses greater than 9 km in some depocenters.

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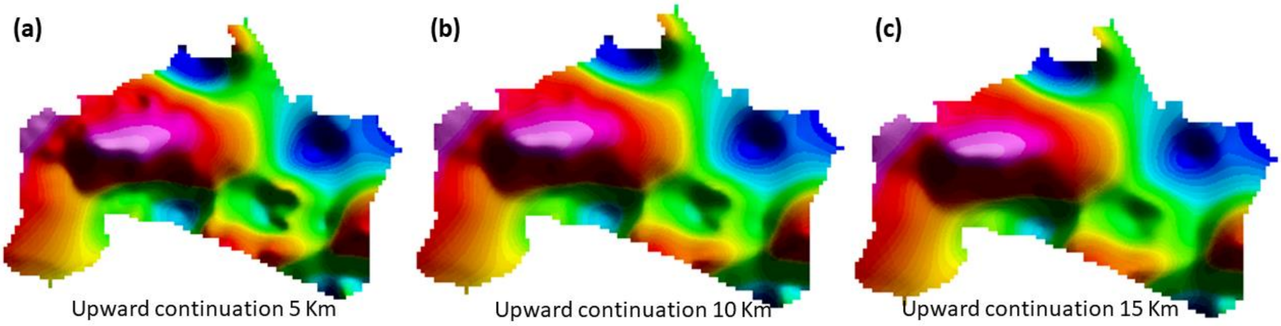

Figure 7: Bouguer anomaly upward continued maps: (a) 5 kilometers; (b) 10 kilometers and (c) 15 kilometers.

The 5 km upward continuation map (fig. 7a) closely look like the initial maps. We still find the anomalies described above but with a slight smoothing. Compared to previous maps, we notice that the small anomalies of short wavelengths disappear giving way to the anomalies of long wavelengths on the 10 km upward continuation map (fig. 7b). At 15 km of altitudes (fig. 7c), only the sets of long wavelength anomalies remain which are linked to very deep sources. The separation of high intensity anomalies representing basement uplift and low intensities related to depocenters is felt as the height of the continuation increases. The demarcation of anomalies revealing the presence of huge fracture zones around these structures becomes clearly visible.

3.8 STRUCTURAL MAP

The integration of all the geological information resulting from the interpretation of gravity maps has enabled us to develop a structural map that improves our knowledge of the geological structures of oil interest which played a major role in the process of formation and migration of hydrocarbons and in their trapping (fig. 8).

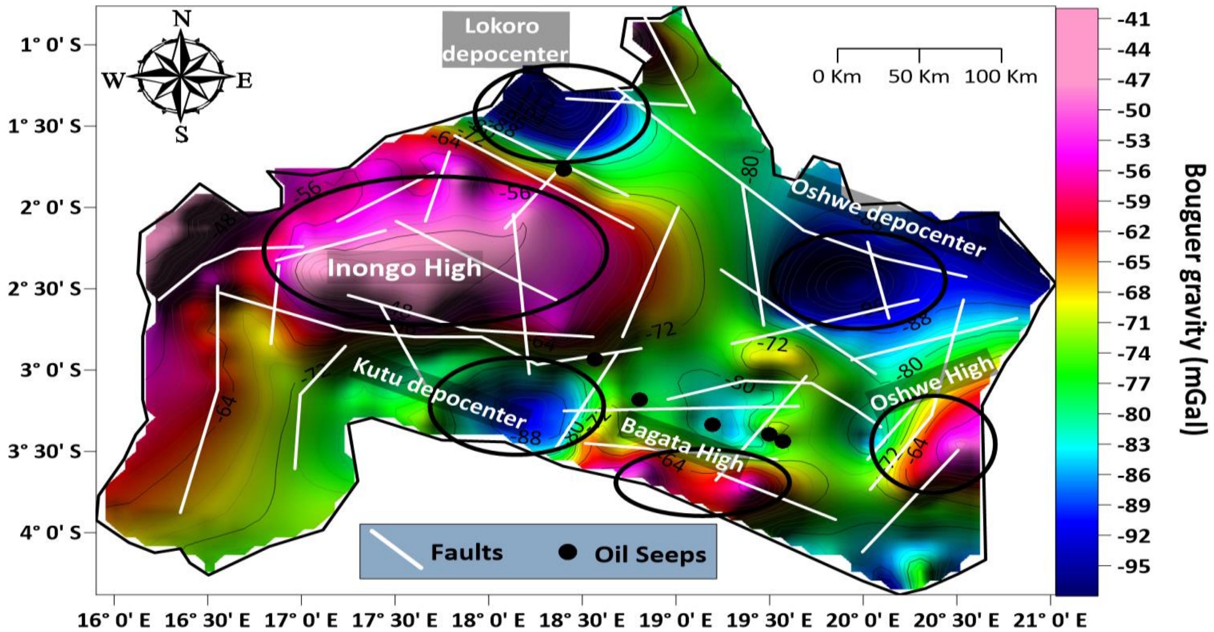

Figure 8: Structural map of the province of Maï-Ndombe.

On the map above, we stand out the following observations:

- Three large depocenters have been identified in the region: The Lokoro depocenter in the North, the Kutu depocenter in the South and the Oshwe depocenter in the East of the province. The gravity anomalies being strongly negative in these places, these zones therefore represent large depressions in which potential source rocks such as the Alolo shale, the Mamungi as well as the Kole formations can reach the degree of maturity. The oil seeps located near of the Lokoro depocenter in the beaches of Lake Maï-ndombe would probably be the result of a dysmigration of oil from the source rocks of this depocenter;
- It should also be noted that Tondozi et al., 2018 [10] showed from the seismic and gravity profiles, that the great salt layer of the Neoproterozoic thickened in the depressions of the Congo Basin. These large negative gravity anomalies of almost circular shape can also indicate the presence of a very thick salt layer in the depocenters;
- Reading this structural map shows us that the Inongo high is the highest geological structure while the Lokoro depocenter is the deepest geological structure in this province. These two structures being close, a part of the

oil formed in the Lokoro depocenter could easily migrate along the large faults to be trapped in the upper stages located in the Inongo high. As such, these two structures represent the most important oil targets in this region and should be the subject of much more seismic exploration. It should also be noted that the basement uplift in this area has created faults which could constitute excellent oil traps.

VI. CONCLUSION

The main objective that we pursued in this study was to analyze and interpret gravity data in order to improve the knowledge on the geological structure of the province of Maï-Ndombe in DR Congo. These data were processed using regional-residual separation methods, horizontal and vertical derivatives, and upward continuation. This is how we identified three major depocenters: Lokoro, Oshwe and Kutu. The gravity anomalies being strongly negative in these places, these zones thus represent depocenters in which the potential source rocks will be able to reach the degree of maturity. The oil seeps located near of the Lokoro depocenter in the beaches of Lake Maï-ndombe would probably be the result of a dysmigration of oil from the source rocks of this depocenter. We were also able to identify three structural highs: Bagata, Oshwe and Inongo which are very interesting areas that can trap large quantities of hydrocarbons. The Inongo high and the Lokoro depocenter are the most important oil targets in this region, and therefore will require further seismic exploration.

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