Choice of suitable regional and residual gravity maps, the case of the South-West Cameroon zone

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Abstract: The quantitative interpretation of gravity anomalies due to shallow structures needs separation between long wavelength anomalies (regional anomalies) and short wavelength anomalies (residual anomalies). The regional-residual field separation can be carried out using the polynomial method. In this case, the so-called regional field of order n is treated as a polynomial of degree n. The present study shows that the degree n must vary between a smallest value $n_{\text{min}}$ and a maximum value $n_{\text{max}}$. This article presents a method to process gravity data that allows determination of $n_{\text{min}}$ and $n_{\text{max}}$ for a given study area. We apply the method to gravity data of the South-West Cameroon zone. In this chosen study area, we find that regional anomaly maps of orders ranging from 1 to 9 and residual anomaly maps of orders ranging from 1 to 8 can be used for suitable interpretation. The analyses show that one may need residual anomaly maps of several orders to perform satisfactory quantitative interpretation of the different intrusive bodies found in a given area.

Keywords: gravity; regional anomaly; residual anomaly; upward continuation; correlation factors; intrusive body

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1. Introduction

On a Bouguer gravity anomaly map, gravity effects of shallow intrusive bodies are often masked by the influence of structures that are located deeper in the crust and generally of larger size. In such cases, it is possible to separate the gravity effects of the deep structures contained in regional anomaly maps and the gravity effects of superficial structures contained in residual anomaly maps. This regional-residual field separation can be carried out using the polynomial method (Agocs, 1951; Abdelrahman et al., 1985; Radhakrishna and Krishnamacharyulu, 1990) in which the so-called regional field of order n is treated as a polynomial of degree n. We can determine the smallest value $n_{\text{min}}$, of the order of the residual field for which all the gravity effects of deep structures are eliminated leaving only those of all intrusive bodies and other superficial structures. However, it is generally observed that the residual of order $n_{\text{min}}$ does not amplify, to its maximum, the gravity effects of all the intrusive bodies. For a given area, the gravity effect of an intrusive body, $c_i$, can be amplified to its maximum by the residual of order $n_i$. It is evident that the best anomaly map for quantitative interpretation of a given geological structure is that which amplifies its gravity effects to their maximum. Thus, one may need residual anomaly maps of several orders to perform comprehensive quantitative interpretation of the different intrusive bodies found in a given area. At the same time, for a given study area, a maximum value $n_{\text{max}}$ has to be assigned to the order n of regional field; this means that any residual field of order $n \geq n_{\text{max}}$ is unusable because of high noise level. In consequence, only residual and regional fields of orders ranging from $n_{\text{min}}$ to $n_{\text{max}}$ can be exploited in a credible way. Having said this, the following question arises: how can $n_{\text{min}}$ and $n_{\text{max}}$ be determined for a given study area?

In this article, we describe a method to process gravity data which we suggest will allow determination of $n_{\text{min}}$ and $n_{\text{max}}$ for a given study area.

2. Regional-Residual Separation

Regional-residual separation of gravity anomalies was performed using the polynomial method. The idea was to build a polynomial of suitable degree that generates an analytical area that fits the experimental surface by the least squares method (Agocs, 1951; Abdelrahman et al., 1985). This analytical surface represents the regional field. In practice, the so-called regional field of order n is treated as a polynomial of degree n. At a point $(x, y)$ on the surface, the regional field of order n can be written as (Radhakrishna
and Krishnamacharyulu, 1990)
\[
F_n(x; y) = \sum_{p=0}^{n} \sum_{q=0}^{p} C_m A_m(x; y), \quad (1)
\]
where \(C_m\) is a real coefficient, \(A_m(x; y) = x^q y^{p-q}\) and for every pair of points \((p, q)\), \(m = \frac{1}{2} [p (p + 3)] - q + 1;\) with the maximum value of \(m\) being \(\frac{1}{2}(n+1)(n+2)\).

Let \(G(x; y)\) be the value of the anomaly at a chosen point with coordinates \((x; y)\) on the surface; then the least square method gives:
\[
\sum_{i=1}^{n} G(x_i; y_i) \cdot A_k(x_i; y_i) = \frac{1}{2(n+1)(n+2)} \sum_{m=1}^{n} C_m \sum_{i=1}^{n} A_k(x_i; y_i) \cdot A_m(x_i; y_i), \quad (2)
\]
where \(k = 1, \ldots, \frac{1}{2}(n+1)(n+2)\).

By developing equation (2), \(\frac{1}{2} (n+1) (n+2)\) equations are obtained which allow for the determination of \(\frac{1}{2}(n+1)(n+2)\) coefficients \(C_m\). \(F_n(x; y)\) can then be calculated using equation (1) and the residual of order \(n\) deduced by
\[
R_n(x; y) = G(x; y) - F_n(x; y). \quad (3)
\]

3. Choice of Regional and Residual Anomaly Maps

In this section, we select regional and residual anomaly maps that can serve as the basis for a credible analysis of the geological structures of a particular basement. We then describe a method to process these gravity data that allows the determination of \(n_{\text{min}}\) and \(n_{\text{max}}\) and we apply our method to gravity data of the Southwest Cameroon zone, which lies between latitudes 2°24′N–4°00′N and longitudes 9°55′E–11°30′E. These gravity data were first collected during gravity surveys of Central Africa by ORSTOM (Collignon, 1968). They were later completed by surveys of Princeton University in 1968, University of Leeds in 1982, IRGM and University of Leeds between 1984 and 1988 (Poudjom-Djomani et al., 1996). The data acquisition campaigns were carried out using cars, along roads or tracks suitable for vehicles. The ORSTOM measurements were made at intervals of 3 km while the other measurements were made at intervals ranging from 4 km to 10 km. The coordinates were determined from topographic maps and compass routes; the altitudes were obtained by barometric leveling using the Wallace & Tiernan or Thommen (type 3B4) altimeters and GPS (Global Positioning System). The gravimeters used were the Lacoste & Rombert (model G, n° 471 and 823), Worden (n° 69, 135, 313, 1153), North American (n° 124 and 165), World Wide (n° 36) and the Canadian Scintrex (n° 305G) gravimeters. The measurements were connected to the gravitational bases of the ORSTOM base network in Africa, known as the Martin network (Duclaux et al., 1954). The gravity values were measured with an average precision of 0.2 mGal. The error on the coordinates of most stations was around 0.1 minute, and varied from 0.1 to 1 minute for some hard-to-reach stations, i.e., approximately 200 to 2000 m. This error was less than 200 m for coordinates measured by GPS. A Bouguer reduction density was 2.67 g/cm³. The reference system chosen was the IGSN71 (International Gravity Standardization Network 1971). The data acquired by ORSTOM were attached to the reference system of Postdam 1930. In order to maintain homogeneity, all the compiled data were converted into the IGSN71 system. The distribution of points of measurement of gravity is shown in Figure 1.

3.1 Determination of \(n_{\text{min}}\)

The smallest value \(n_{\text{min}}\) must correspond to the order of the residual field that fully captures the gravity effects of all the intrusive bodies of the study area. The upward continued field at optimum height (Zeng HL et al., 2007) gives the regional field in which the gravity effects of all intrusive bodies are eliminated. To determine \(n_{\text{min}}\), we use the analytical method based on the minimum square deviation between the regional field and the upward continued field at the optimum height \(h_0\). We explain this method below, after briefly discussing the upward continued field at different heights and describing our procedure for determining \(h_0\) (Figure 2).

3.1.1 The upward continued field at different heights

The upward continuation ranges from the anomaly at height \(z = 0\) to the anomaly at height \(z > 0\). This operator acts like a filter by attenuating the short wavelengths, thereby revealing the anomalies related to deeper structures with respect to the continuation height (when \(z\) increases, the depth of the top of the anomaly source increases). Let \(g(x; y, z)\) be a function defined in the spatial domain in 3 dimensions; its Fourier transformation in two di-

Figure 1. Distribution of gravity measurement points.
G\left(kx, ky, h\right) = G\left(kx, ky, 0\right)e^{-\lambda h}k^2x+k^2y; \quad (4)

\begin{align*}
C_f &= \sum_{i=1}^{M} \sum_{j=1}^{N} g_1(x_i, y_j) \cdot g_2(x_i, y_j) \\
&\quad \sqrt{\sum_{i=1}^{M} \sum_{j=1}^{N} g_1^2(x_i, y_j) \sum_{i=1}^{M} \sum_{j=1}^{N} g_2^2(x_i, y_j)}, \quad (5)
\end{align*}

We can then do the inverse transformation of G\left(kx, ky, h\right) to obtain g(x, y, h). We have used the FOURPOT program to calculate the upward continuation (Pirttijärvi, 2009).

### 3.1.2 The optimum upward continuation height

The optimum upward continuation height \( h_o \) of the gravimetric field is determined by the empirical method of Zeng HL et al. (2007). It consists of determining the Bouguer upward continuation height where the correlation between the upward continued fields, at the successive heights, presents a maximum deflection. The steps of data treatment done for the determination of the optimum height are as follows:

1. **Upward continuation of Bouguer anomalies** are calculated at many heights that are separated by regular intervals.
2. **Correlation factors** between the upward continued fields \( g_1 \) and \( g_2 \) at two successive heights are calculated using the relation (5) proposed by Abdelrahman et al. (1989).

\[
C_f = \sum_{i=1}^{M} \sum_{j=1}^{N} g_1(x_i, y_j) \cdot g_2(x_i, y_j) \\
\sqrt{\sum_{i=1}^{M} \sum_{j=1}^{N} g_1^2(x_i, y_j) \sum_{i=1}^{M} \sum_{j=1}^{N} g_2^2(x_i, y_j)}, \quad (5)
\]

where \( M \) and \( N \) are the number of sampling data along \( x \)-direction and \( y \)-direction respectively.

3. The correlation factor is plotted as a function of increasing continuation height by making each correlation factor correspond to the lower of the two successive heights.

4. **Deflection** at each height is calculated by the gap between the correlation factor curve and the line joining the two ends of the curve.

(5) The curve of variation of the deflection with respect to the continuation height is plotted. This curve attains a maximum at the height \( h_o \) corresponding to the optimum upward continuation height in the study area. In fact, Deflection is maximal when the maps of upward continuation at the two successive heights are such that one results from a structure of the subsurface consisting of a set of regular and extended layers while the other comes from a structure still containing localized intrusive bodies that disturb the regularity of its upper layer. This is why the upward continuation at the optimum height \( h_o \) gives a map of anomalies corresponding to a structure of the subsoil constituted of a set of regular and extended layers, so that the layer which is just above this structure is not extended linearly because disturbed by localized intrusive bodies.

The optimum height \( h_o \) has previously been determined (Koumetio et al., 2012) from the gravity data of the South-West Cameroon zone used in this study and its value is equal to 35 km.

To obtain \( n_{\text{min}} \), correlation factors between the Bouguer gravity anomaly map upward continued at a height \( h_o \) and the regional anomaly maps of different degrees are calculated. Then, the curve given these correlation factors as a function of the order of the regional field is plotted. Finally, \( n_{\text{min}} \) is taken to be equal to the degree of the regional anomaly map for which its correlation factor with the Bouguer anomaly map upward continued at a height \( h_o \) is maximal.

Applying this method to the gravity data of the South-West Cameroon zone described above, knowing that its \( h_o = 35 \) km, allows us to obtain the graph of Figure 2, which shows that the map of Bouguer anomalies upward continued at height \( h_o \) has a maximum correlation with the map of regional anomalies of order 1, which implies that \( n_{\text{min}} = 1 \) for the South-West Cameroon zone.

### 3.2 Determination of \( n_{\text{max}} \)

It has already been stated in Section 2 that the regional gravity anomaly has values with relatively large deviations from those of the Bouguer gravity anomaly when the degree \( n \) of the polynomial is small. In this case, the thickness \( e \) of the portion of the crust causing the corresponding residual gravity anomalies is relatively large. The thickness \( e \) gradually decreases as \( n \) increases. Thus the maximum value \( n_{\text{max}} \) of \( n \) is obtained when \( e \) tends to zero, which means that the regional anomaly map of order \( n_{\text{max}} \) has a very large correlation with the Bouguer gravity anomaly map.

To determine \( n_{\text{max}} \), we calculate the correlation factors between the Bouguer gravity anomaly map and the regional gravity anomaly maps of different degrees. We then plot the curve given these correlation factors as a function of the order of the regional field. Finally, \( n_{\text{max}} \) corresponds to the degree of the regional gravity anomaly map for which its correlation factor with the Bouguer gravity anomaly map is the first value on the asymptote of the curve.

The application of this method to the gravity data of the South-West Cameroon zone described above allows us to obtain the graph of Figure 3, which shows that \( n_{\text{max}} = 9 \) for the South-West Cameroon zone, which lies between latitudes 2°24’N–4°08’N and longitudes 9°55’E–11°30’E.
4. Discussion

The gravity data of the South-West Cameroonian zone (Collignon, 1968; Poudjom-Djomani et al., 1996) allow us to plot the Bouguer gravity anomaly map (Figure 4a). The regional-residual separation was carried out using the polynomial method (Radhakrishna and Krishnamacharyulu, 1990). Then we plot the regional gravity anomaly map of order 1 (Figure 4b), the regional gravity anomaly map of order 9 (Figure 4c), the residual gravity anomaly map of order 1 (Figure 5a), the residual gravity anomaly map of order 2 (Figure 5b) and the residual gravity anomaly map of order 3 (Figure 5c).

The regional gravity anomaly map of order 9 (Figure 4c) has almost the same intrusive bodies and the same isogals curves (but they are smoother on the order 9 map) as are seen on the Bouguer gravity anomaly map (Figure 4a); the maximum value (–1

![Figure 3](image-url)

**Figure 3.** Correlation factor between the grid of Bouguer gravity anomaly values and those of regional anomaly maps, as a function of the order of the regional field.

![Figure 4](image-url)

**Figure 4.** (a) Bouguer gravity anomaly map of the study area; (b) Regional gravity anomaly map of order 1; (c) Regional gravity anomaly map of order 9.
mGal) is the same for the two maps. This is in agreement with the result \( n_{\text{max}} = 9 \) for the South-West Cameroon zone. The regional gravity anomaly map of order 1 (Figure 4b) shows that the deep structures are oriented NNE-SSW, confirming the predominance of a submeridian tectonics in the region (Owona Angue, 2012; Koumetio, 2004). Figure 4b shows also that the anomalies’ values increase steadily from the East to the West, but without suffering perturbations as is the case on the Bouguer gravity anomaly map (Figure 4a). The absence of the above mentioned disturbances on the regional gravity anomaly map of order 1 shows that the effects of intrusive bodies were completely removed at that order. This is in agreement with the result \( n_{\text{min}} = 1 \) for the South-West Cameroon zone.

These values of \( n_{\text{min}} \) and \( n_{\text{max}} \) suggest that a credible analysis can be made of regional gravity anomaly maps with order \( n \) ranging from 1 to 9 and of residual anomaly maps of order \( n \) ranging from 1 to 8. The residual of order 9 is eliminated because all residuals anomalies of order \( n \geq 9 \) are strongly associated with noise as the regional anomaly map of order 9 can already be confused with the Bouguer anomaly map.

There is a gradual decrease in the maximum values of anomalies resulting from dense intrusive bodies when moving from the residual gravity anomaly map of order 1 to the residual gravity anomaly map of order 3, especially for anomalies found between Edea and Kribi, and those around Ngog Mapubi and Matomb. Also, there is a gradual increase in the minimum values of anomalies due to two intrusive bodies of low densities when going from the residual gravity anomaly map of order 1 to the residual gravity anomaly map of order 3, especially anomalies located around Bipindi and Pouma (Figures 5a, 5b and 5c). This indicates

![Figure 5.](image-url)
that the effect of a portion of each of these intrusive bodies has not been taken into account by residual gravity anomaly maps of orders greater than 1. This means that it is the residual anomaly map of order 1 that amplifies the effects of intrusive bodies located between Edea and Kribi, and those around Ngog Mapubi, Matomb, Bipindi and Pouma. Thus, it is the residual gravity anomaly map of order 1 that is suitable for quantitative interpretation of the intrusive bodies mentioned above. The maximum value of anomalies due to the intrusive body at Lolodorf increases from 1 mGal on the residual gravity anomaly map of order 1 to 17 mGal on the residual gravity anomaly map of order 2; it then decreases to 16 mGal on the residual anomaly map of order 3 (Figures 5a, 5b and 5c). This means that the effect of the intrusive body at Lolodorf is amplified by the residual gravity anomaly map of order 2, which is suitable for its quantitative interpretation.

In the seismological study by Tokam (2010), the depth to the top of the lower crust in the area of this present study was estimated to about 18 km. Tokam’s seismological study also determined that the lower crust is made up of basic rock types with a density that is nearly constant. The depth of about 18 km to the top of the lower crust and the constancy of its density can also be seen in the gravity model proposed by Owona Angue et al. (2011) along a profile extending from Kribi to Lolodorf. Koumetio et al. (2012) showed that the upward continuation of Bouguer anomalies at a height of 35 km has a maximum correlation with the regional gravity anomaly map upward continued at optimum height of 17.5 km. This also means that the residual gravity anomaly map of order 1 shows the effects of structures located at depths greater than the optimum height h/2 = 17.5 km. It has been established in this study that the Bouguer gravity anomaly map upward continued at optimum height of h = 35 km has a maximum correlation with the regional gravity anomaly map of order 1, which means that the regional gravity anomaly map of order 1 presents the effects of structures located at depths greater than h/2 = 17.5 km. This also means that the residual gravity anomaly map of order 1 shows the effects of structures located at depths less than h/2 = 17.5 km, which can be approximated to 18 km.

Indeed, the seismological data of Tokam (2010) and Tokam et al. (2010), consisting of 5 shear waves velocity models, were recorded for two years on a temporary network of 32 broadband seismological stations deployed throughout the Cameroonian territory. Four of the 32 stations operated in this study area. These are the stations CM01, CM05, CM06 and CM07 placed on the map of Figure 5c. Tokam (2010) and Tokam et al. (2010) represented shear waves velocity (V_S) models for the 32 stations. We extracted the models of the stations CM01, CM05, CM06 and CM07 (Figure 6). They represent the vertical variations of the structure of the subsurface over a depth of 80 km, that is to say the crust and a superficial part of the mantle. Authors such as Christensen and Mooney (1995) have shown that in Precambrian basement regions such as ours, mantle rocks are already present when V_S ≥ 4.3 km/s. The studies of Tokam (2010) and Owona Angue et al. (2011) show that the lower crust rocks are present when 4 km/s ≤ V_S ≤ 4.3 km/s. Thus, Figure 5c allows us to say that under the stations CM01, CM05, CM06 and CM07, we locate on the one hand the depth of the Moho at 28 km, 28 km, 45.5 km and 43 km respectively and on the other hand the depth of the roof of lower crust at 17.75 km, 17.75 km, 17.75 km and 20.25 km respectively. It can be seen that there is a large variation in Moho depth between the coastal zone and the Congo craton, whereas this variation is small in the case of the depth of the lower crust roof, which we can estimate on average as about 18 km in our study area.

Ultimately, one can say that the results of the studies of Tokam (2010), Tokam et al. (2010) and Owona Angue et al. (2011) mentioned above corroborate the results of this work as they make it clear that the residual gravity anomaly of order 1 of this study area eliminates the effects of the mantle and lower crust while retaining all the effects of all intrusive bodies and other geological structures in the upper crust. Since the depth to the boundary between the upper and lower crust is almost constant in this study area, this limit can be approximated to a planar surface; this observation further justifies the value of 1 obtained for n_min. Further corroboration is that in the Adamawa zone (Cameroon), Noutchogwe (2010) found that the Bouguer gravity anomaly map upward continued at optimum height has maximum correlation with the regional gravity anomaly map of order 4. This allows one to write that for the Adamawa zone n_min = 4. This result is under-

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**Figure 6.** Shear wave velocity models of four seismological stations located in the study area (modified after Tokam, 2010). Stations CM01 and CM05 are in the Coastal sedimentary terrain while CM06 and CM07 are in the Congo Craton terrain. The depths in km of the top of lower crust and of upper mantle are shown as numbers on each model.

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standable because the structure of deeper layers of the Adamawa area takes into consideration the effects of the lithospheric thinning and of the rise of the Moho (Poudjom-Djomani, 1993; Poudjom-Djomani et al., 1992). So, the surface representation of the regional field of order \( r_{\text{min}} \) in the Adamawa area must be curved.

5. Conclusions
In this article, we have described a method of processing gravity data that allows choice of the orders of the regional and residual gravity anomaly maps that can permit a credible analysis of the geological structures of the basement under study. In the chosen study area, it was found that regional anomaly maps of orders ranging from 1 to 9 and residual anomaly maps of orders ranging from 1 to 8 can be credibly analyzed. Analysis of residual gravity anomaly maps of orders 1, 2 and 3 in this study area led to the following conclusions:

1) The residual gravity anomaly map of order 1 is suitable for quantitative interpretation of intrusive bodies located between Kribi and Edea, thus located to the northwest of Ambam, at Matomb, at Bipindi and at Pouna;

2) The residual gravity anomaly map of order 2 is suitable for quantitative interpretation of the dense intrusive body at Lodorof.

These results make it clear that one may need residual anomaly maps of several orders to perform full quantitative interpretation of the different geological structures found in a given area.

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